The Design and Implementation of EarthScope's USArray Transportable Array

in the Conterminous United States and Southern Canada

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A note on the purpose of this document: This report documents the design and implementation details of the complete as-built Transportable Array (TA) 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 exactly what equipment was used in the TA, how it was installed, and how it was operated.

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1. Introduction

This report reviews the design, implementation, and operation of key aspects of the Transportable Array (TA) as deployed in the conterminous United States (the "Lower 48" or L48). The Incorporated Institutions for Seismology (IRIS) operated this array of ~400 seismographs between 2004 and 2015. The TA is the largest element of the multidisciplinary USArray facility that in turn is a major component of the National Science Foundation (NSF)-sponsored EarthScope program. Underway since 2003, EarthScope investigates the geologic structure and dynamics of the North American continent. In addition to USArray, EarthScope includes the Plate Boundary Observatory and the San Andreas Fault Observatory at Depth, and a research grant program for funding PI-led scientific proposals. In total, the EarthScope observatory is comprised of multidisciplinary observing components, including seismic, geodetic, strain, magnetotelluric, LiDAR, and drill core sampling.

The foremost goal of the L48 TA was to collect robust, uniformly spaced observations of the seismic wavefield at many different scales and bandwidths (Figure 1-1). To this end, TA 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 occupied for 18–24 months. This 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 ~2,100 km north-south by ~850 km east-west. Altogether, 1679 TA stations were installed and operated, and the migrating L48 TA footprint was removed by October 2015 (Figure 1-2).

Specific elements of the TA operated in longer-term, semi-permanent deployments before, during, and after the passage of the TA 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 (Figure 1-2). 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 1679 TA stations includes these, but omits a handful of TA network code stations that were used for various demonstration and testing purposes and that did not use the standard TA design or instrumentation (Appendix A).

In addition, several state agencies and regional network operators adopted 79 TA stations. Some groups absorbed the stations into their networks and altered their configuration, while others hired IRIS to continue to operate these stations under the TA network code as part of the Education and Research Network (EARN) program. EARN service peaked at 33 stations. Finally, IRIS operated 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 led by NSF and operated into 2018, when the USGS absorbed most stations into their operation. In this way, the legacy of the TA discussed in this report continues beyond its original intent.

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

- Those elements of TA design and implementation that may 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.
- The design and implementation of the TA, so that other station / network operators have access to key details about the construction or installation procedures. We try to emphasize information about operation policies and strategies over transitory technical details (e.g., brands of cellular hardware).

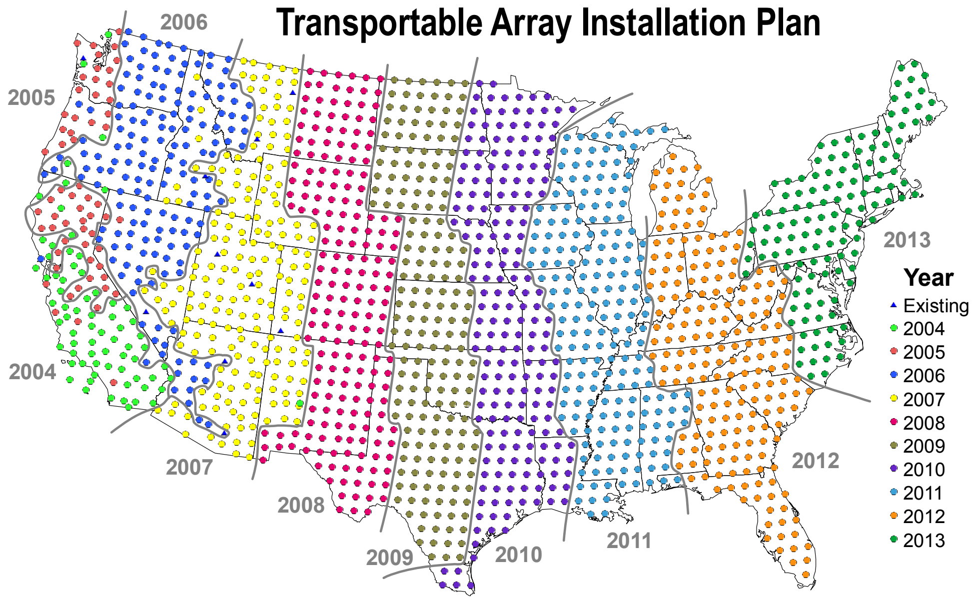


Figure 1-1. Map of 10-year deployment plan for the TA, showing the nominal grid spacing of 70 km between stations and illustrating the planned year-by-year deployment progress. Note: The westernmost stations reflect the actual deployment locations.

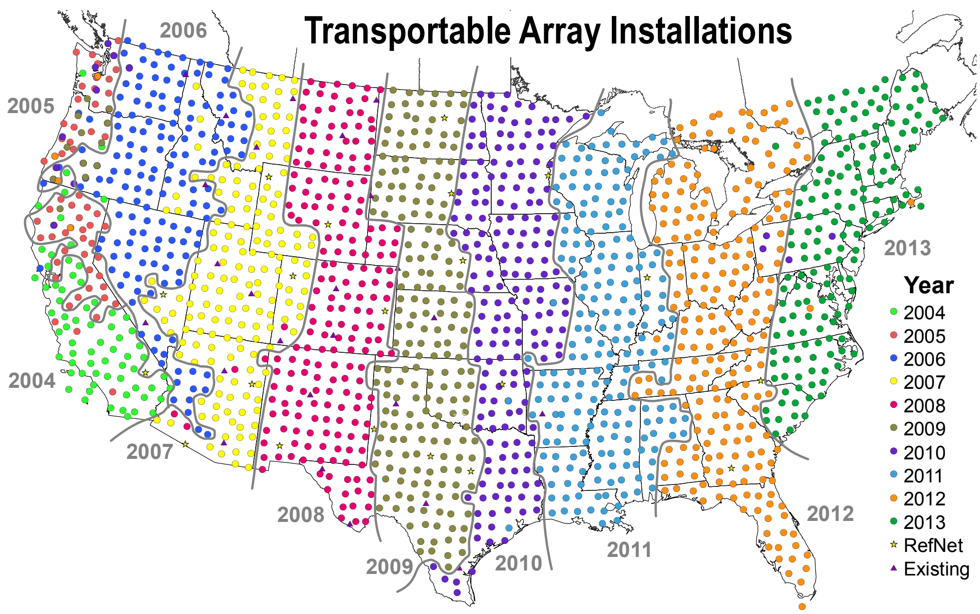


Figure 1-2. Map of the 10-year TA as built. The final station locations achieved the planned grid, and the year-by-year progress followed the initial plan quite closely.

Please also note that this report only addresses the TA as it was deployed in the conterminous United States and southern Canada in the period 2004–2015. Subsequently, the TA was deployed across Alaska and adjacent parts of Canada, with a station spacing of 85 km. The Alaska TA was fully deployed in fall 2017 and will operate continuously to 2019 and perhaps longer. Numerous, fundamental aspects of the TA implementation were changed for the deployment in Alaska and Canada. A similar report for that deployment is expected.

1.1 GOALS AND OBJECTIVES OF THE EARTHSCOPE/USARRAY/TA

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.

From a technical perspective, the TA was designed at the outset with high aspirations for data integrity, quality, and quantity while recognizing the large geographic scale of the project, and the large number of stations. The overarching philosophy for TA deployment and operation was to use a manufacturing approach, with the goal of creating uniform and consistently high-quality seismic stations with low maintenance requirements (Figure 1-3). Stations were constructed and installed by a small number of professional field crews that used the same plans and equipment, as much as possible, for every site. Sites were selected at locations away from potential disturbances, in remote or protected locations far from cultural noise sources. Vaults were constructed to be resistant to external effects (pressure, temperature, fire, and moisture). Stations were autonomously powered and wirelessly networked to allow flexibility in site selection and improve reliability by minimizing wire-induced high-voltage fault transients. Hardware encompassed observatory-grade sensors, dataloggers, storage, and communications. Standardized, custom-designed hardware enclosures and fittings ensured that there were minimal points of failure within the station. Downstream from the station, a data collection center received, analyzed, and displayed incoming state-of-health and waveform data streams in near-real time and facilitated the complete archiving of all data collected by each station at the IRIS Data Management Center (DMC).

Figure 1-3. Photo of station TA.W52A (Murphy, NC), with solar panel assembly in front of an infrasound sensor cage and buried seismometer vault.

The functional requirements of the TA implementation included:

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

1.2 TRANSPORTABLE ARRAY DEPLOYMENT

Deploying the L48 TA required the coordination of staff and resources that were distributed across the country at the IRIS offices (Washington, DC, and Seattle, WA), the Array Operations Facility (AOF, New Mexico Tech University), the Array Network Facility (ANF, University of California, San Diego), and Honeywell Technology Solutions Inc. (Albuquerque, NM), as well as at numerous small awardees. Some staff members were already experienced with the process of collecting seismic data in support of IRIS activities such as the Global Seismographic Network (GSN) or the Portable Array Seismic Studies of the Continental Lithosphere (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, 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 occurred 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, 200 stations each year in a seasonal process that was repeated over eight years (Figure 1-4). 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.

ROLE OF CONSTRUCTION: The construction team consisting of an IRIS supervisor and two to three construction contractors focused on constructing the civil works that were as close to uniform and secure as possible. Tasks included excavation, cementing of an underground vault, laying conduit, emplacement of pole to support the solar panels, and erection of livestock fencing as needed. The vault was left sealed but ready for instrumentation.

ROLE OF INSTALLATION: The installation team consisted of two persons with expertise in instrumentation to install the seismometer, datalogger, and communications

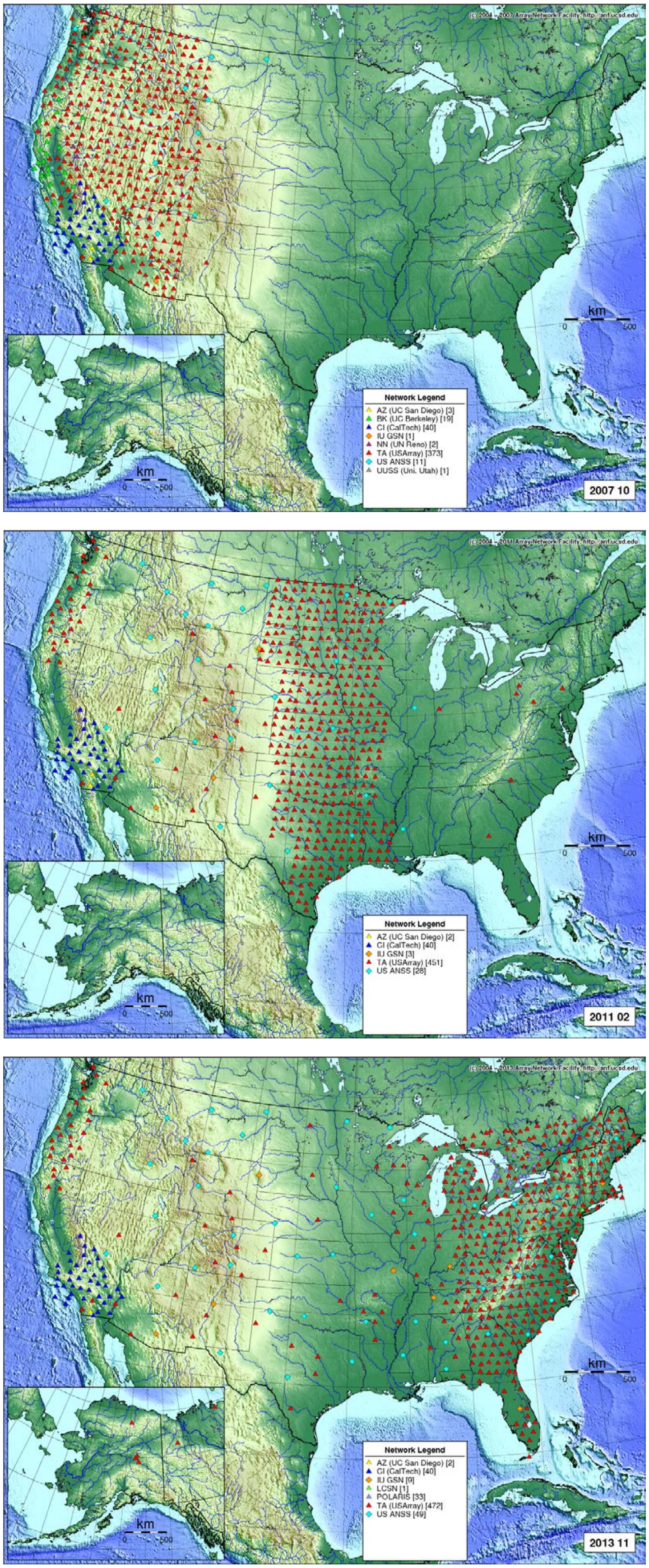


Figure 1-4. A sequence of deployment snapshots generated by the Array Network Facility, showing the TA "rolling" across the mid-continent (http://anf.ucsd.edu/stations/deployment_history.php). The top map shows the array as of October 2007, the middle map is a snapshot from February 2011, and the bottom map shows the array in November 2013, two months after the final stations were deployed.

and power systems. The two-phase process allowed the construction and installation tasks to proceed independently depending on weather, landowner availability, and a host of other logistical factors. The crews worked at northern latitudes or high elevations during the summer and 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. A construction manual and parts reference can be found here: http://www.usarray.org/researchers/obs/transportable/l48_ta_report.

ROLE OF REMOVAL: A separate team swept along the western portion 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 miles away. The removal crew also recovered the grounds of each site to the satisfaction of the landowner.

ROLE OF THE AOF AND SUPPORTING MANAGEMENT: 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 within this facility directed construction contractors, managed the permits, and oversaw engineering design and documentation for all stations. TA management, as IRIS personnel, actively oversaw and coordinated these activities.

ROLE OF THE ANF: Relying on strong coordination with the field crews, initial data collection from newly deployed stations most often occurred while the installation crews were still on site. Strict requirements for systematized notification of equipment installed at the site led to certification of new TA stations after a few days of comprehensive data and metadata assessment by the ANF, which received and monitored all incoming data and provided station metadata for forwarding to the IRIS DMC for archiving. Waveform and state-of-health time series were monitored by the ANF to maintain data integrity at each station.

After a station was certified, service personnel performed any necessary visits to the station to address any issues identified by the remote monitoring of station performance. The ANF was also responsible for finalizing the archiving of each station as it was closed, comparing the received data with the onsite records (stored on a Quanterra Packet Baler). The data from the onsite Baler was amended with any telemetered data that filled an onsite gap, and the entire record was replaced at the IRIS DMC, representing a transition from R to Q in the miniSEED data type (waveform data). 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.

2. Transportable Array System Overview

2.1 PRINCIPLES OF THE TA STATION DESIGN

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 and 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 station was designed for very low power operation, ~4 W and included the capabilities for different modes of telemetry. This design also 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 can be separated from the seismic instruments to be near a power source or at a location far enough away that the large 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 simple installation. The enclosure could be cut onsite to adjust the vertical dimension to the local conditions, and the internal mounting of equipment was designed to adjust to varying heights within the enclosure.

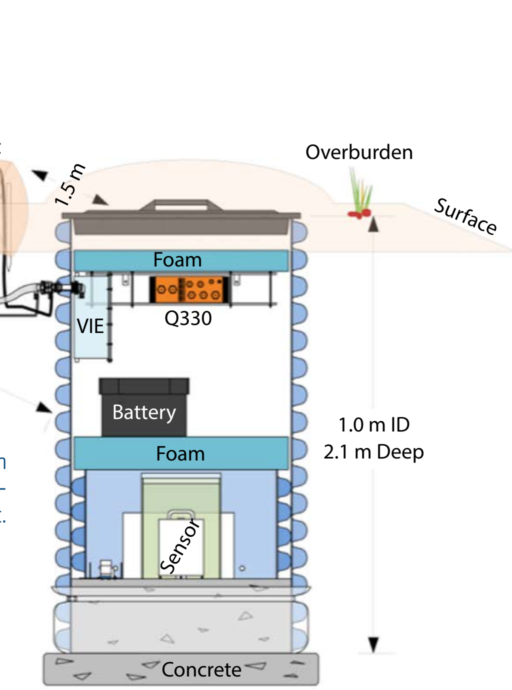


Figure 2-1. Cutaway illustration of a typically deployed TA station for a first generation vault.

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 for Internet service (e.g., Hughes DirectWay), 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, using the same commonly available construction materials and designs. The initial design was field tested before being extended to the TA. Notable changes to the design of stations 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.

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. The Baler provided a permanent onsite archive of all recordings, creating an onsite backup to the telemetered data.

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. This analysis was followed by calls to obtain local assistance as needed and set up visits. Potential for cellular 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 3.1) that entailed evaluating potential locations, assessing local conditions, verifying cell coverage or VSAT capability with specific protocols, and talking to potential hosts and other locals. 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. Choice 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

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

Table 2-1. General criteria used for selecting TA sites.

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

Table 2-2. Key principles applied to site selection and permitting.

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.

TA 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. In addition, in California, Nevada, and New Mexico, the TA cooperated with regional network operators to obtain permits, primarily with public land agencies.

The station code assigned to each station (which conforms to SEED format) consists of three characters representing geographic location (Figure 2-2). 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 or if

[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 2-2. Breakdown of TA station codes, with examples.

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 the 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 placename-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.

When the L48 TA was active, USArray policy was to disclose the station locations to only two decimal places of accuracy on web-based tools that were designed for general public outreach to limit inappropriate uses (e.g., geocaching) of TA stations. Station locations were actually measured to an accuracy of five decimal places in latitude and longitude, or meter-scale resolution. These high-accuracy locations were always made available via the standard data access tools at the IRIS DMC. Only the various "Google map" style interfaces at the DMC used the reduced-accuracy locations.

2.3 VAULTS AND CONSTRUCTION

TA vaults were designed to provide a dry, thermally stable, secure, structured environment for data acquisition. The type of deployed vault 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 to increase thermal stability.

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 2-3). 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 impermeable material, an impermeable apron was placed around the tank mound to shed water away from the disturbed area. The top of the plastic pipe was typically completely covered with a mound of soil making it fairly unobtrusive. We tried to keep it out of the wind and out from under trees, so we often selected hillsides or ridge saddles.

In 2011, the second generation vault was introduced (Figures 2-4 and 2-5). Freeman Engineered Products produced this custom vault in response to an RFP 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 air pockets in the liquid concrete beneath the tank. The integrated floor eliminated the need for the rubber membrane and greatly improved the waterproofness of the

Figure 2-3. Construction of TA.BNLO using first generation vault.

Figure 2-4. Construction of TA.H17A, Yellowstone National Park. The site used the second generation vault.

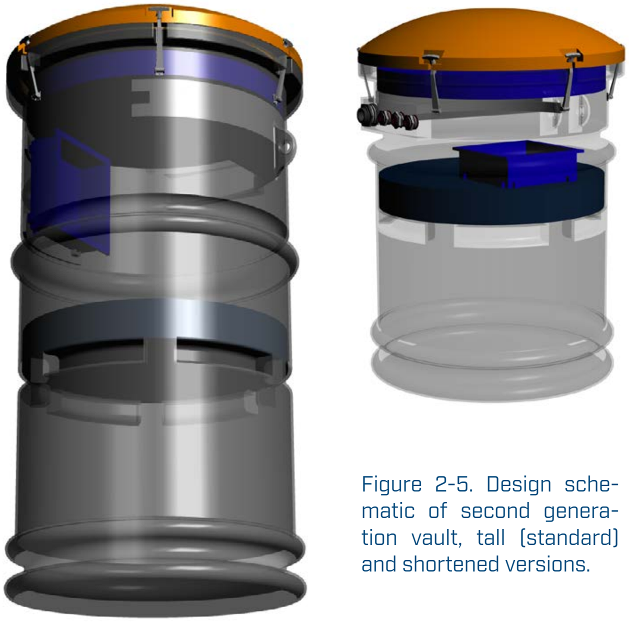


Figure 2-5. Design schematic of second generation vault, tall (standard) and shortened versions.

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 vault interface enclosure (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

Overall, the depth of the vault, paired with the internal insulating layers, led to improved thermal stability compared to more typical shallow vaults, reducing a potential source of noise. The first generation vault performed well at many sites, but 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 entry into 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.

The mound of soil covering the buried vault was an important insulator, reducing thermal variation at the sensor. It also provided a measure of fire protection, keeping the plastic tank away from contact with flame and igniting, as well as 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.

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 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.

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. Extensive notes and photo documentation were taken at each station to record the site conditions, exact instrument serial numbers, and any important items of note. 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 2-6). 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.

The installation procedure began with establishing a permanent reference mark, as described in section 1.9.1 below, and then emplacing the sensor and any secondary instruments, connecting the power supply elements, interconnecting the station components,

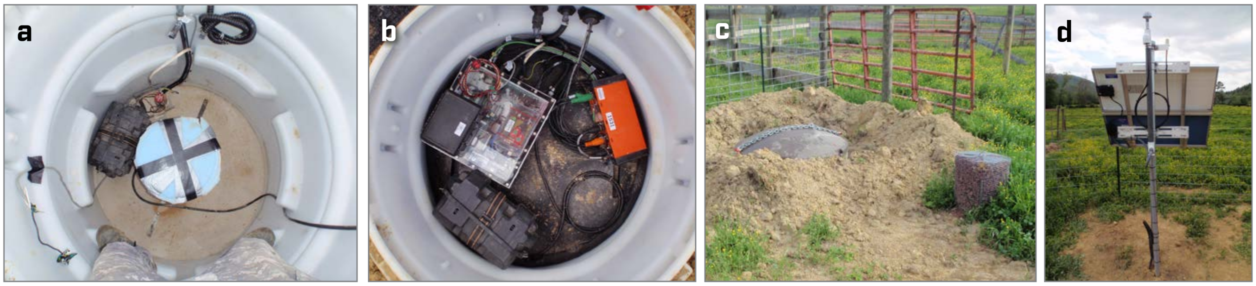


Figure 2-6. TA.W52A (Murphy, NC), with completed lower chamber, with seismometer wrapped in blue foam insulation and battery to its left (a), completed upper chamber (b), mostly buried vault with infrasound enclosure (c), and solar/gps/communications mast (d). Note that this is a shorter version of the second generation vault, with resting VIE configuration.

via the VIE, configuring station information, and establishing the telemetry capability. Cellular modems were the standard design for installation. VSAT and/or radio setup required an extra 8 to 15 hours onsite 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. 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. Some of the more relevant details in the station design are discussed below.

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 2-7). 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 contains:

- Power regulation circuit board with numerous LED indicators
- Quanterra Baler 44, including USB media for data storage
- Connector interface circuit board
- PV Charge controller
- Modems, radio, or satellite terminal equipment

Figure 2-7. (a) Vault interface enclosure unit with lid removed and (b) as installed within vault (TA.L62A), with (c) close-up on the connectors (TA.D60A).

- 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 inches, with a 0.5 inch 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 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 of 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 (Figure 2-8). 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 2-9). 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).

External communications modules (i.e., those physically distinct from the station) were nearly always powered by host AC (Figure 2-10). The power consumption of the AC-hosted equipment (whether VSAT or cable modem or DSL modem) was about 25 W, and amounted

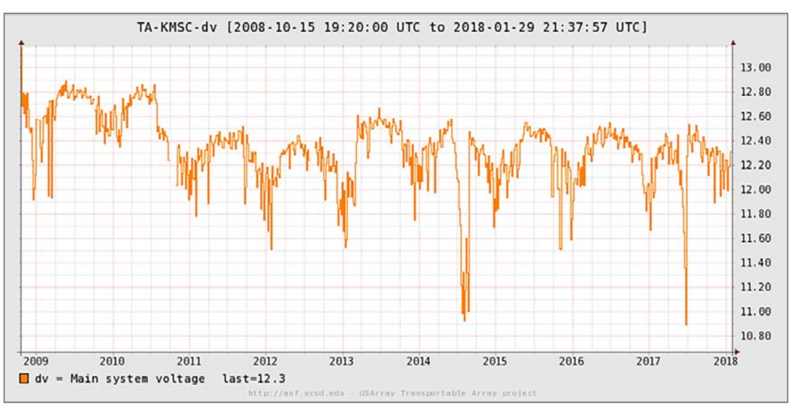


Figure 2-8. Voltage levels at TA.KMSC (a RefNet station that did not use grid-based naming scheme), showing seasonal variations in power levels based on input from solar panels.

Figure 2-9. TA.KMSC, a site with good skyview and cellular telemetry only requires a single panel.

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 photovoltaic (PV) solar arrays sized for the expected amount of sun (Figure 2-11). 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 6.7 m (22 ft) 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, 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.

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. A handful (1.7%) of stations used STS-2.5 and STS-5A posthole broadband

Figure 2-10. TA.D16A, a site with AC VSAT and radio relay to the station.

Figure 2-11. TA.N02C, a site with DC (Solar) VSAT

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 2-12). 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 2-13). 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 2-14). We concluded that CMG-3Ts were most likely to fail under the demands of this operation, and we relied upon these less as the deployment progressed.

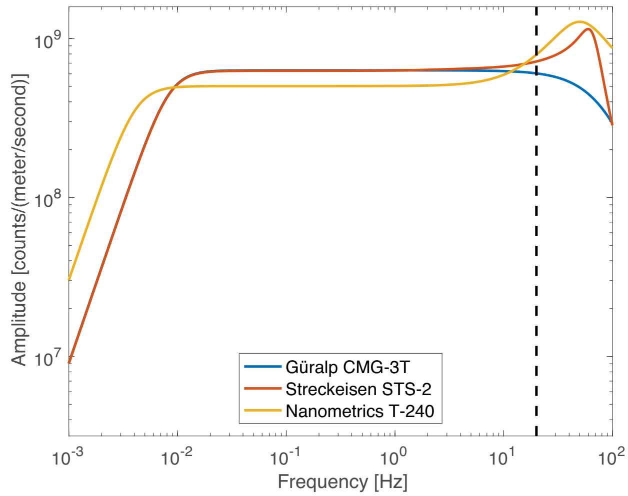


Figure 2-12. Individual responses of the three main broadband seismometers operated by the TA. Dashed line indicates the Nyquist frequency at TA stations.

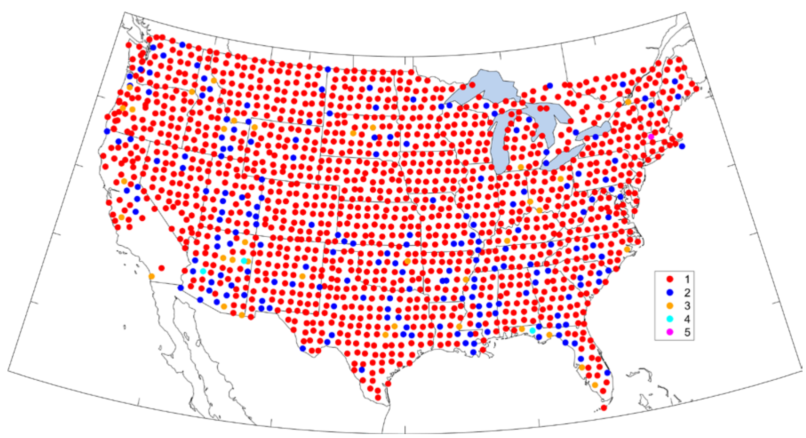


Figure 2-13. Number of broadband seismometers installed at each TA station through 7/20/17.

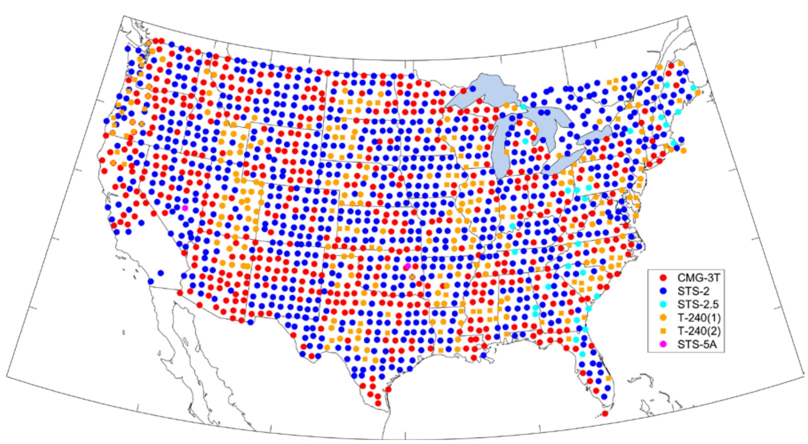


Figure 2-14. First broadband seismometer installed at each TA station.

Strong Motion Sensors

We operated strong motion sensors at a handful of TA stations 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 2-15). These instruments have a frequency response that is flat to acceleration (Figure 2-16). The Kinematrics 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 2-17). 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.

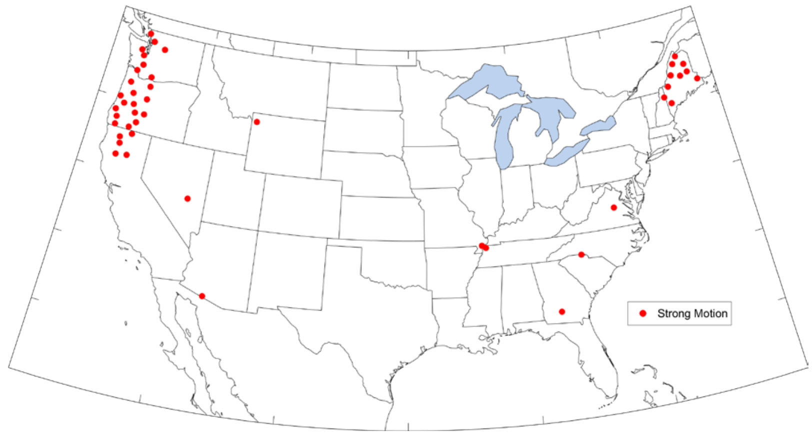


Figure 2-15. TA stations that operated strong motion instruments, through 9/30/2015.

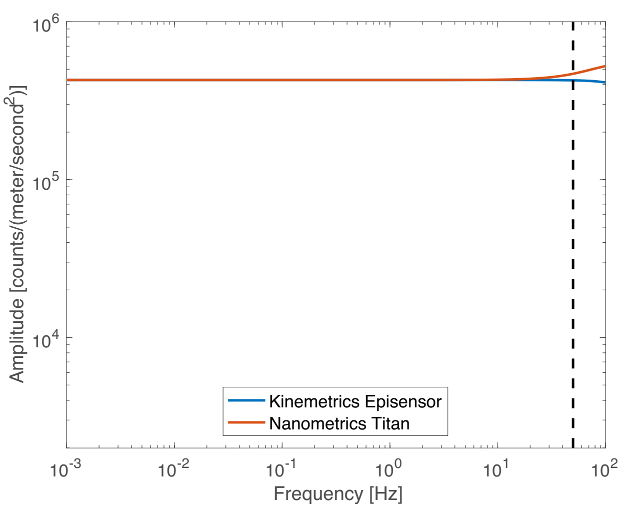


Figure 2-16. The responses for the two types of strong motion instrument operated by the TA. Dashed line indicates the Nyquist frequency at TA stations.

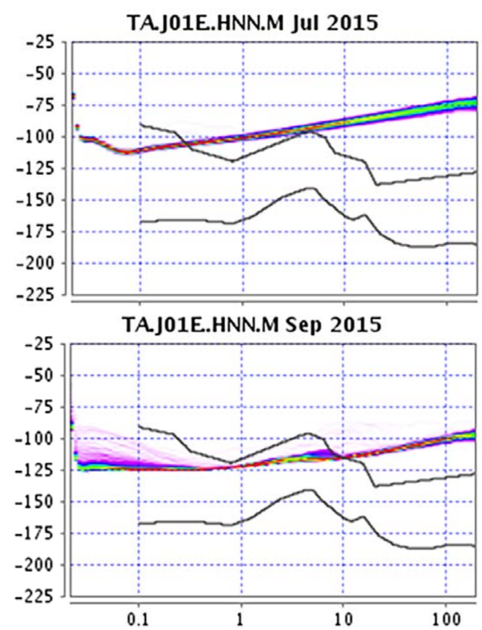


Figure 2-17. Example of the effect of "zinc whiskers" in monthly power spectral density estimates, before and after replacement of the sensor.

Auxiliary Sensors

The TA began to add environmental and atmospheric observations to stations midway through the L48 deployment (Figure 2-18). In late 2009, the Quanterra Environmental Processor 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, temperature, and relative humidity measurements. 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 2-19). 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). 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 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 Q330. 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).

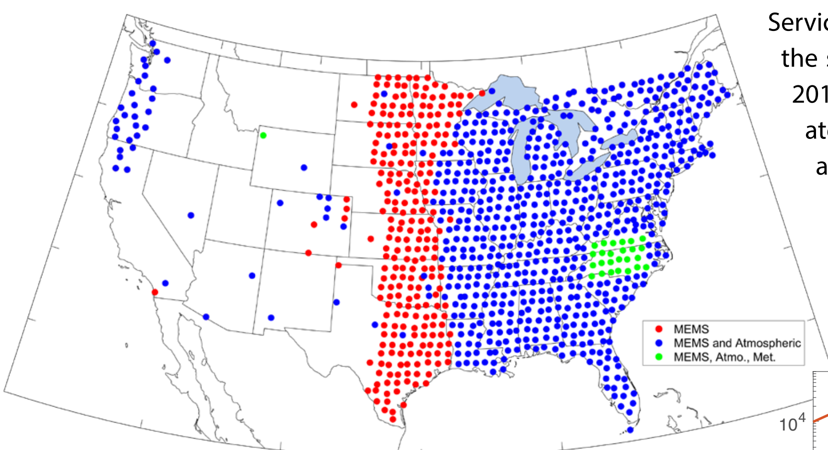


Figure 2-18. Locations of TA stations with auxiliary atmospheric and meteorological sensors. Red = MEMS only. Blue = MEMS, barometer, and infrasound. Green = MEMS, barometer, infrasound, and meteorological packages.

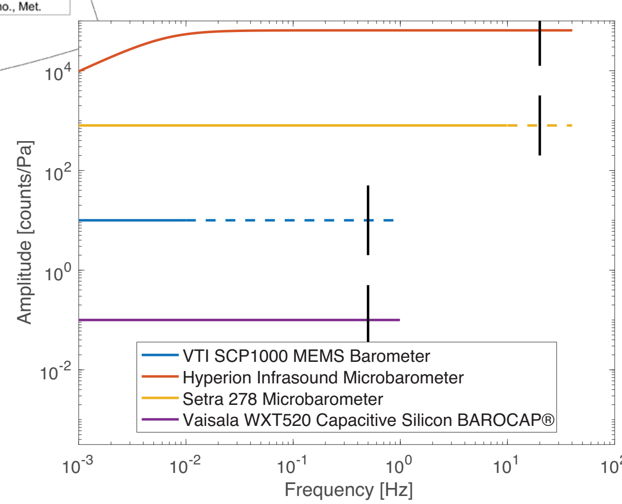


Figure 2-19. Responses of the various pressure sensors used at TA stations. Dashes show where instrument responses are not calibrated. The lines terminate at the instrument sampling rate, and the black bars show the Nyquist frequency for each instrument.

Magnetic Response of Broadband Sensors

All three broadband seismometers used by the TA have magnetic responses that may become sources of instrument noise under certain conditions (Table 2-3). In general, any force feedback seismometer, which uses ferromagnetic metals in its construction, is likely to register some level of magnetic sensitivity. This appears as a "compass needle" effect (e.g., Forbriger, 2007) when the spring is torqued by changes in the field intensity and direction. In addition, the coils of the seismometer's actuator 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 noise from geomagnetic activity relates to the geomagnetic latitude of installation, the type of sensor, local site effects, and any shielding with permalloy casing. 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 geomagnetic events. These effects are inferred to be more prevalent at high latitudes and during strong geomagnetic activity.

Albuquerque Seismological Laboratory has conducted a suite of tests on the STS-2, CMG-3T, and T-240 sensors using a Helmholtz coil to provide a consistent, site-independent measure of magnetic sensitivity for each instrument, with magnetic signal varying between periods of 1 and 10 seconds. In these tests, variation of a vertical magnetic field from ±0.00065 T produces a spread signal depending on both the seismometer and the component. 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.

Sensor	s_Z [m*s^{-2}/T]	s_N [m*s^{-2}/T]	s_E [m*s^{-2}/T]	|S| [m*s^{-2}/T]
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 2-3. Magnetic sensitivity of each component and the overall sensor response.

In addition, local currents from a variety of human-generated sources can generate magnetic fields that cause noise on TA broadband sensors. Station site selection mitigates some environmental factors by station placement, and many smaller sources are recognized and avoided during the design of the station. 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 was initially addressed by extending the distance between the seismometer and Baler within the TA vault, which generally resolved the issue. However, when 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 2-20). Due to the shear

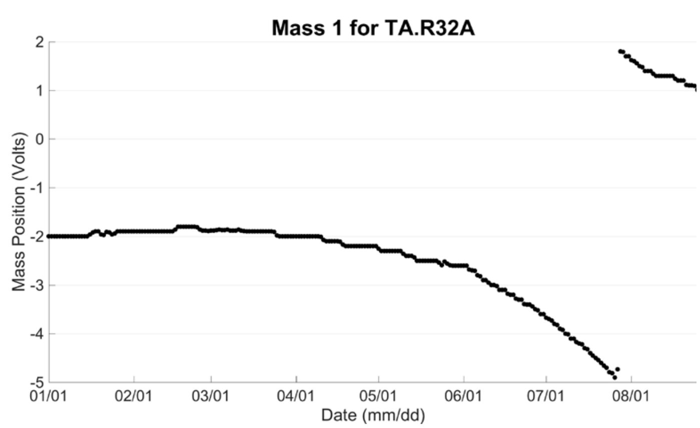


Figure 2-20. An example of mass position drift and recentering is shown for TA.R32A, which operated an STS-2 with limits of ±12 V.

quantity of stations to monitor, it was determined early in the deployment that automating the process of sending mass recenters would be critical (Figure 2-21). Mass recentering commands were issued by an automatic network-centered quality control process managed by the ANF that accounted for different voltage thresholds depending on the model of seismometer. (Figure 2-22) 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, 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 (Figure 2-23). The most recenters required by a station was 291 (H32A), while 51 stations required none.

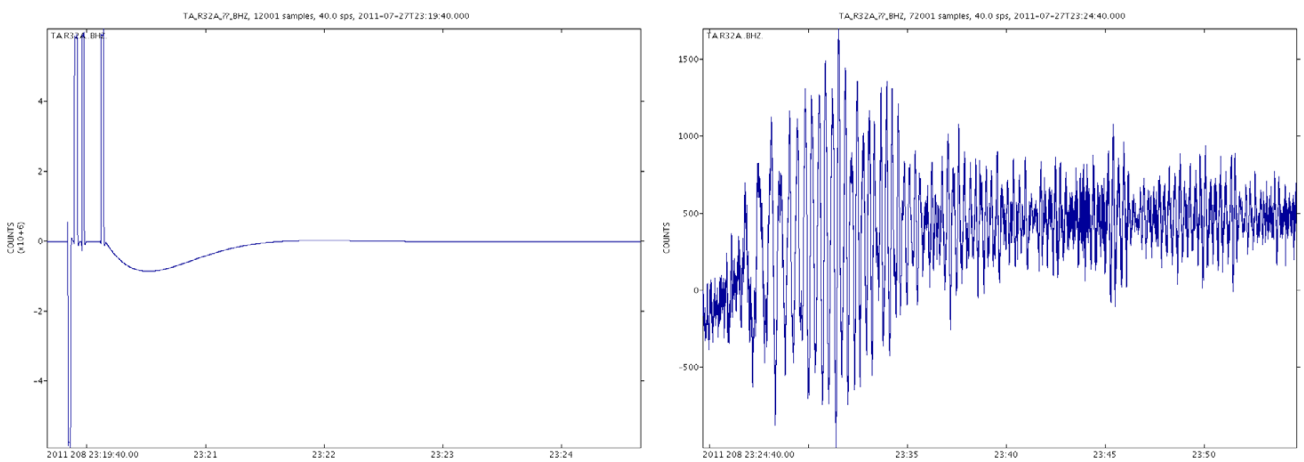


Figure 2-21. Example recentering on TA.R32A shows the recentering and settling of instrument over a time interval of five and an additional 30 minutes. Note that the top and bottom plots have different vertical scales.

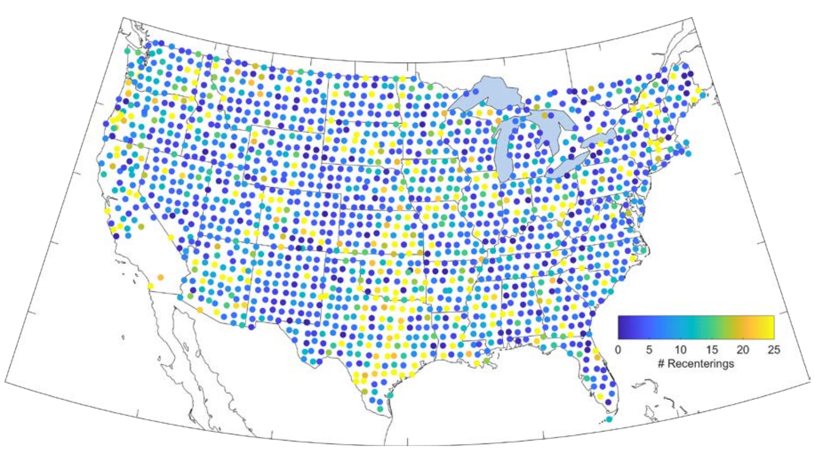


Figure 2-22. Mass recenters at each TA station through 7/20/17. Color scale saturates at 25.

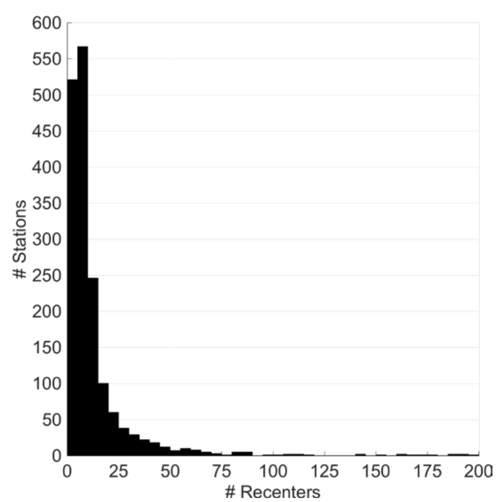


Figure 2-23. Histogram of recenters for all TA stations.

Broadband Seismometer Emplacement and Orientation

A process of 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 2-24). The Octans uses the effect of Earth's rotation on laser interferometric paths, a phenomena known as the Sagnac Effect (https://en.wikipedia.org/wiki/Sagnac_effect), 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 have magnetic susceptibility, 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 onsite. Orientation measurements were used to create permanent reference mark(s) on the tank bottom (Figure 2-25). A metal ruler was fastened 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. We 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 during servicing or displacement from a large nearby earthquake to which it may not be able to

Figure 2-24. Orientation of an STS-2 seismometer at TA.N15A using the Octans. Notice the shock watch stickers that might indicate an Octans had suffered a crippling impact. Once oriented, the sensor is then packaged and insulated.

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 2-25). 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 2-26). These observations were shared as they were discovered with the relevant network operators, who have in turn undertaken reassessments of their orientations based on the experience and practices of the TA. Octans and APS are now commonly used in the installation of permanent seismometers.

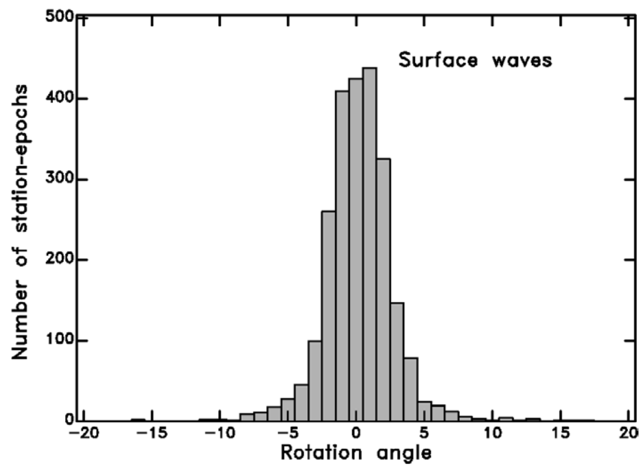


Figure 2-25. Histogram showing the distribution of robust median rotation angles for 2365 station-response epochs of the surface-wave data set (Ekström and Nettles, 2018).

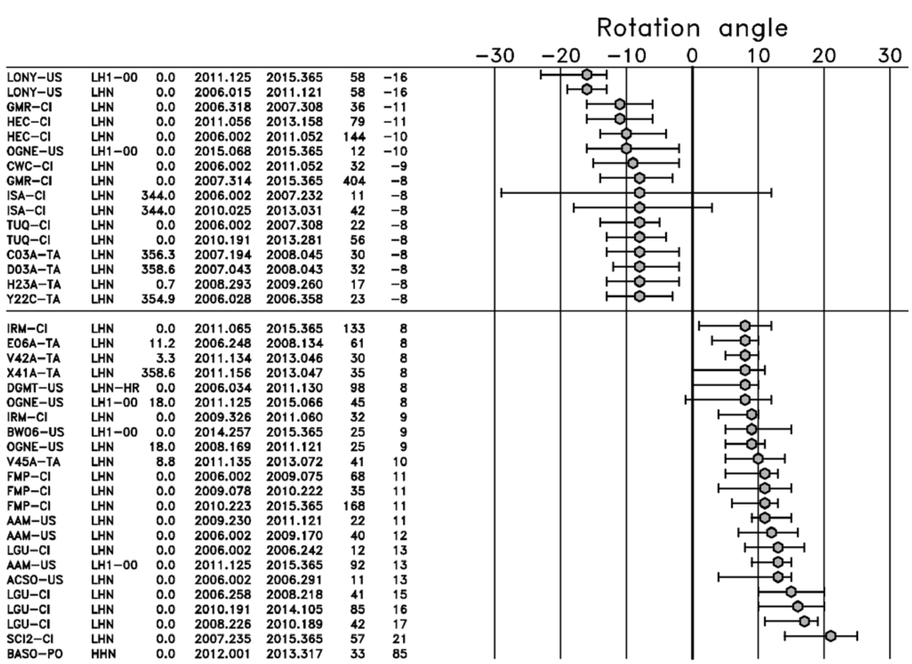


Figure 2-26. Estimated rotation angles for stations and epochs that deviate >7° from the reported orientation (Ekström and Nettles, 2018). The uncertainty of each estimate is given by the horizontal error bar and corresponds to the range of the second and third quartiles of individual measurements. Station, 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 2-27). The Q330 digitizes three to six channels with 24-bit resolution and uses a Quanterra Packet Baler to permanently store time-series data onsite. 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 Baler44CT, 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 nine stations in seismically quiet locations, 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 considerations 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 are 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 filter. The Q330 allowed the choice of linear phase (acausal) filters or minimum phase (causal) filters, depending on the application. 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.

At a typical TA station, research-grade seismic and atmospheric data are sampled at 40 sps and delivered in real time (that is, typically fewer than two seconds). Lower sample rate data (1 sps) from the sensors were also provided which 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.

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.

Figure 2-27. Typical Q330 installation, TA.D56A.

Data from the TA are archived in Standard for the Exchange of Earthquake Data (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 uses shorthand nomenclature to identify timeseries with a set of abbreviations, usually letters, to represent the location where the data was recorded and some characteristics of the instrument and sample rate. The form of data itself consists of two parts, a concatenation of digital, compressed time-series packets and a set of response descriptions that describe an epoch of the packetize data. 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 generally means all those channels share the same physical locale. The station code is up to five characters and must be unique within the two letter network code. For example, TA_H17A is the station code H17A within the TA network code. Conventions used for station codes were covered in section 2.2. An extensive set of TA channel definitions is shown in Tables 2-4 to 2-7). 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

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 (usec)	1
VCO	Q330	voltage control oscillator value (range 0-4095, median = 2048, no units)	0.1
VEA	Q330	GPS antenna current (mA)	0.1
VEC	Q330	system input current (mA), not including Baler, sensors, etc. that share power connection via Q330 connector	0.1
VEP	Q330	input power supply voltage (150 mV)	0.1
VKI	Q330	internal temperature (°C)	0.1
VPB	Q330	percentage of telemetry packet queue in use for current Data Port (0.1%)	0.1
VM[1-6]	Q330	boom position channels (0.1 V)	0.1

Table 2-4. Channels associated with the Q330, location code "_ _". sps = samples per second.

Channel	Instrument	Parameter (unit)	sps
LDM	QEP	MEMS absolute barometric pressure (hPA)	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 (usec)	1
LCO	QEP	oscillator control value	1

Table 2-5. Channels associated with the Quanterra Environmental Processor, location code EP. sps = samples per second.

prevalent in TA SEED data. In practice, requests to the 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.

In addition, there are a handful of rarely used or "dummy" channels that are archived for one or more TA stations. These are either not intended for use or indicate a temporary configuration using one or more test instruments and thus may not provide the same utility as standardized TA data. This includes micro-barometers and infrasound microphones operated at several TA stations in 2008–2010 and testing of an infrasound sensor at two TA stations (Appendix B). QEP and VM0 are more common 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.

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 2-6. 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	40
LDF	Hyperion NCPA	infrasound, relative barometric pressure	1
BDO	Setra 278	absolute barometric pressure (hPA), no hPa offset	40
LDO	Setra 278	absolute barometric pressure (hPA), no hPa offset	1
LWD	Vaisala WXT520	wind direction (° clockwise from N)	1
LWS	Vaisala WXT520	wind speed (0.1 m/second)	1
LDV	Vaisala WXT520	exterior pressure (0.1 hPA)	1
LKO	Vaisala WXT520	exterior temperature (0.1°C)	1
LIO	Vaisala WXT520	exterior humidity (0.1%)	1
LRO	Vaisala WXT520	rain intensity (0.1 mm/hour)	1
LRH	Vaisala WXT520	hail intensity (hits/cm2/hour)	1
LKH	Vaisala WXT520	heater temperature (0.1°C)	1
LEH	Vaisala WXT520	heater voltage (0.1 V)	1
LEW	Vaisala WXT520	supply voltage (0.1 V)	1
LER	Vaisala WXT520	reference voltage (0.001 V)	1

Table 2-7. Channels associated with atmospheric and meteorological instruments, location code EP. sps = samples per second.

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 such, cellular and AC VSAT provided communications at nearly all TA stations (Table 2-8, Figure 2-28). Sierra Wireless Raven X cell modems were used extensively, including nearly all stations in the central and eastern United States where mobile coverage was well established even in rural regions. 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 so as to provide electrical isolation—an air gap between station equipment and these devices. That 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 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 tuning during the initial phase of the TA. 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. As a result, it often required a duty cycle of the power to the terminal in a ratio of one hour on, four hours off, which introduced latency to the data flow and indeterminancy 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,

Type	Percent of Stations	Estimated Onsite Man-hours	Man-hours for Additional Communications Setup
Internal Cellular	84%	10	
Ext. VSAT w/AC	9%	20	4 AC enclosure + 4 VSAT + 2 Radios
Ext. VSAT DC	6%	25	9 DC (avg) + 4 VSAT + 2 Radios
Ext. Radio to Internet	1%	18	2 Radios + 2 Cabling + 4 mount enclosure

Table 2-8.

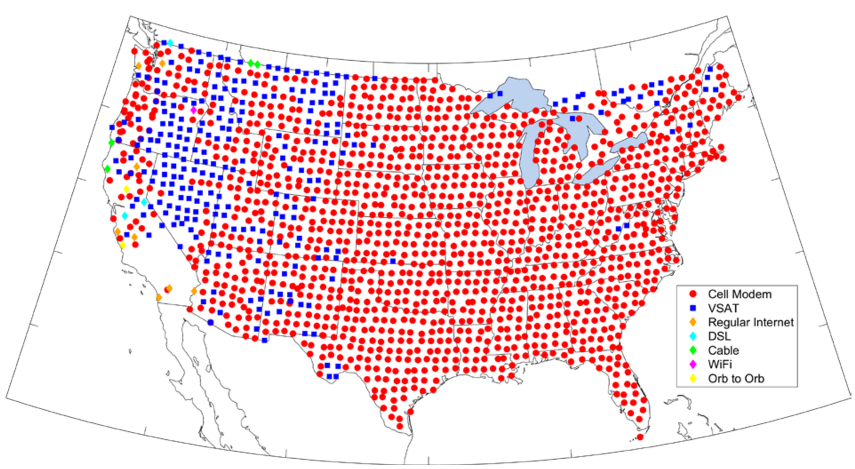


Figure 2-28. Final telemetry configuration for TA stations, through 7/20/17.

which was accomplished via Antelope registration parameters. To ensure reliable modem operation, a routine daily power cycle for the modem was added to the VIE configuration when it was introduced.

Network Design

The overarching network of the TA is a distributed set of hosts linked via Internet Protocol (IP) to a central set of computers (Figure 2-29). The station 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 adds some complexity to allow the external client to reach the datalogger. The datalogger implements a point-of-contact packet outbound from it to a list of receivers in order to convey the IP address, serial number, and other information to discover a host on 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, acknowledge timeouts, and retransmission intervals are adjustable to types of communication such as radio links, cellular, or VSAT. On either end of the communication process are circular buffers of packetized data that allow clients to add or process packets independently of transit irregularities.

Transmitted data are of two types: (1) those within a packet representing one or more channel time series segments with the attending descriptive channel

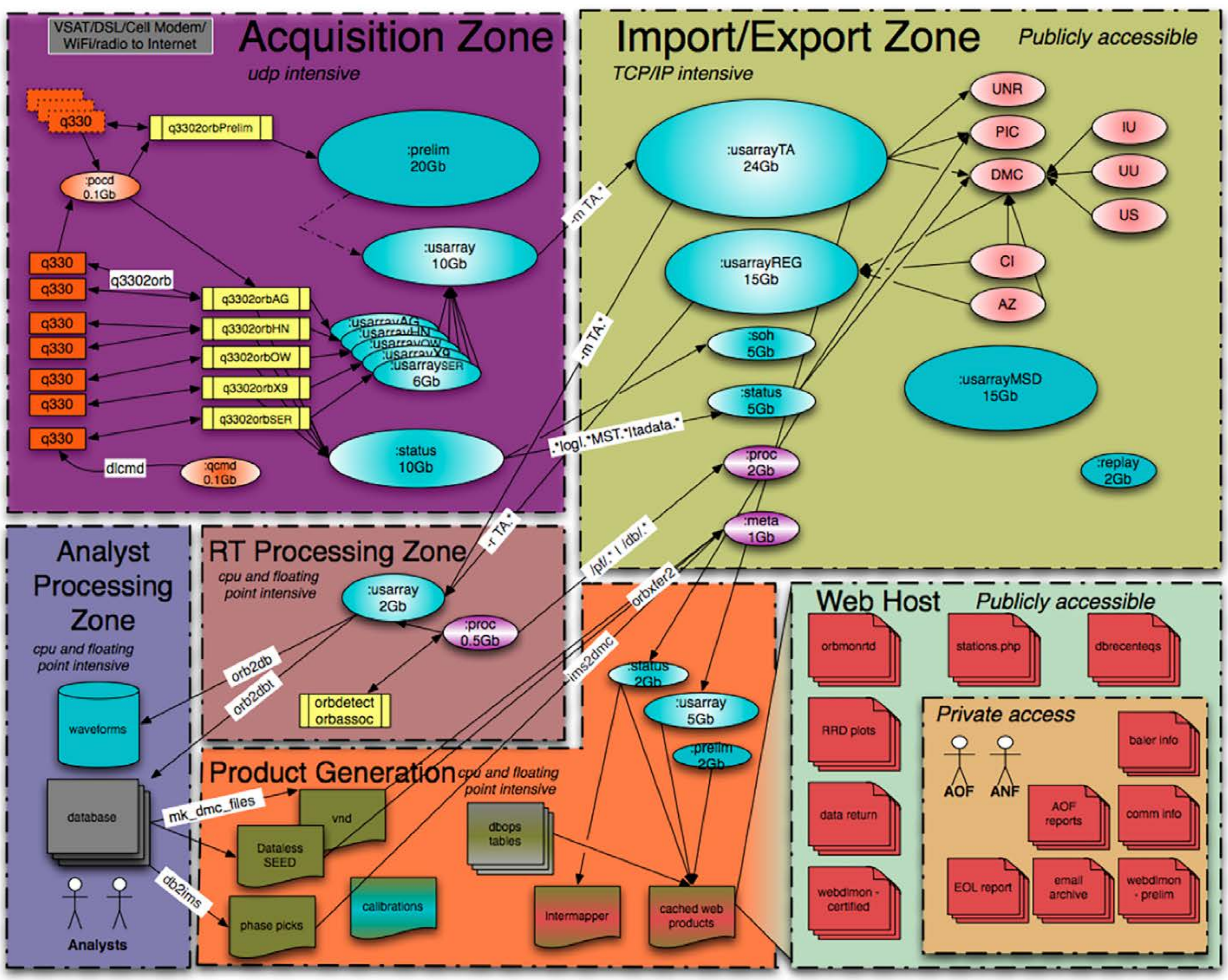


Figure 2-29. Representation of how data are acquired and flow through the ANF.

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 536-byte packets using a data record sequence number to reorder retransmitted packets. When a connection is broken, data are queued in memory and resume transmission 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 Systems. 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 JSON 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 exceptionally high data return from the TA stations.

Quality control measures operated within the TA data handling process and spanned three categories; data accuracy, data integrity, and signal quality. Data accuracy screening was similar to the initial certification process for stations and ensured that the metadata accurately describe the channel. Data integrity related to continuity of the time series as it was transmitted and reassembled in different volumes. 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. At the station, the datalogger itself performed an amplitude calibration and issued a calibration error if found out of range, which indicated that the amplitude may be inaccurate. Similarly, the datalogger reported when time labels were known to be inaccurate. Data integrity was often tabulated by packet handling processing that detected gaps in a time series and reported gaps per day, gaps in the last hour or 24 hours, and percent of data return for a day. For signal quality review and synoptic assessments of data quality, within the ANF, full-time seismic analysts 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, a data specialist at the IRIS DMC reviewed all data at 1 sps in large panels of stations and prepared a weekly report that highlighted station signal quality problems and provided a positive annotation that every station was reviewed. On a weekly basis, a senior 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). That list of issues and the DMC signal quality report were combined and reviewed by TA management to form a prioritized plan for mitigation of problems that was subsequently discussed in weekly telephone conference calls with all staff. The comprehensive screening for new problems, tracking of existing problems, and guidance by management as to what to address next were important steps in the quality control process.

3. Data and Data Quality

3.1 BASIC CHARACTERISTICS

Continuous time-series data and metadata for the TA were archived using the FDSN standards for SEED. Time-series data for all channels were bundled and archived in miniSEED at the IRIS DMC. These data were paired with metadata curated by the ANF, and both may be accessed using a variety of standard tools. The ANF attempted to limit updates to TA metadata to twice per week, preferably Monday and Friday. Updates were needed for each new station, changes to equipment for existing stations, and closing completed stations. The goal of TA data handling was to provide continuous data volumes for researchers that were updated whenever possible for completeness. To this end, balers were rotated from the field when stations were removed, to be reconciled against the archived real-time data and to restore any segments missed due to telemetry disruption. In fact, the local archive generally replaced the previous real-time archive, but added any telemetered segments that were not present locally, which often resulted from local media failure. This was an important milestone in the archiving process that had a measurable impact on data totals, increasing data return by over 1%.

Understanding the robustness of these data was a major TA effort, led by dedicated staff at the IRIS DMC. The efforts centered on optimizing data integrity and data quality, characterizing data return, and assessing the noisiness of the TA network relative to global benchmarks.

3.2 DATA INTEGRITY – UPTIME AND COMPLETENESS

Data integrity involves measures of data completeness, typically by monitoring the fraction of expected data returned for both individual TA stations and the entire 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 whenever possible. 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 Advanced National Seismic System (ANSS) and other regional network stations. During the first several years, the data return of the TA rose from ~90% to 95%, then 99%, as the network become more efficient and improved both its station uptime as well as real-time telemetry performance (Figure 3-1).

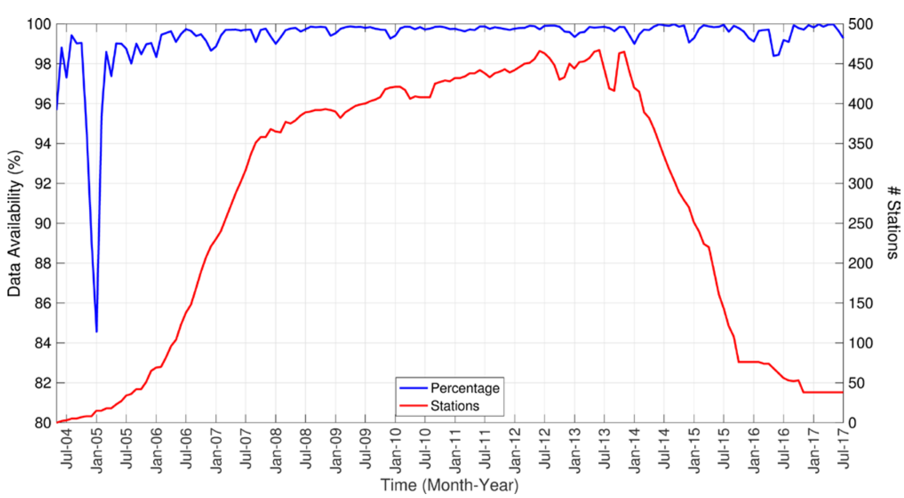


Figure 3-1. The averaged data availability and deployed station count for the TA per month through 7/1/17.

For this report, we more closely examined the true data availability for the TA. We incorporated metrics for "percent_availability" and "dead_channel" from the IRIS quality control metric database MUSTANG. By factoring in whether one or more channels from a station are "dead" or flat-lined, usually due to sensor failure, this discards durations where scientifically useless data was delivered and archived. Because TA stations were closely monitored, this 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. The mean uptime of all TA stations was 99.7%. This 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 (Figures 3-2 and 3-3).

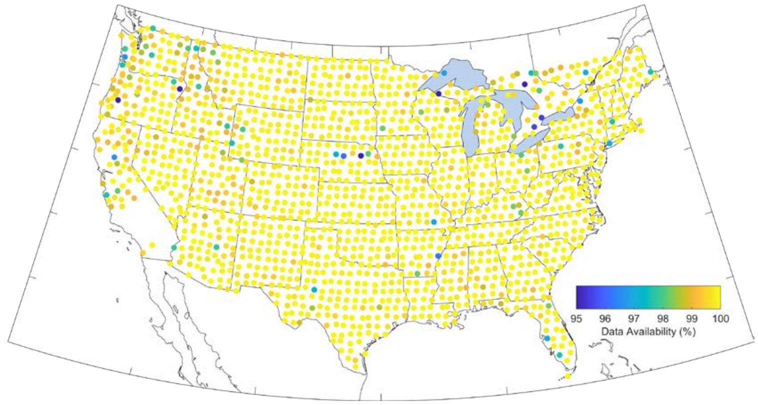


Figure 3-2. Final data availability for the TA through 7/1/17.

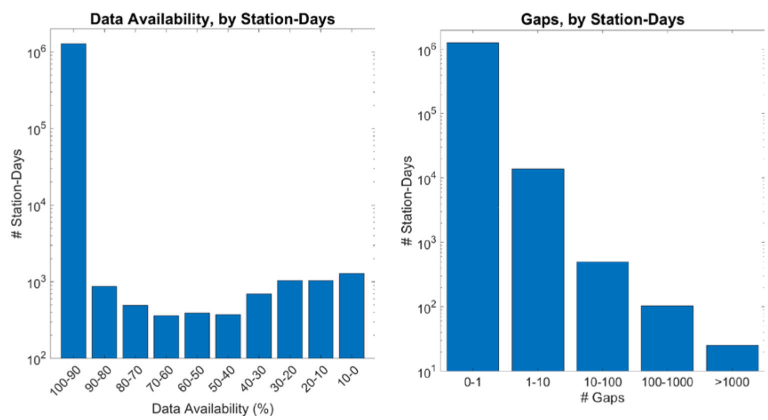


Figure 3-3. Histograms of data availability (left) and gaps (right) by station-day.

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 particularly an issue during the early years of the TA, when the limitations of various telemetry options were still being discovered at specific stations. Only 14,432 out of 1,274,090 station-days contained one or more gaps. Overall, 118 TA stations operated with one or fewer gaps during their entire operation, with the gap often being associated with the first day of recording (Figure 3-4). As a result, most TA stations operated for considerable durations before experiencing a

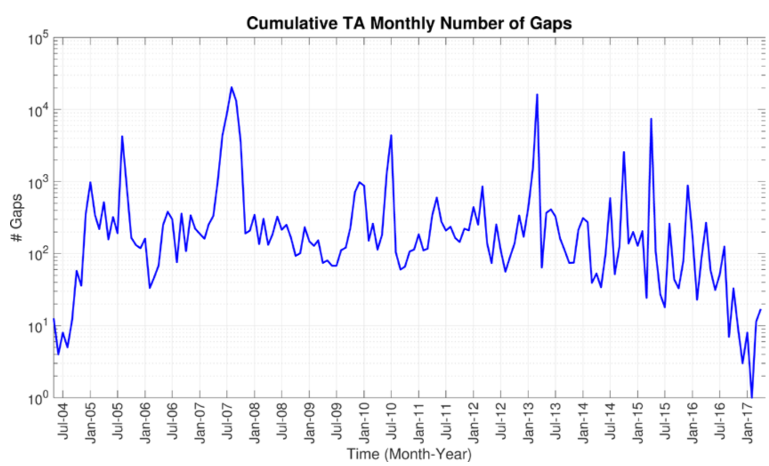


Figure 3-4. Cumulative gaps per month for the TA through 5/7/17.

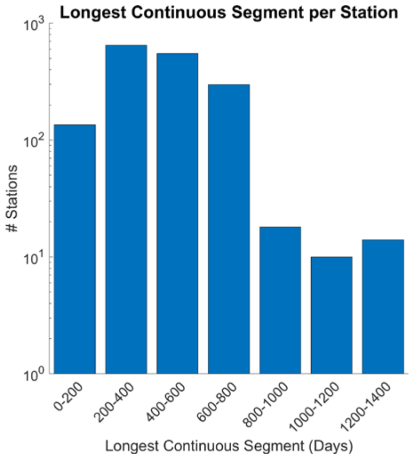


Figure 3-5. Histograms of longest continuous segment of data per station.

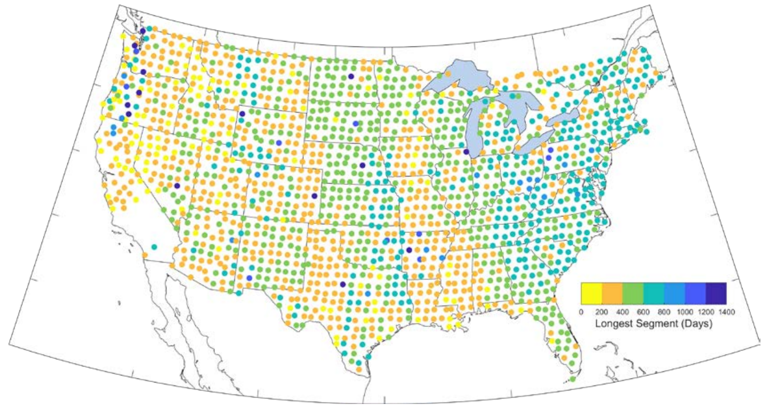


Figure 3-6. The longest continuous segment of day for the TA through 5/7/17.

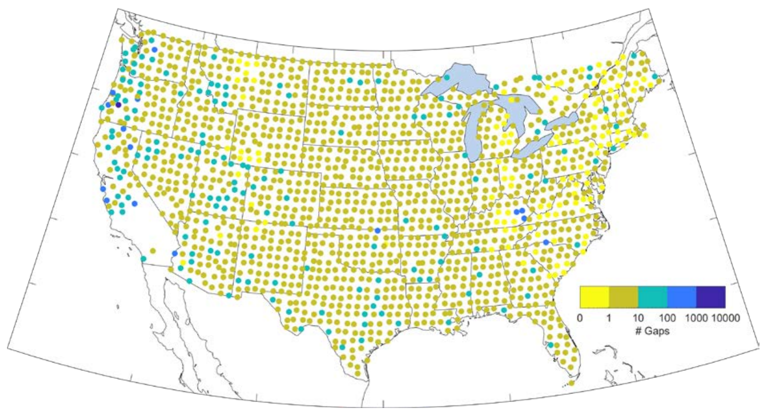


Figure 3-7. Cumulative gaps for the TA through 5/7/17.

gap in the archived time series (Figure 3-5). The length of longest continuous segment of data at a single station ranges from 50.9 to 1303.3 days, with the mean being 437.9 days, or more than half the length of a typical deployment (Figure 3-6). The prevalence of gaps decreased as the network moved into the eastern United States (Figure 3-7), which manifests in the related increase in longest continuous segment at a regional scale.

3.3 SIGNAL QUALITY – NOISE PERFORMANCE

Assessment 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. 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 derived 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.

We use the spectra here to 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 and by station (Figure 3-8). 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 (Figure 3-9). 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 to using a rigid and thoroughly insulated subsurface vault to house the seismometers.

Although in almost all cases below the NHNM, the spectra of stations varied widely across the TA (Figure 3-10). The different broadband sensors operated in the

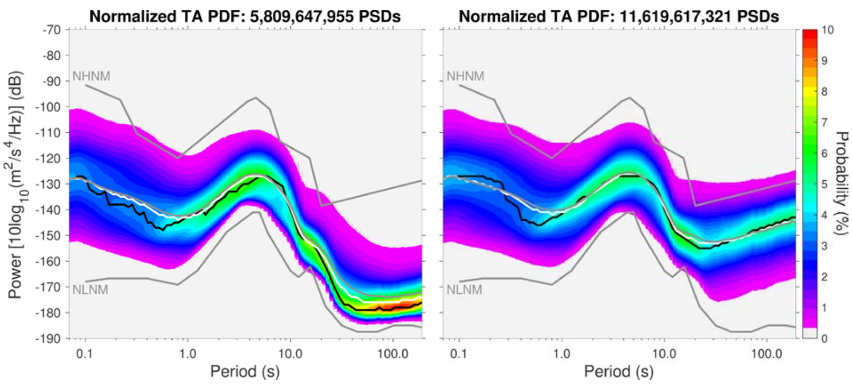


Figure 3-8. Composite probability density function of all power spectral density measurements for vertical (left) and combined horizontal components (right) for all TA stations operated through 7/1/2017. The mean (gray), median (white), and mode (black) of all spectra are displayed along with the NLNM 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.

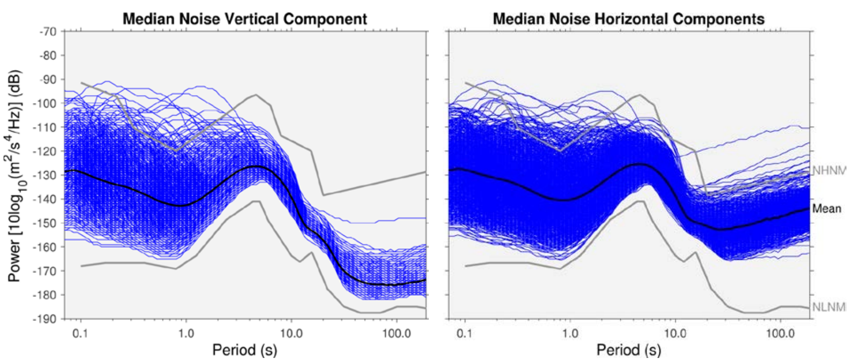


Figure 3-9. The median spectra (blue) of the vertical (left) and averaged horizontal (right) components for each TA station through 7/1/2017, with the mean (black) of all stations and the NHNM/NLNM (gray).

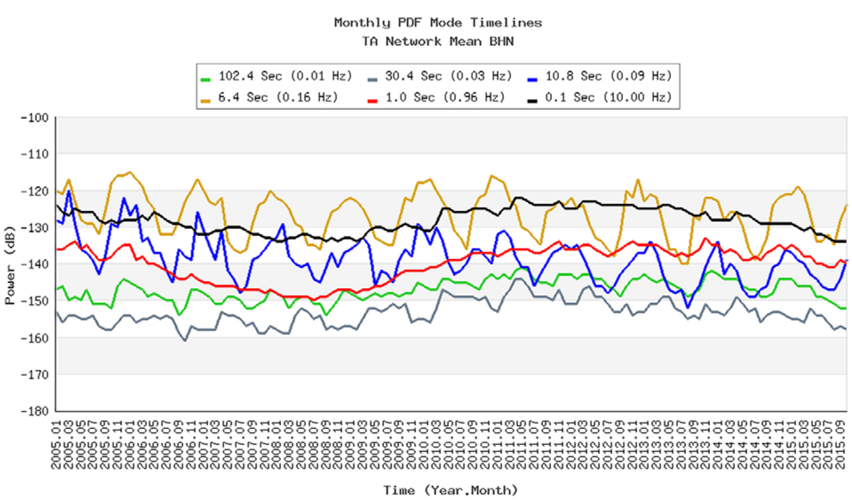


Figure 3-10. During the operation of the TA, this regularly produced view by the IRIS DMC shows the mode of the monthly cumulative TA PDF of station power spectra for six different periods of interest for monitoring array performance.

network all showed a consistent level of performance. Thus, we are confident that each instrument is able to faithfully record the local ambient noise state from vault emplacements throughout the TA footprint. Performance 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 of from pressure and temperature variations (Figures 3-11 to 3-14). Regional trends related to both cultural and environmental sources of noise and in some cases correlate with various geologic structures. 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. The noise level of the TA at certain periods had a strong seasonal effect. 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.

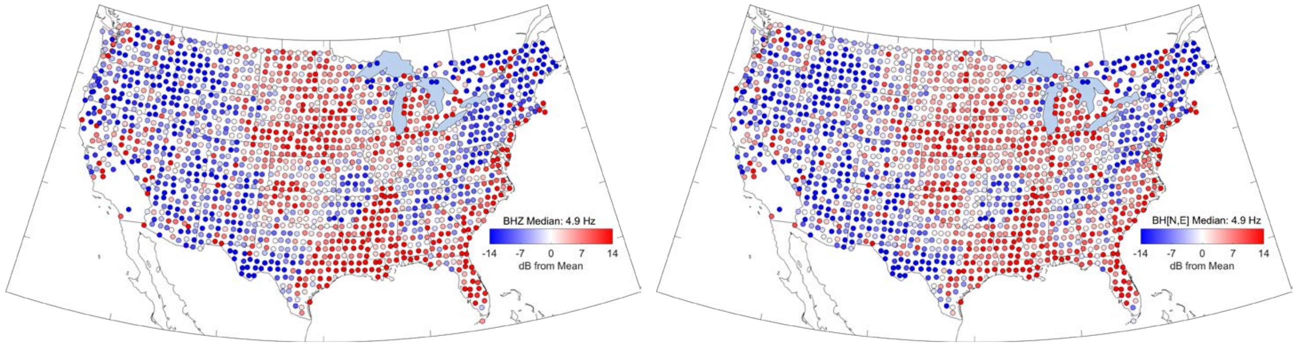


Figure 3-11. Deviation from the mean of the median noise spectra at ~4.9 Hz for the vertical and averaged horizontal components. Color scale limits are based on the approximate 10th and 90th percentile distribution of measurements.

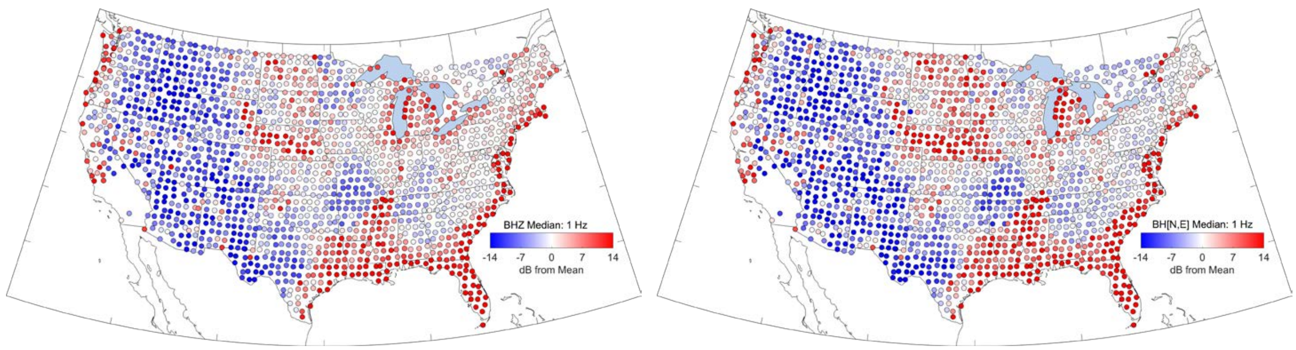


Figure 3-12. Deviation from the mean of the median noise spectra at ~1 Hz / 1 sec.

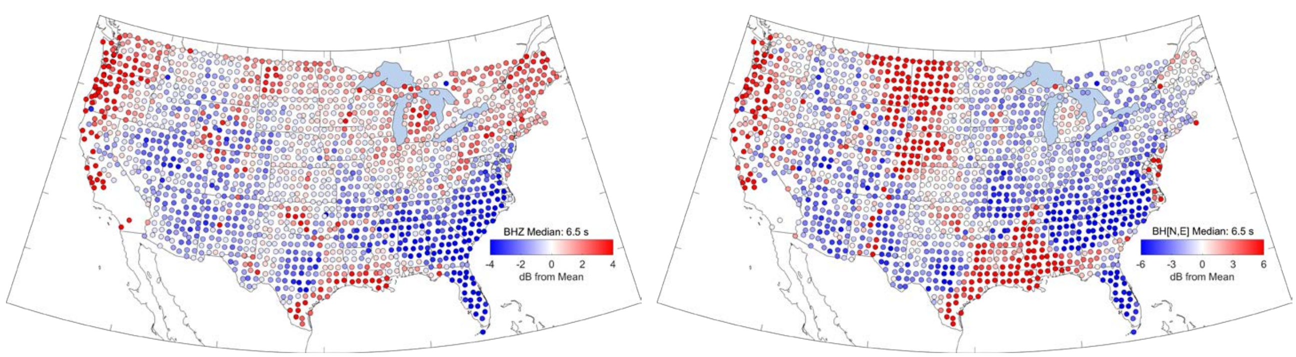


Figure 3-13. Deviation from the mean of the median noise spectra at 6.5 sec.

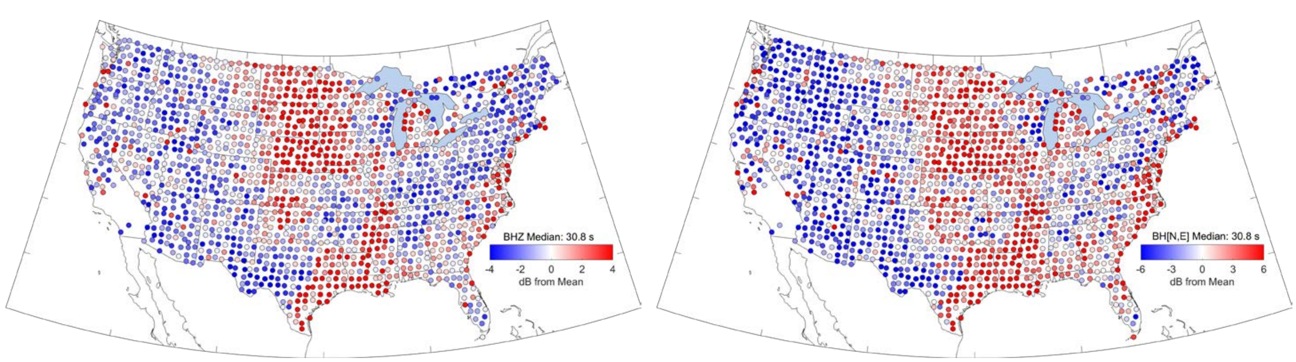


Figure 3-14. Deviation from the mean of the median noise spectra at 30.8 sec

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. Calibrations were conducted over 1.5–4 hours at 0.001–20 Hz.

In September 2009, the TA underwent to a network-wide calibration experiment (Figure 3-15). 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 in two four-hour windows and lasted at 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 able to be identified, and subsequent assessment showed that most problems appear to be in the sensor calibration circuits. 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 (Figure 3-16).

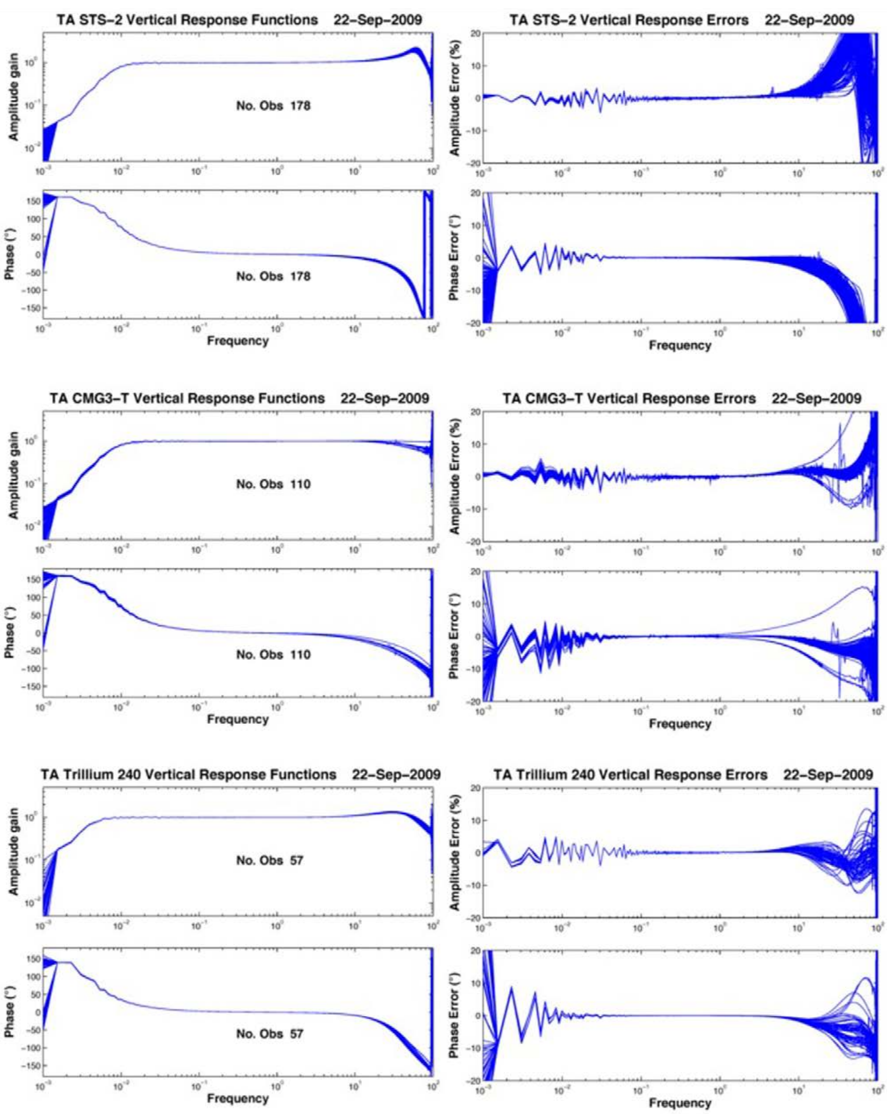


Figure 3-15. Amplitude and phase response functions (left) and errors relative to the nominal response (right) derived from the calibration experiment.

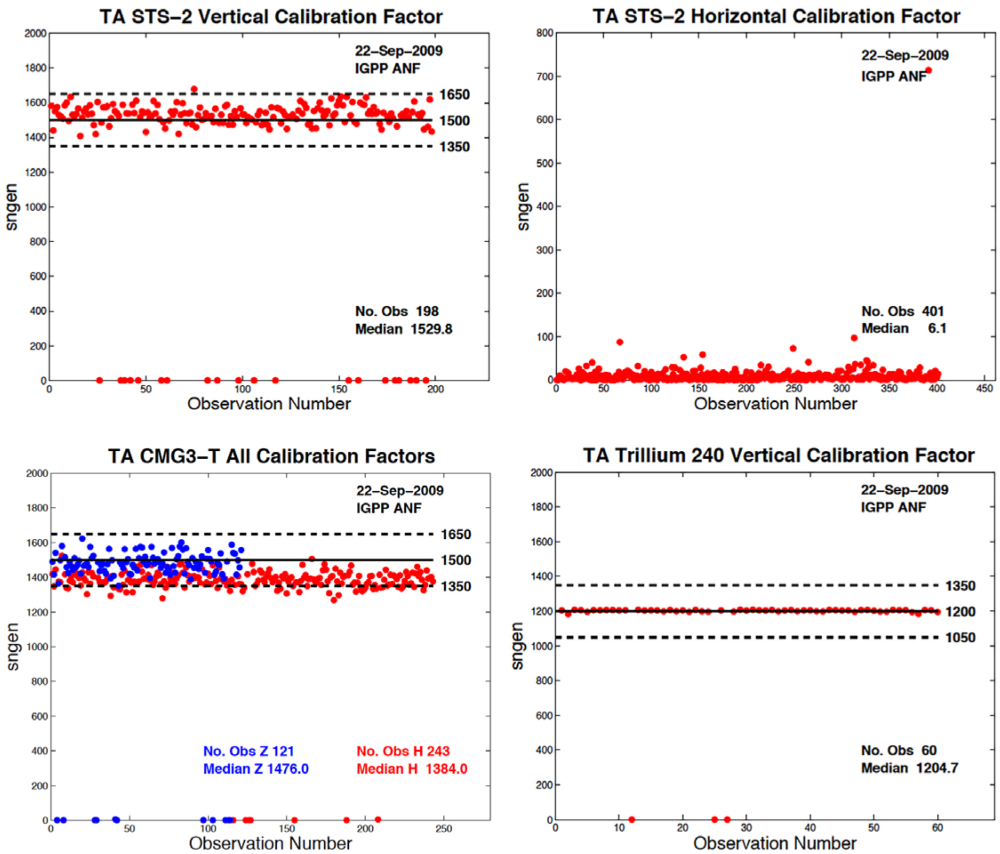


Figure 3-16. Calibration factor plots for various instruments and components show the spread of results within reasonable bounds and outliers.

3.5 PROMINENT AND DOCUMENTED ISSUES

Several cryptic or nuisance-level issues cropped up during the operation of the TA, some of which are thoroughly documented but still unresolved. These constitute the "known knowns" that may impact the quality of TA data. The IRIS DMC logged a Data Problem Report (DPR) noting each occurrence of these issues. When a signal was absent or clearly flatlined, no report was produced. In cases where boom positions were offscale for extended periods or half amplitudes were exhibited on a channel, these oddities were, for the most part, noted. Occasionally, some were missed. The DPRs are searchable by station and publicly accessible: http://ds.iris.edu/ds/nodes/dmc/data/dpr. There are currently no mechanisms in place within the IRIS Data Services for feedback from scientific users to report suspected anomalies to operators or to a collective reporting scheme, other than the DPR.

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 3-17). This behavior sometimes resolved spontaneously or after a calibration but recurred in some instances. The issue was permanently resolved by the replacement of one or more components, including the Q330, cabling, and sensor. The issue related to 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

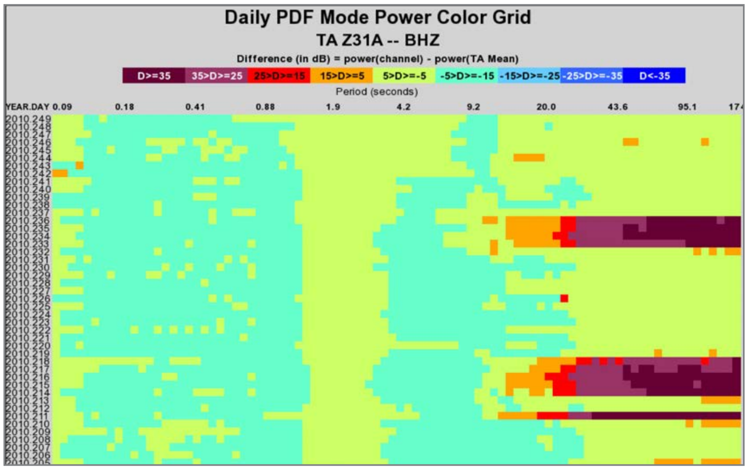


Figure 3-17. Example of a “half amplitude” time series.

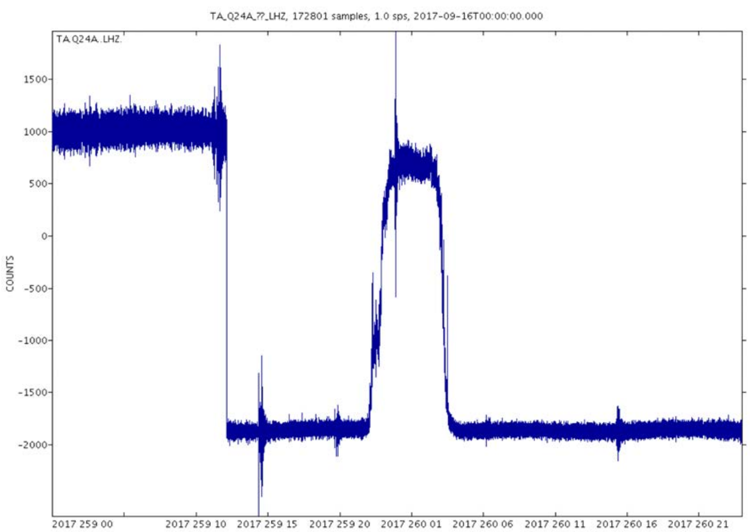


Figure 3-18. SNOFLU clearly manifested on the noise spectra for TA.Z31A.BHZ.

be reset, even remotely, by exercise of control functions or a power cycle of 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.

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 3-18). 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. 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.

4. Operational Characteristics

4.1 SITING AND PERMITTING

Initial reconnaissance was performed in most cases by teams of trained undergraduates that worked during their summer breaks (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 ten week session in the summer. At the beginning of the summer the students received training/orientation via a multi-day USArray Siting Workshop which 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, 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 U.S. Fish and Wildlife Preserves, BLM/USGS, U.S. Bureau of Reclamation, 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 landowners included ranches/farms, homesteads, and vacant lots. In interactions with federal- and corporate-owned land, the role of the student was to determine the agency responsible, introduce the project, establish an office contact, and

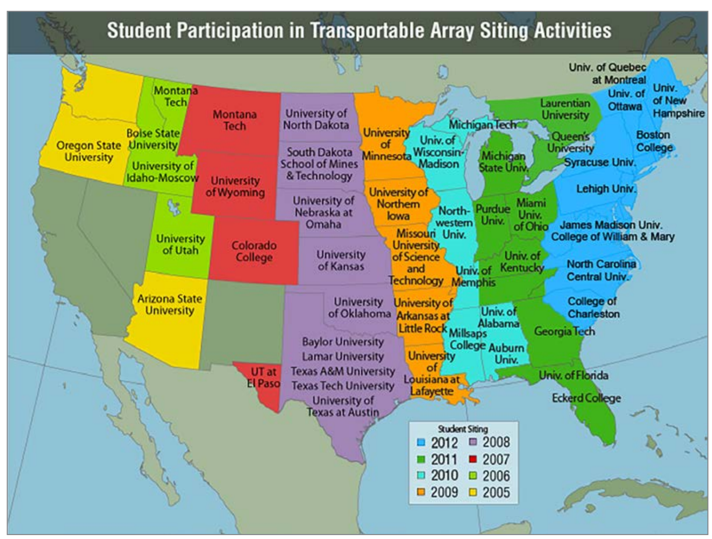
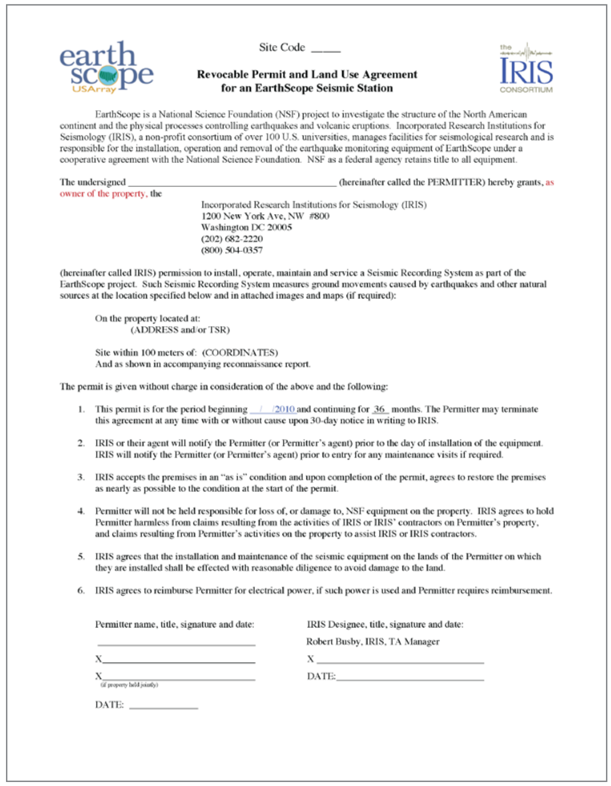


Figure 4-1. Universities with students participating in TA siting, by year and region. TA stations in California, Nevada, and New Mexico were selected using a similar process, but with the assistance of regional network operators.

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, a verification visit was conducted by TA staff within a few weeks to finalize the location and confirm basic understanding of project commitments with the landowner and confirm 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. Sample permit for a TA station.

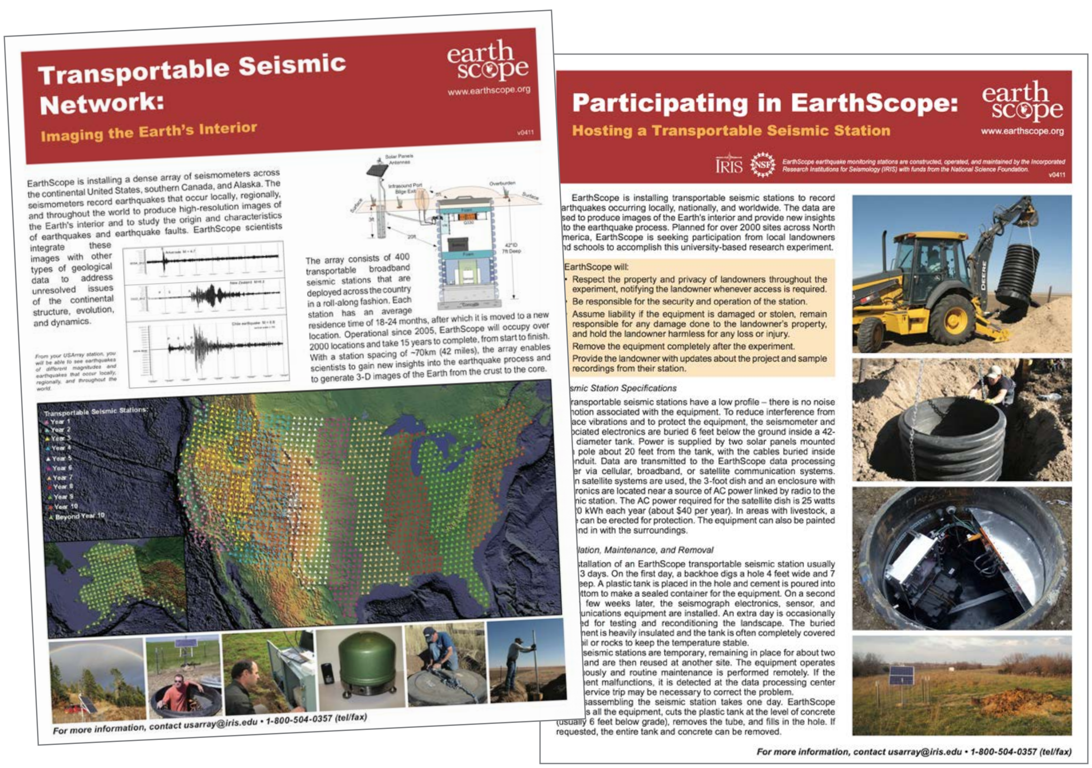


Figure 4-3. Information pamphlet given to prospective station hosts.

4.2 STATION HOST ENGAGEMENT

During the 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).

Figure 4-4. Example of *onSite* newsletter provided to all landowners hosting TA stations.

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.

Figure 4-5. USArray Station Monitor splash page.

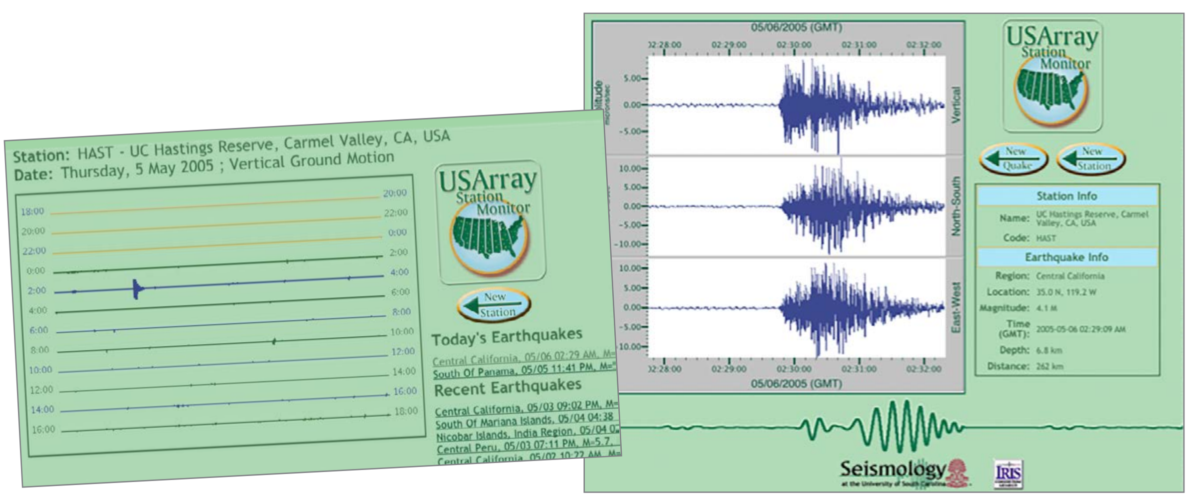


Figure 4-6. Original views of the station monitor, showing 24 hour helicorder and event specific seismograms.

4.3 FIELD ACCEPTANCE CRITERIA AND CERTIFICATION PROCESS

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 not able to be immediately and thoroughly assessed, but over time, performance often correlated with the quality. The acceptance of stations was linked to performance incentives, with 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 (impaired communications, poor mass positions, etc.), and could not be certified, then installation crews returned to the station to rectify the issue(s) that resulted in a failed certification.

4.4 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 was 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 DLMon, which displayed status information relevant to various systems (power, communications, GPS) 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-sourced network monitoring software produced by ISTI to monitor and control data acquisition software 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 into 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 after being archived. 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 a certain period, color grid plots show over or below average spectral performance over time, and maps of noise performance at selected periods for the entire TA (Figure 4-9).

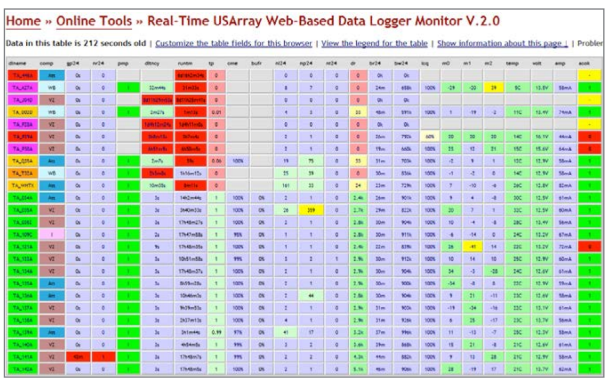


Figure 4-7. Example view of DLMon for L48 TA stations.

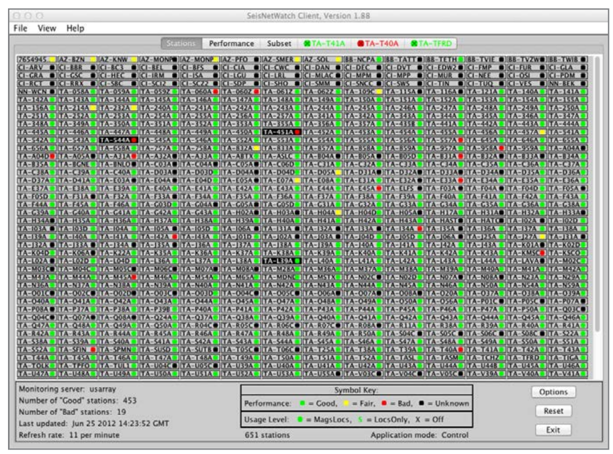


Figure 4-8. Reactor control panel view in SeisNetWatch.

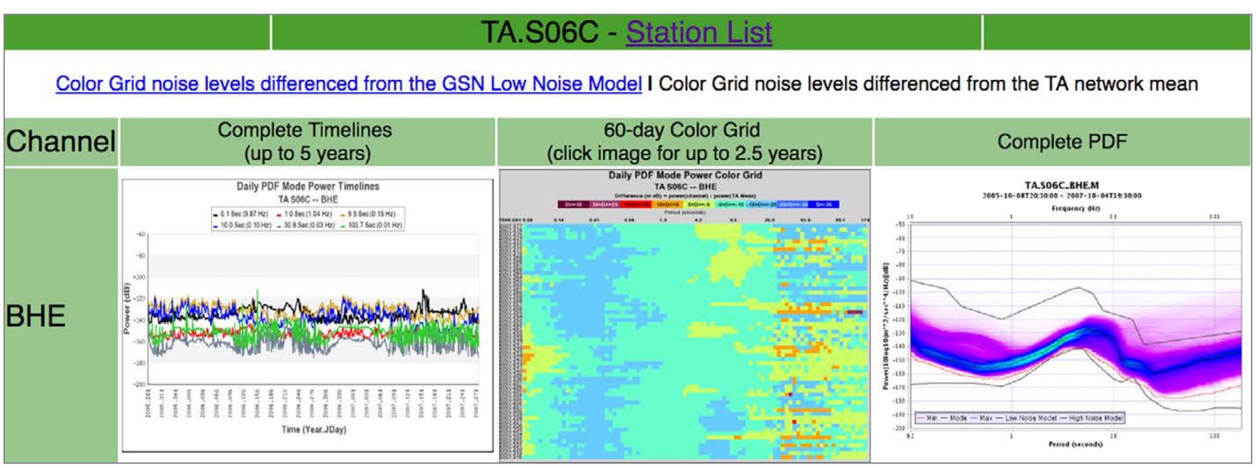


Figure 4-9. Example of detailed noise performance views for TA.S06C.

4.5 SERVICING

Routine maintenance to the TA was performed by a few roving field engineers with prioritized service schedules driven the active monitoring performed 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 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.

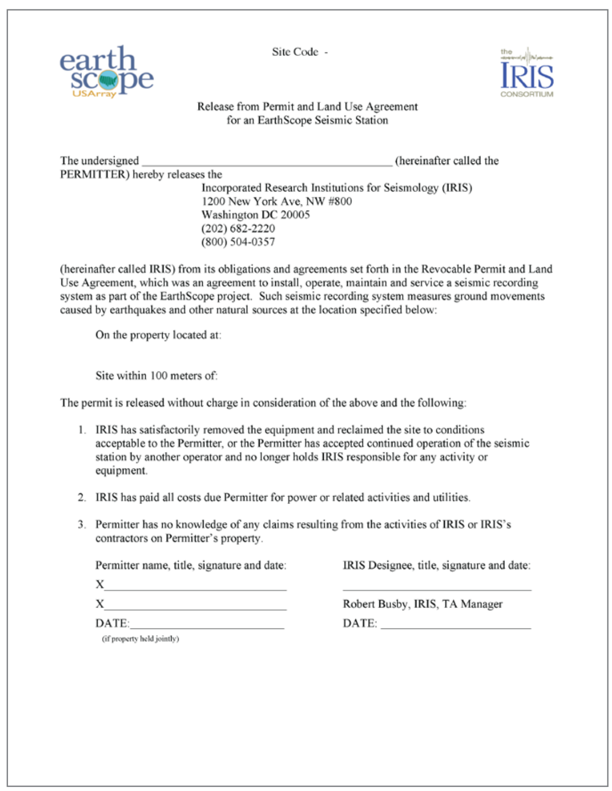
Service visits were scheduled to honor the terms of how a station was permitted, such as seasonal unavailability and need for providing advanced notification to landowners. Work was completed and a standard email-based report identified activities performed, condition of the station, and any equipment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

4.6 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 4-10).

Shutting down the data acquisition and "closing" the station followed a predetermined procedure. To prevent defective equipment from being transferred to a new station that was being installed further to the east, approximately two weeks before equipment removal, final step and random binary calibrations were performed and reviewed. 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 OCTAN 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 per the wishes of the permit holder. The removal crew would then repackage the seismic equipment, batteries, solar panels, and appropriate communications equipment required for the installation crew to use at the next station the following month. Most equipment went directly to an installation storage



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 4-10. The station release form used for the TA.

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 removal 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 which 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. There' 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 report the key parameters related to the stations deployment and its recording history over the course of the deployment time period (Figure 4-11). 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 as a reminder of their participation in the project.

4.7 WHAT WORKED WELL

- 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 aided the organization to engage as a team. Creating advanced entries into a hyperlinked wiki

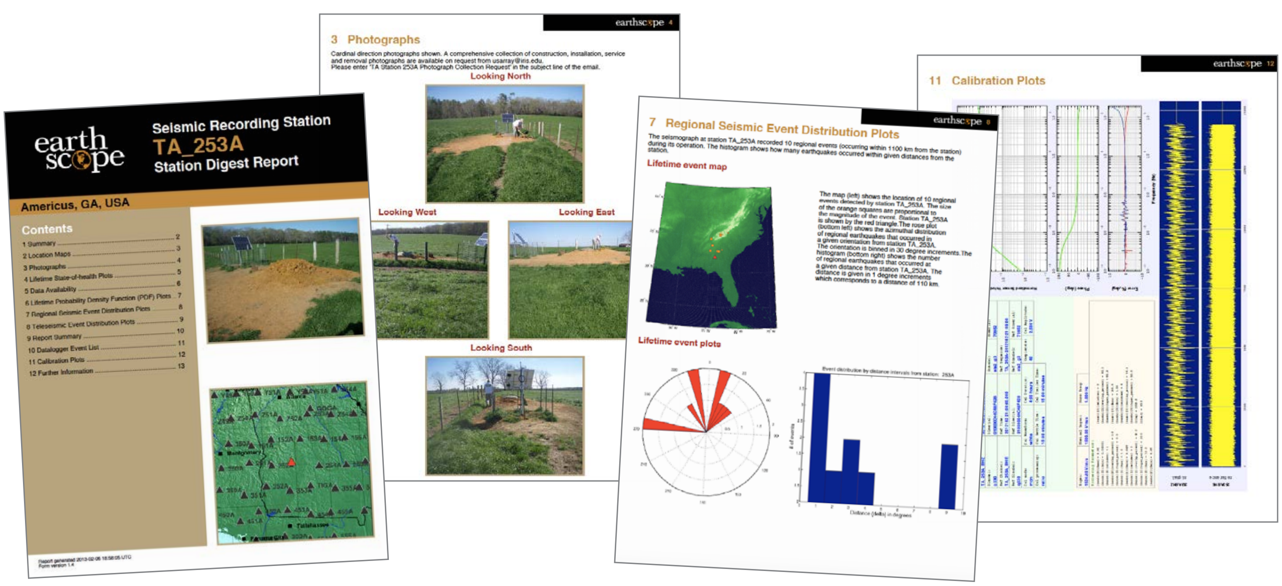


Figure 4-11. Sample pages from the station digest produced following the completion of TA.253A.

with database history is perhaps the next step for longer-term deployments, but the TA there were a lot of stations that transitioned quickly.

- 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.

- Holding 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.

4.8 LESSONS LEARNED

QEP Disconnect

Initial QEP implementation contained a bug such that if station suffered from power brownout, the 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.

Baler Data Mixing with Antelope in Real Time

This process is very 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 was, in fact, in the DMC archive as compared to local storage, and it was less difficult to simply build as complete of volume as possible and resend that. 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.

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 workaround 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 were utilized extensively in Alaska and then subsequently in Lower-48 upgrades. A seismometer emplaced in a shallow borehole far out-performs a shallow pit vault, even one on bedrock, and is much easier to maintain.

Updating Metadata

Metadata were updated at and distributed from the ANF on an as-needed basis, typically twice per week during the duration of the Lower 48 deployment. Metadata updates were needed for station installations, removals, equipment swaps, 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 the email announcing a change arrived at the ANF.

Tracking the equipment history at each site was accomplished using the batch file processing functionality of the Antelope software program dbbuild. All information to be included in these batch files was collected from the installation, service, or removal reports sent to the ANF by the field crews. These loosely formatted text files would track the equipment installed at a station for a particular time period and would reference externally available response files. The response files were collated within Antelope based on the specifications released 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 was deemed acceptable. The dbbuild program would render a database with the location and response information for all stations from which 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 4-12). Metadata used a simple naming convention which included both the SEED network and station codes and a date/time for when the file was generated. This 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 email summarizing what changes had been released helped end-users be aware that changes had been made (Figure 4-13). Because of the rapidly changing footprint and systematic updates of metadata, endusers had to adapt their previous practices and download metadata often.

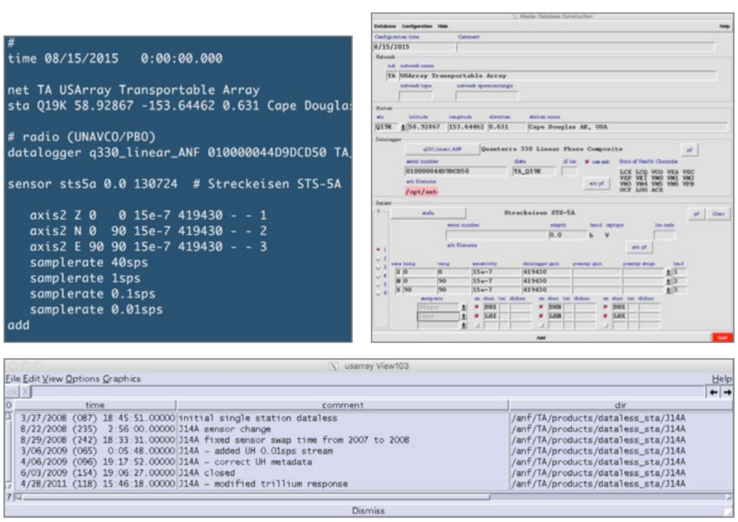


Figure 4-12. (top left) Example input from batch file input for dbbuild metadata generation, (top right) GUI interface to dbbuild, (bottom) view of database table that tracked metadata updates.

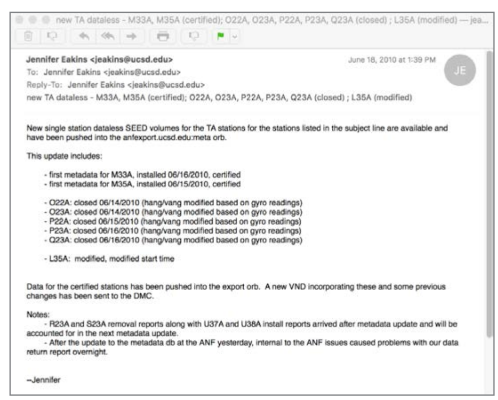


Figure 4-13. Example email documenting "what changed" in the latest metadata update.

5. Conclusions

The widely acknowledged success of the Transportable Array was the result of careful planning and execution at every stage of its evolution. Nearly 1700 seismic stations were operated using the same design and operational principles. The TA viewed each station as part of a 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.

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. 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. Seismologists must think about a staged approached, with repeatable, validated methods that have been well tested and refined. These steps should provide a conceptual framework for approaching similar projects and completing tasks in an organized fashion.

Most important, the TA's success was due to the dedication and commitment of the TA 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 considerable difficulties in field conditions, the distributed team and management framework, and the TA's massive scale.

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Appendix A. Omitted TA 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. Non-Standard TA 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

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