Bulletin of the Seismological Society of America

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Data Quality of Collocated Portable Broadband Seismometers Using Direct Burial and Vault Emplacement

by Kasey Aderhold, Katherine E. Anderson, Angela M. Reusch, Mary C. Pfeifer, Richard C. Aster, and Tim Parker

Abstract  Temporary broadband sensor deployments have traditionally been predominantly emplaced using shallow vaults that require more materials, personnel, and time than direct burial. However, new developments in seismometer and seismograph technology are increasingly facilitating systems that can be directly buried in earth or snow without vault enclosures. We analyze data from two identical shallow vaults installed adjacent to two identical direct burial sites in soft floodplain alluvial and shallow water table conditions near Socorro, New Mexico. Data recorded from these four sensors over eight months in 2012 were assessed to determine if the emplacement type had a significant and systematic effect on data quality. We used metrics derived from power spectral density analysis to examine temporal trends in noise (instrument, installation, and site noise), signal-to-noise ratio for teleseismic and local earthquakes, and magnitude-squared coherence of both noise and earthquake signal recordings. We found that noise on the vault sensors is higher during the transition from spring to summer than for the direct burial sensors. This difference is especially evident on the horizontal components at long periods between 20 and 170 s, with an average of 5.3 dB more noise on the vaults than the direct burials from April to June, indicating enhanced tilt susceptibility for vault emplaced sensors. However, most variability in data quality is comparable between sensors with differing emplacement methods and between sensors with the same emplacement method in this four-station experiment. We conclude that the direct burial emplaced sensors at this test site performed as well as the vault emplaced sensors and that direct burial is preferable when considering data quality and ease of installation.

Online Material: Figures of daily median noise levels within the microseism band, monthly probability density functions for the magnitude-squared coherence, and coherence self-noise analysis results.

Introduction

Temporary broadband seismic deployments have been driving advancements in seismological investigation into seismic sources and Earth structure for decades (e.g., Aster et al., 2005). The emplacement method of choice for temporary broadband deployments has overwhelmingly been a shallow vault-style design, in which a hole that is substantially larger than the seismometer is excavated to accommodate bulky installation materials. The vault is designed to protect the sensor from the elements, insulate it from temperature and surface noise, and couple the sensor stably with the ground (Trnkoczy et al., 2002). Vault-style sensor emplacement often requires significant manpower, installation times of hours to days, and materials that cost hundreds of dollars or more per site. Direct burial emplacement, in contrast, requires an augered or otherwise excavated hole that is only slightly larger than the instrument itself and approximately one hour or less to install a station, while utilizing a fraction of the manpower, tools, and materials.

To assess if direct burial is a feasible cost- and time-attractive emplacement alternative to vaults while not compromising data quality, we present a quantitative comparison between data recorded by collocated sensors using the two emplacement types. Four identical broadband sensors were installed in two identical shallow vaults and two identical direct burial sites in close proximity at an alluvial high-soil-moisture location near Socorro, New Mexico. Eight months of data recorded during 2012 from these four sensors were intercompared to determine any systematic quality differences using
metrics derived from power spectral density (PSD) analysis, signal-to-noise ratios (SNRs), and magnitude-squared coherence (MSC). These data quality metrics were also monitored with time, given that sudden but inevitable seasonal changes such as freeze–thaw, soil-moisture levels, and high winds are likely to have different effects on sensors installed in different emplacement conditions.

Site Selection

The installation location (33.96° N, 106.85° W) is a soft site characterized by ∼1.2 m of recent mud and silt floodplain deposits overlying deeper alluvial fill of the central Rio Grande rift (Cather, 2002). This area is prone to flooding from the river and from adjacent arroyos, and the water table is shallow, varying from many centimeters to several meters deep, depending on the season. Sources of local seismographic noise are likely to include wind, variations in precipitation and soil moisture, temperature cycles, nearby riparian (cottonwood and tamarisk) vegetation, a natural gas pipeline within 2 km, as well as seismic and tilt coupling from vegetation and grazing cattle that may sporadically come within meters of the site (Anderson et al., 2012, 2013). Two Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL)-style shallow vaults and two direct burial deployments were collocated within a 4 m² area (Fig. 1a,b). All deployments used Güralp CMG-3T sensors with a long-period corner frequency of 120 s and a gain of 1500 V/m/s. CMG-3Ts are not designed for direct burial, but the two directly buried sensors in this experiment were retrofitted with waterproof cable connectors and cables. Data were collected on two 6-channel Quanterra Q330 digitizers with 1 and 40 Hz sampling and telemetered to the nearby PASSCAL Instrument Center at New Mexico Tech in Socorro. Data were subsequently archived at the Incorporated Research Institutions for Seismology (IRIS) Data Management Center under the YE temporary network code. The site was powered with four 65 W solar panels and two 100 amp-hour lead acid batteries contained, along with the dataloggers, charge controllers, and a cell modem, in a very small aperture terminal box sited next to the sensors. A posthole sensor was also installed within the site during the study, but recordings from this station are not analyzed here.

The PASSCAL-style shallow vaults (Fig. 1a) consisted of concentric plastic barrels: an inner 15 gallon barrel with an open bottom for housing the sensor and an outer 55 gallon...
barrel with a locking lid. Both barrels were installed in the ground over a 20-cm-high cement pier with open-cell foam and styrofoam disks for thermal insulation and air circulation buffering. The direct burial emplaced sensors were contained in a heavy plastic bag and installed on top of 5 cm of compacted all-purpose sand with fine sand gently tamped around the sensor. The plastic bag covering the direct burial sensors was later removed after it was deemed not necessary for protection. Additional dirt was mounded on top of the sensor installations to provide further insulation and thermal mass to minimize temperature fluctuations. The installation was then covered with a tarp for protection from rain. The vault and the direct burial sensors were both situated at a depth of about 1 m from the top of the mounded dirt to the sensor base. Sensor specifications are reported in Table 1.

Data Return

There were two sensor failures that occurred during this study, with direct burial 2 (Table 1) performing poorly beginning on 22 September 2012 and continuing through November, as well as a failure with the BHE component of direct burial 1 on 18 November 2012. A conclusive reason for the failure of the direct burial sensors during this study could not be determined, though both instruments failed most significantly on the BHE component. Lightning strikes were investigated as a possible cause; however, there were no storm cells or lightning strikes reported within three days of either failure (U.S. National Lightning Detection Network and NEXRAD, see Data and Resources). A compromised power source may be the cause of a failure. Data recorded during the eight-month period from 1 January 2012 to 31 August 2012, excluding a telemetry gap on 17 January 2012, was chosen for the analysis to utilize periods of time when all sensors were functioning properly.

Data Quality Analysis

Eight months of data from January to August 2012 recorded on all four emplaced sensors were compared to determine if the two emplacement methods showed a systematic effect on data quality. To do this, we calculated PSD, SNR for teleseismic and local earthquakes, and coherence of the sensors for both noise and earthquake signal recordings. We also monitored and accounted for any discrepancies in data return. This analysis was focused on assessing use of such data in research, as well as examining relevant temporal trends in data quality at scales from seconds to seasons.

Power Spectral Density

To characterize seismic noise levels, we used the method of McNamara et al. (2009) to compare baseline data qualities through PSD probability density function (PDF) analysis. PSDs were calculated with PQLX software (McNamara and Boaz, 2011) using continuous 1 hr time-series segments of data overlapping by 50%, resulting in 48 PSDs per day per sensor. The instrument response was deconvolved from the signal to allow comparison of the calculated PSDs to the new low-noise model (NLNM) and new high-noise model (NHNIM) (Peterson, 1993), baselines for seismic station performance that remain widely used despite more recent proposed models (Berger et al., 2004; McNamara and Buland, 2004; Castellaro and Mulargia, 2012). Earthquake and most other signals are highly sporadic, so robust central tendency estimates for the background noise at a seismic station are best characterized using the median of the PDFs at each frequency interval without resorting to event culling.

Median PSD PDFs from eight months of data for each sensor are reported in Figure 2a. There was not a perceptible difference between the overall trends of the 10th and 90th percentiles of the PDFs and the medians of the PDFs. The site may be generally characterized, relative to the Peterson noise models, as being high noise at shorter periods. The high horizontal-to-vertical noise ratio observed here is typical of shallow vaults (e.g., Anthony et al., 2015) and reflects the coupling of local tilt into horizontal component signals (e.g., Wielandt and Forbriger, 1999). As is often observed, long-period vertical site noise is more coherent than the long-period horizontal site noise. The median PSD PDFs of all eight months of data show that the direct burial sites had highly comparable noise levels to the vaults except for the horizontal components at long periods (15 s ≤ T), for which the east component of both of the direct burials had less noise than the vaults.

To highlight differences between the recorded noise levels more clearly, the mean was taken of the four median PSDs of the direct burial and vault sensors for each respective component at each frequency to calculate an average comparison PSD of all stations. The difference between this all-station average PSD and the median PSD of each sensor was then calculated at each frequency, with negative values showing a higher probability of less noise power than the average and

Table 1

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Station Code</th>
<th>Thickness of Thermal Mass (cm)</th>
<th>Failure Date (yyy/mm/dd)</th>
<th>Evidence of Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vault 1</td>
<td>DBT2</td>
<td>30</td>
<td>None</td>
<td>10–13 cm mark on pier</td>
</tr>
<tr>
<td>Vault 2</td>
<td>DBT2A</td>
<td>30</td>
<td>None</td>
<td>10 cm mark on pier</td>
</tr>
<tr>
<td>Direct burial 1</td>
<td>DBT2.00</td>
<td>60</td>
<td>2012/11/18</td>
<td>Water in cable housing</td>
</tr>
<tr>
<td>Direct burial 2</td>
<td>DBT2A.00</td>
<td>76</td>
<td>2012/09/22</td>
<td>None</td>
</tr>
</tbody>
</table>
positive values showing a higher probability of more noise power than the average (Fig. 2b). This analysis shows that the predominant difference in noise level is on the east component, for which the median power levels of both direct burial stations at periods greater than 15 s are at least 2 dB lower than both vault stations. Between the highest-noise vault station and the lowest-noise direct burial station on the east component, this performance difference grows to about 9 dB at 100 s. The north component does not show this effect, with direct burial 1 performing similarly to the vault stations and only direct burial 2 having lower noise. There is some separation in station performance at longer periods on the vertical component, but all station medians stay within a 4 dB spread of each other at all periods. At periods less than 10 s on all three components, all four stations stay within 1 dB of the ensemble mean.
Temporal trends in background noise are also an important metric of consistent station performance. Daily temperature cycles and weather patterns change strongly with the season in central New Mexico, with winter months potentially bringing the effects of ground freeze and thaw, spring months characterized by high winds, and summer months heralded by monsoon rains. To explore how these seasonal changes affect the data quality of the differing emplacement types at this site, median PSD PDFs were taken for each day and divided into three useful period bands: short period ($0.1–1 \text{s}$), microseism ($2–20 \text{s}$), and long period ($20–172 \text{s}$). Dividing the result into separate frequency bands is valuable, because there is a strong frequency dependence on sources of noise and the performance of these stations. These differing bandwidths are also distinctly important to a variety of research applications. Median daily PSD PDFs were interpolated, and the difference between the PSD and the NLNM was calculated at each frequency from 0.1 to 172 s. This difference between daily PSD PDFs and the NLNM was then averaged across each band to create basic seasonal noise level metrics. Because all sensors are compared to the same baseline noise model, these differences can then be compared to one another and provide an accurate average power, or power difference, of the noise for each day. This analysis was performed on all three components of the four sensors in the study, and the results of the microseism and long-period band are reported in Figure S1 of the electronic supplement to this article and Figure 3, respectively.

It is well known that teleseismic body waves have a contribution to ambient seismic background through extended coda and aftershock signals that confer small amplitude motion to the surface over a long period of time, and it is possible that this phenomenon is measurable in this analysis (Boué et al., 2013). Days on which an $M_w \geq 7$ earthquake occurred are indicated. Although every $M_w \geq 7$ earthquake does not mark a day of higher than average noise, many high-noise days do line up with an $M_w \geq 7$ earthquake, and we disregard these days to concentrate on locally or regionally generated background power trends.

The vertical component is ubiquitously the lowest noise component, usually with a separation from the horizontals of at least 20 dB, whereas the noisier east and north components overlap one another (Fig. 3). Some of the distinct trends on the vertical component of direct burial 2 may be due to the drift of the sensor’s mass position, which can add long-period noise on the vertical component of CMG-3T sensors. This prompts a mass recenter command from the datalogger and a corresponding abrupt decrease in vertical noise after the sensor settles. If a gradual increase in vertical long-period noise follows the trend of vertical mass-position drift and an abrupt decrease in vertical long-period noise coincides with a mass recenter and mass voltage decrease, then the long-period vertical noise is almost certainly related to mass position. Mass recenters were triggered by the horizontals of direct burial 2 on 8 March and 10 June 2012, coinciding with a drop in the vertical long-period noise of the station. An additional mass recenter on 1 August 2012 does not show a clear drop in long-period noise.

The horizontal components of all four sensors show a decrease in noise in the microseism band from April through August in Figure S1, reflective of a typical seasonal decrease in northern Pacific storms during that time period (e.g., Hasselmann, 1963; Given, 1990; Aster et al., 2008). The horizontal components of the direct burials showed an average decrease of 3.6 dB from January–March to April–June on the horizontal components, compared with an average decrease of only 1.9 dB on the vault sensors. On the long-period band, the two direct burial sensors display fairly consistent noise levels, with a decrease of noise from April to June on the horizontal components consistent with this scenario. The vaults, however, show a general increase in noise beginning in April in the long-period band, which tapers off through August. On average, the horizontal components of the vaults have 5.3 dB more noise from April to June than the direct burials at long periods. The source of this noise is likely local environmental effects occurring in the spring months. Average maximum–minimum temperature differentials are highest during April, May, and June, with a 36°F monthly average differential during this time period, 4°F greater than the average temperature differential of all other months (Arguez et al., 2012). The experimental site is also very near the Rio Grande, with clay-rich alluvium and a variable and shallow water table. Discharge is mainly driven by snowmelt and is recorded on two U.S. Geological Survey (USGS) water-data sites near the sensors, one 18.2 km directly north and one 3.7 km directly south. These sites show identical trends, with a relatively steady daily discharge of 700 ft$^3$/s from January through March, disrupted on 4 April 2012 by the largest spike to over 2000 ft$^3$/s, followed by lesser spikes of 1500, 1000, and 700 ft$^3$/s before decreasing to zero flow by the end of July (USGS New Mexico Water Science Center National Water Information System, see Data and Resources). During demobilization, we observed evidence of repeated flooding from the interior floor of the vaults, with water levels to within 15 cm of the top of the cement pier. Residue of previous moisture beads on the interior top of the inner barrel of the vaults and moisture on the inside of the open-cell foam was also found, but there was no evidence of water flowing in from the top of the vault so we concluded that water must have entered through the base. The direct burial sensors were above this inferred maximum water table. Repeated wetting and drying of the clay-heavy sediment from changes in the average discharge of the Rio Grande could be responsible for the increase in observed long-period noise observed on the vault sensors in the spring months.

Magnitude-Squared Coherence

A useful metric for intercomparing the similarity of signals at collocated seismic stations is to calculate their coherency, a fundamental measure of how similar the phase and amplitude structure of time series data are as a
function of frequency. Values of coherency between two time series range from near 0 (indicating incoherence) to 1 (indicating perfect resemblance). The complex coherency function is the cross-spectral power density function normalized by the square root of the product of the PSD functions of the two time series to be compared. The cross spectrum is the discrete Fourier transform of the cross-correlation function between two time series \(X \text{ and } Y\), which is

\[
R_{xy}(n) = \sum_{t=-\infty}^{\infty} X(t)Y(t-n),
\]

and the cross spectrum is the Fourier transform of the cross correlation at a specific angular frequency \(\omega\):

\[
P_{xy}(\omega) = \sum_{k=-\infty}^{\infty} R_{xy}(m)e^{-j\omega k}.
\]

The angular frequency \(\omega\) can be converted to frequency \(f\) by the simple relation

\[
\omega = 2 \times \pi \times f.
\]

MSC \(C_{xy}(f)\) is calculated in this study using

\[
C_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)},
\]

in which \(P_{xy}(f)\) is the cross spectrum of the two equally sampled time series \(X\) and \(Y\), and their associated power spectral densities are noted by \(P_{xx}(f)\) and \(P_{yy}(f)\), respectively. MSC was calculated for each hour of data recorded from January through August of 2012, using the Welch’s overlapped averaged periodogram method (Welch, 1967) with 1 hr windows, an overlap of 30 min, and a standard Hamming window. With three components (BHE, BHN, BHZ) and three station cou-
Seismic sensors are typically installed with great precision and care, but orientation errors occur in the field and can be up to 10° (Ekström and Busby, 2008). Sensor alignment errors can add a significant amount of uncorrelated noise on the horizontal components, and slight variations from the vertical allow noise to leak onto the vertical component, particularly in the microseism band (Ekström and Busby, 2008). Sensor alignment errors are similar to those found for many Advanced National Seismic System stations prior to 2011 and are attributed to uncertainties arising from the use of a magnetic compass to estimate horizontal orientation during sensor deployment (Ringler et al., 2013). The remaining uncorrelated noise levels of the direct burial sensors were within a few decibels of the vaults sensors, with an improvement over the vault sensors in the long periods of 10 s or greater on the BHE component.

A significant amount of uncorrelated noise remained in the microseism band on the BHZ component after the rotation in the horizontal plane. This prompted a further rotation of the data to minimize uncorrelated noise in the vertical plane using the same methodology as for the horizontal components. The vertical rotation was done iteratively for dip and azimuth with increments of 0.05° and 1°, respectively. The rotations that minimized the uncorrelated microseism noise were dips and azimuths of 0.2°/10°, 0.35°/175°, 0.4°/20°, and 0.3°/125° for vault 1, vault 2, direct burial 1, and direct burial 2, respectively. Any tilt noise from off-vertical alignment on this scale is negligible for the previous temporal noise analysis due to these small angles. The uncorrelated noise that remained in the microseism was higher in the direct burials, and the noise that remained in the long periods was higher in the vaults. This incoherent noise can come from additional sources other than the seismic wavefield alone, such as non-seismic vault-localized ground strains in a relatively high-noise site (Ringler et al., 2011). Further results from this analysis are available in Figures S2 and S3.

To ensure that our results are not affected by calculating the MSC of misaligned stations, we tested the effect of orientation errors on MSC in a controlled way. We took the recorded data of the BHE component of vault 1 for the month of December 2011 and rotated it in the horizontal plane by 1°, 2°, 3°, 4°, 5°, 10°, and 20° to simulate a misalignment. We took each rotated recording and performed the same MSC analysis outlined previously on the original vault 1 data (Fig. 5a,b). Calculating the coherence of the original signal to the slightly rotated signal is a method that fully isolates the effects from a misaligned sensor. Misalignment of the vertical plane was also tested for eastward dips of 0.2°, 0.4°, 0.8°, 1.6°, and 3.2° from the vertical (Fig. 5c,d). The effects in MSC for rotations of the horizontal plane from 1° to 5° were minimal, with a maximum 0.01 decrease in MSC at frequencies of 0.3 and 2 Hz. Similarly, MSC was only reduced by a maximum of ~0.015 with a 0.4° rotation of the vertical plane and only at the longest frequencies. With larger rotations in both the horizontal and vertical plane, reductions of MSC are

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Figure 5. Results of MSC analysis of original data and rotated data from the BHE component of vault 1 during the month of December 2011. (a) PDF of MSC of vault 1 station and vault 1 station rotated by 20° in the horizontal plane. White lines show median PDF of 1°–20° rotations. (b) Median PDFs for 1°, 2°, 3°, 4°, 5°, 10°, and 20° rotations in the horizontal plane. (c) PDF of MSC of vault 1 station and vault 1 station with 3.2° rotation of the vertical plane. White lines show median PDF of 0.2°–3.2° rotations. (d) Median PDFs for 0.2°, 0.4°, 0.8°, 1.6°, and 3.2° rotations in the horizontal plane. The color version of this figure is available only in the electronic edition.

For all months, the vertical components of the direct burial sensors are more consistently coherent with one another than any other component–station pair at longer periods to about 10 s, past which MSC drops off rapidly (Fig. 4). This is in contrast to the vertical component of the vaults, which are less consistently coherent but show higher levels of vertical component coherence at longer periods to approximately 100 s. The direct burial vertical components also show consistently higher MSC through the microseism band than do the vaults. Both horizontal components show comparable MSC between vault–vault and direct burial–direct burial comparisons during all months at periods above 10 s, excluding a dip at 1 Hz. The 1 Hz frequency is often associated with cultural noise, but this decrease in coherency may also be due to wind noise (Given, 1990; Wilson et al., 2002). Temporal trends of MSC can be best observed in the plots in Animations S1–S3. From June to August, the coherence of direct burial to direct burial horizontal components stay steady at 1 Hz, whereas the vault-to-vault horizontal components decrease in coherence. This difference could be due to the additional 30+ cm of thermal mass above the direct buried sensors, providing more protection from temperature changes in the summer months. At periods longer than 10 s, the coherence of direct burial to direct burial horizontal components vary up to 0.3 in MSC, whereas the vault horizontal components vary up to 0.6 in MSC between January and June.

Dissimilar-Emplacement MSC

When dissimilar emplacement-type sensors are compared, we find that MSC is comparable to the analysis done in the previous section with same emplacement types at periods higher than 10 s for all three components (Fig. 4). The one exception is a drop around 1 s in MSC between vault 1 and direct burial 1 on the BHE component during August. On the vertical component at periods longer than 50 s, the MSC is higher between vault 1 and direct burial 1 than the MSC between direct burial 1 and direct burial 2. Thus, MSC in recorded signals can be lower between two sensors with the same emplacement than two sensors with different emplacement in this experiment.

Hourly MSC

Hourly MSC values were integrated across three frequency bands of 0–0.2, 0.2–5, and 5–20 Hz to produce coherency metrics for the long-period, microseism, and short-period bands (Fig. 6a). These integrated values were normalized by the ideal MSC to compare the three bands to one another (Anderson et al., 2012). Coherence values of zero indicate the data gaps on 17 January 2012. The short-period and long-period bands are much less coherent than the microseism band, rarely dipping below 0.8 coherence in both vault-to-vault and direct burial to direct burial comparisons over all months and all three components. Short-period coherency typically falls around 0.7 for all stations and all components. The BHE components show the most temporal change in behavior in the long-period band, with a range in coherency of 1.0–0.6 coherence in January at both station pairings increasing to a range of 1.0–0.5 for direct burial–direct burial and 1.0–0.3 for vault–vault coherence in June. These temporal changes in coherence are well above the uncorrelated noise of the sensors from misalignment, suggesting that these sensors are recording a source of noise that temporally changes in coherence and is recorded differently based on emplacement type.

To investigate temporal cycling of coherence, each month of hourly coherences was converted to the frequency domain by taking the fast Fourier transform for each band and for all six vault and direct burial station pairings (Fig. 6b). A distinct diurnal cycle can be identified at the 0–0.2 Hz band, evident in the sinusoidal pattern of the lowest frequency plots on both the direct burial and vault in June.
The strongest cycle appears in the lowest frequency band for all components, with the highest amplitude corresponding to a daily cycle on the east component (Fig. 6b). The vertical component (not shown) displays only a slight diurnal peak on the lowest frequency band, less than one-third the amplitude of the east component. The amplitude of the daily cycle increases in the later months, with the highest amplitude in August. This daily cycle of long-period noise could be explained by temperature and atmospheric pressure, both diurnally varying factors known to cause uncorrelated noise on sensors (Given, 1990; Sleeman and Melichar, 2012; Custódio et al., 2014). We believe that the decline in MSC of the direct burial sites in June at long periods is due to wind-driven spatially variable strain, such as ground tilt from tree roots. Relationships between environmental factors, emplacement type, and noise require further analysis.

Signal-to-Noise Ratio

The ratio of earthquake SNR recorded by sensors is included in this study because the most common use of PASSCAL seismic stations is to record earthquakes. Teleseismic earthquakes were taken from the National Earthquake Information Center global earthquake search and were selected for $M_w \geq 6$ and within distances of $30^\circ$–$90^\circ$ from the installation site (National Earthquake Information Center, 2013). Twenty-three teleseismic earthquakes representing a wide range of depths and faulting styles were used in this analysis, evident from their Global Centroid Moment Tensor mechanisms (Ekström et al., 2012). Local earthquakes were taken from the New Mexico Tech Seismological Observatory (2013) earthquake archives, with distances up to 10 km from the site, representing magnitudes of $1 \leq M_L \leq 0.1$. Six of these local earthquakes had a clear onset to distinguish the event signal from the noise and were included in the analysis. The vertical waveforms were filtered with a second-order, single-pass band-pass filter between 0.5 and 3 Hz for teleseismic events and a second-order, single-pass high-pass filter with a corner of 1 Hz for local events. $P$-wave arrivals were calculated to first-order using the TauP Toolkit (Crotwell et al., 1999) with the IASP91 1D Earth model (Kennett and Engdahl, 1991) and then were manually repicked. Two windows of data were selected before and after the manually picked arrival for the noise and signal windows, each with lengths of 40 s for teleseismic and 1 s for local earthquakes. The SNR was defined as the ratio of the root mean square (rms) of the signal over the rms of the noise.

All stations have a median SNR of 17 or above and a mean SNR of greater than 26 for teleseismic earthquakes...
occurring between 1 January and 31 August 2014, recorded on the vertical component (Table 2). Both mean and median are shown, but the median SNR is less biased by the greater signal of the largest earthquakes. The differences of SNR between sensors for these strong teleseisms, not surprisingly, are insignificant for the frequency range of 0.5–3 Hz. Both direct burial stations had slightly higher SNR than both vault stations for all six of the local earthquakes, but the differences were not significant (Table 3).

Coherency of pre-event noise and coherency of earthquake signals between the four sensors was compared using the largest event that occurred during the study period, the $M_w$ 7.7 earthquake near Japan on 14 August 2012. The MSC, as defined in the previous section, was taken on the pre-event noise, and a signal window was defined by 15 min of unfiltered data windowed on either side of the $P$ arrival (Fig. 7).

The signal portion is always more coherent than the noise, particularly at low frequencies of less than 0.1 Hz but also at high frequencies of about 10 Hz. Signal coherency is of comparable magnitude between all station pairings, with the dissimilar pairing of vault 1 and direct burial 1 showing the highest values. This suggests that emplacement type does not have a detectable impact on the coherence of recorded events between adjacent sensors.

**Conclusions**

We conclude that, in this high-noise and soft-soil site, broadband sensors with direct burial emplacement have very similar data quality to collocated sensors with vault emplacement over an eight-month record. PSD PDF analysis shows that all components of directly buried sensors have comparable noise levels to sensors emplaced in vaults. However, the sites show differing responses to seasonal changes that we attribute to the soil column, with horizontal components of the direct burial sensors at long periods showing less noise beginning in early April, whereas the vault sensors show increased noise, with these trends continuing into mid-July. This represents an improvement of 5.3 dB in mean noise levels on horizontal components of the direct burial sensors over the vault sensors at long periods during the spring transition, when these moist soils are undergoing vadose zone drying and/or shallow freeze–thaw, and indicating that direct burial sensors were in this case more resistant to tilt-coupled noise from these processes.

Diurnal cycling of MSC is apparent in both vault and direct burial comparisons and is most obvious in the long-period band of all components starting in mid-July. August shows the widest range of MSC in both emplacement type comparisons, cycling from 0.1 to 1. The MSC PDFs show that the direct burial to direct burial comparisons have a smaller range of coherence values around 1 Hz than the vault-to-vault coherency. This could be explained by atmospheric-pressure-induced tilt known to produce incoherent signals even at sensors colo-

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Date (mm/dd in 2012) with $M_w$</th>
<th>V1</th>
<th>V2</th>
<th>DB1</th>
<th>DB2</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>01/23 (6.1)</td>
<td>6.7</td>
<td>6.6</td>
<td>6.7</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>01/30 (6.4)</td>
<td>6.7</td>
<td>6.6</td>
<td>6.7</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>03/05 (6.1)</td>
<td>6.7</td>
<td>6.6</td>
<td>6.7</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>03/14 (6.1)</td>
<td>6.7</td>
<td>6.6</td>
<td>6.7</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>04/17 (6.1)</td>
<td>6.7</td>
<td>6.6</td>
<td>6.7</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>05/14 (6.1)</td>
<td>6.7</td>
<td>6.6</td>
<td>6.7</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>05/25 (6.1)</td>
<td>6.7</td>
<td>6.6</td>
<td>6.7</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>06/11 (6.1)</td>
<td>6.7</td>
<td>6.6</td>
<td>6.7</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>06/22 (6.1)</td>
<td>6.7</td>
<td>6.6</td>
<td>6.7</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>07/20 (6.1)</td>
<td>6.7</td>
<td>6.6</td>
<td>6.7</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Data Quality of Collocated Portable Broadband Seismometers Using Direct Burial and Vault Emplacement
cated to within 1 m, as well as increased incoherency due to the vault void space (Ringler et al., 2011).

The signal-to-noise analysis shows similar values for high-signal-to-noise teleseismic events recorded at all four stations, as well as for lower signal-to-noise local events down to $M_L$ of 0.1. Coherence of the largest recorded earthquake ($M_w$ 7.7) during the field experiment did not appreciably differ between same and dissimilar emplacement types.

We compare data quality between vault-sited and shallow directly buried sensors to show that the time and cost advantages of direct burial do not appreciably degrade data quality in a soft soil environment. Noise recorded by vault-sited sensors is generally higher in amplitude during the transition from spring to summer as compared to the direct burials. This increase is especially evident on the tilt-coupled horizontal components at long periods between 20 and 170 s. Levels of noise, and diurnal changes in the levels, are similar at all sensors from cultural activity, wind noise, local tilting, and temperature fluctuations. We conclude that direct burial broadband sensors in this environment were essentially equivalent in data quality to the shallow vaults and can be superior.

Although this was a closely monitored and maintained site, two directly buried sensors failed on separate occasions. Although this does not necessarily indicate that these standard CMG-3T sensors were ill suited for the direct burial environment, we do not endorse directly burying broadband sensors that are not purposely built for direct burial. This work suggests that the community would be well served by developing and deploying robust broadband sensors that can be routinely installed via direct burial using the methods discussed in this article.

To improve data quality for portable broadband sites, we suggest employing a similar augured direct burial technique over vault installation to reduce the cargo load for each instal-

### Table 3

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Date (mm/dd in 2012) with ($M_L$) $^*$</th>
<th>Mean</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>04/26 (0.3) 05/03 (0.2) 06/04 (0.7) 06/04 (1.1) 06/10 (0.9) 08/04 (0.1)</td>
<td>2.33</td>
<td>2.31</td>
</tr>
<tr>
<td>V2</td>
<td>3.179 2.03 1.81 1.72 2.66 2.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DB1</td>
<td>3.226 1.97 1.73 1.76 2.59 2.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DB2</td>
<td>3.481 2.05 1.92 1.81 2.83 2.77</td>
<td>2.48</td>
<td>2.41</td>
</tr>
<tr>
<td></td>
<td>3.228 2.12 1.98 1.83 2.89 2.77</td>
<td>2.47</td>
<td>2.44</td>
</tr>
</tbody>
</table>

$^*$Station names: V1, vault 1; V2, vault 2; DB1, direct burial 1; DB2, direct burial 2.

$^*$The date of the earthquake is on top with the local magnitude from the New Mexico Tech Seismological Observatory ($M_L$) below in parentheses.
loration and to reduce noise from nonseismic sources. An augered posthole design has been utilized for seismic emplacement in icy environments and includes an all-in-one datalogger and sensor design to further reduce installation materials (Bernsen et al., 2014). Streckeisen STS-4B and Trillium 120PH sensors installed in deeper posthole/borehole systems show improvement over deeper Transportable Array–style vaults in the long-period band on the horizontal components. Methods for securing the cables and sensors within these configurations have been developed to further improve station performance (Frassetto et al., 2014). These techniques will soon be deployed on a large scale in EarthScope USArray Transportable Array activities in Alaska and Canada (Busby et al., 2013).

Data and Resources

All data used in this study can be obtained under the network code YE from the Incorporated Research Institutions for Seismology Data Management Center at ds.iris.edu/mda/YE (last accessed February 2015). Next Generation Radar (NEXRAD) was obtained from www.roc.noaa.gov (last accessed April 2014). United States Geological Survey New Mexico Water Science Center National Water Information System was obtained from waterdata.usgs.gov/nm/nwis/sw/ (last accessed February 2015).

Acknowledgments

The seismic instruments were provided by Incorporated Research Institutions for Seismology (IRIS) through the Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) Instrument Center at New Mexico Tech. The facilities of the IRIS Consortium are supported by the National Science Foundation under Cooperative Agreement EAR-1261681 and the Department of Energy’s National Nuclear Security Administration. The authors appreciate the valuable comments of two anonymous reviewers that helped to improve this article. Thank you to the numerous researchers and students who contributed to all stages of this long-term project and especially to the entire staff at IRIS PASSCAL Instrument Center, including Noel Barstow, Ptnia Miller, George Slad, and Bruce Beaudoin.

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Manuscript received 3 December 2014;
Published Online 1 September 2015