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*Short Note*

# Repeatability of Testing a Small Broadband Sensor in the Albuquerque Seismological Laboratory Underground Vault

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**Abstract** Variability in seismic instrumentation performance plays a fundamental role in our ability to carry out experiments in observational seismology. Many such experiments rely on the assumed performance of various seismic sensors as well as on methods to isolate the sensors from nonseismic noise sources. We look at the repeatability of estimating the self-noise, midband sensitivity, and the relative orientation by comparing three collocated Nanometrics Trillium Compact sensors. To estimate the repeatability, we conduct a total of 15 trials in which one sensor is repeatedly reinstalled, alongside two undisturbed sensors. We find that we are able to estimate the midband sensitivity with an error of no greater than 0.04% with a 99th percentile confidence, assuming a standard normal distribution. We also find that we are able to estimate mean sensor self-noise to within ±5.6 dB with a 99th percentile confidence in the 30–100-s-period band. Finally, we find our relative orientation errors have a mean difference in orientation of 0.0171° from the reference, but our trials have a standard deviation of 0.78°.

*Electronic Supplement:* Table of dates of the trials used as well as *Q*–*Q* plots for the statistics collected from the sensor tests.

## Introduction

Our ability to record high-fidelity seismic signals is fundamentally limited by the performance of the instrumentation used. The evaluation and testing of such equipment has been the subject of a number of studies (e.g., Hutt *et al.*, 2009; Wielandt, 2012). One of the large limitations in observational seismology is unwanted natural background noise (e.g., site noise, sensor noise, sensor sensitivity to nonseismic noise sources, etc.). To better constrain sensor noise, a number of techniques have been developed to remove the common background signal (Holcomb, 1989; Sleeman *et al.*, 2006; Tasič and Runovc, 2013). Further work has been done on the variability of sensor self-noise using a long-running collection of three broadband seismometers (Sleeman and Melichar, 2012). At long periods (e.g., 100 s period and greater), the reproducibility of the self-noise of the Streckeisen STS-2 as compared to the Streckeisen STS-1 sensor has been questioned (Widmer-Schnidrig, 2003; Berger *et al.*, 2004; Sleeman *et al.*, 2006; Ringler and Hutt, 2010) and might not be reproducible to better than 7 dB at 1000 s period. This suggests that even in well-controlled environments we may not be able to fully constrain the self-noise of an instrument. However, this does not necessarily mean that the self-noise of these instruments is varying to this degree; it just means that our ability to reproduce the self-noise calculation is limited by the wide range of noise sources involved. Different sensors of the same model type are known to have variable self-noise (Ringler and Hutt, 2010). However, the variability of these estimates while reinstalling the sensor but keeping the sensors and test conditions fixed is relatively unknown. By constraining the repeatability of commonly estimated sensor parameters (e.g., midband sensitivity and self-noise), we attempt to quantify reproducibility of sensor evaluation as well as the contribution of sensor noise and installation noise to sensor deployments. Such lower bounds could indicate that the error bounds in our testing methods are larger, in certain cases, than differences in the self-noise of sensors in certain testing setups.

There have been a number of seismic deployments where site conditions and installation methods are evaluated (e.g., Wilson *et al.*, 2002; Aderhold *et al.*, 2015; Anthony *et al.*, 2015; Wolin *et al.*, 2015). By constraining the variability of the sensor self-noise calculation as well as our ability to constrain important sensor parameters, it might be possible to explain some of the variability found in various field installations. This variability could get attributed falsely to variability in site noise, local conditions, or installation methods used, when it is simply the variability from installation to installation. As observational seismology makes more use of the seismic noise field (e.g., Tsai, 2011), it will be important to better understand the contribution of site noise as well as instrumentation noise, along with the variability of such additive noise sources. Such insights could also lead to better practices in the installation of sensors and in isolating them from nonseismic noise sources.

## Experimental Setup

To estimate the repeatability of estimating various seismic sensor parameters, we installed three Nanometrics Trillium Compact seismometers in the Albuquerque Seismological Laboratory (ASL) cross tunnel (Fig. 1). We used sensitivity and pole and zero models from the Incorporated Research Institutions for Seismology Nominal Response Library. These sensors were picked because they are easy to install and are commonly used in short-term deployments. Also, these sensors have self-noise levels that are typically above the ASL vault noise at periods greater than ~30 s. This will allow for robust long-period noise calculations without the possible influence of varying vault noise levels. Each sensor was connected to a 26-bit Quanterra Q330HR digitizer with a sampling rate of 40 samples per second.

The sensors were all installed along a common north line. We did not make use of any mechanical orientation jigs. With the small diameter and orientation markings for the seismometer on the top of the instrument, the sensor chosen for the study may also represent a worst-case scenario for repeatedly orienting a seismometer to a marked line in a vault. A number of previous studies on orientation errors have made use of Streckeisen STS-2 seismometers and mechanical orientation jigs (Ekström and Busby, 2008; Ringler *et al.*, 2013).

The sensors were covered with a common thermal-insulating box. For each trial, we uninstalled the southernmost sensor, screwed the feet to their stops, and then reinstalled the sensor. The northernmost two sensors were not moved. We conducted 15 trials in total. The dates of the reinstallations are contained in Ⓔ Table S1, available in the electronic supplement to this article. When we reinstalled the sensor, oriented it, leveled it, tightened the feet, and connected it back into the same digitizer. The sensor that was reinstalled had station name TST6 and location code 00, and the two reference sensors had station name TST5 with location codes 00 and 10, respectively. We did not make any effort to match previous Trillium Compact self-noise estimates (e.g., better thermal isolation, installation on a common granite slab, longer settling times), because our goal was to look at the repeatability of a common test and not at methods for optimizing the self-noise estimates of a particular sensor model. Some of the elevated long-period sensor self-noise of the Trillium compacts (Fig. 2) is likely a function of the installation environment (e.g., the sensitivity of the sensor to non-


**Figure 1.** Setup of the three Nanometrics Trillium Compact sensors used in our experiment in the cross tunnel of the Albuquerque Seismological Laboratory underground vault. The rightmost seismometer was the sensor that was reinstalled. All three sensors were connected to 26-bit Quanterra Q330HR digitizers. We used a fiber optic gyrocompass to estimate the north line. For scale, the Trillium Compact is 9 cm in diameter.

seismic noise sources) and not the true self-noise of the sensor, because previous studies have estimated lower long-period self-noise (Ringler and Hutt, 2010). However, the variability in the self-noise estimates suggests that, even at a fixed frequency, there is nontrivial variability after common signals have been removed (e.g., microseisms).

## Methods

Using the experimental setup described above, we treat these sensors as collocated with the assumption that all sensors are recording the same ground motion because of their proximity (Fig. 1), and any differences can be attributed to difference in self-noise estimates. This allows us to estimate sensor parameters relative to each other. We focus on the sensitivity, the self-noise, and the relative orientation of the sensors. Using the three-sensor method of Sleeman *et al.* (2006), we may avoid introducing errors in the self-noise estimates caused by uncertainties in the instrument response (Ringler *et al.*, 2012). Additionally, we focus on the relative orientation and sensitivity, which make use of the midband region of the sensor's frequency response at which the sensor is approximately flat to velocity. For each trial, we picked a visually quiet time period of 6 hrs between installations. We always waited until the sensor was reasonably settled.

### Relative Sensitivity

The secondary microseism signal is ubiquitous and well above the self-noise (discussed in the Sensor Self-Noise section) of the sensors used in the experiments (Sleeman and Melichar, 2012). Therefore, it is possible to estimate the midband sensitivity of the sensors if we assume they should be recording similar ground-motion amplitudes in this band

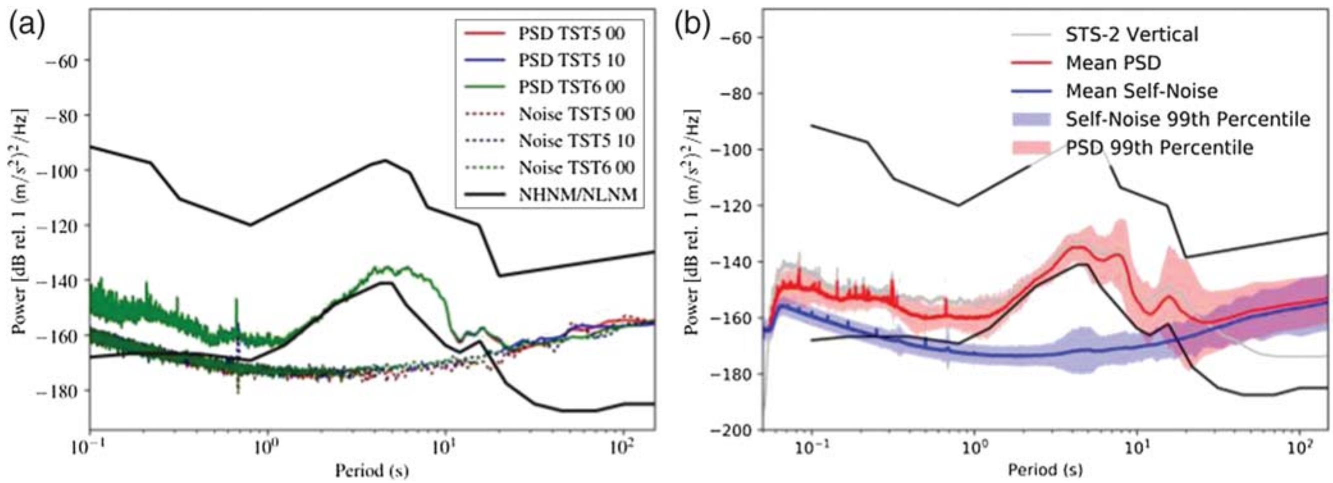


**Figure 2.** (a) Example power spectral density (PSD; solid lines; red, blue, and green) and incoherent self-noise (dashed lines; dark red, dark blue, and dark green) for the BH2 (40 samples per second east–west component) for the trial starting on 16 February 2016 4:59:59 UTC. (b) Pointwise mean PSD estimates along with the 99th percentile confidence regions from the 15 trials (red) along with the mean incoherent self-noise and 99th percentile confidence estimate regions (blue) from the 15 trials. We included the mean PSD for a vertical Streckeisen STS-2 reference sensor (gray). For reference, we included the Peterson (1993) new high-noise model and new low-noise model (NHNM/NLNM, black lines).

(~4–8 s period). For each trial, we estimated the power spectral density (PSD) using Welch averaging (Oppenheim and Schafer, 1975) of our collocated sensors, yielding PSD estimates of the background noise signal. We removed the mean, and 409 s windows (16,360 data points) were tapered with a Hanning taper of length 409 s ($2^{14}$ data points) with 12.5% overlap ($2^{11}$ data points). Figure 2 shows an example PSD for one trial. We then calculated differences in the relative gain by comparing the mean and standard deviation of the ratio of the PSD in the 4–8-s-period band (Table 1 and Fig. 3).

Table 1
Summary Statistics for the Various Parameters Estimated in This Study from Our 15 Trials

| Parameter | Channel | Mean | Standard Deviation | Units |
|---|---|---|---|---|
| Mean ratio 4–8 s period | BH0 | 1.0004 | 0.00024 | Ratio |
| Mean ratio 4–8 s period | BH1 | 0.9999 | 0.00015 | Ratio |
| Mean ratio 4–8 s period | BH2 | 1.0000 | 0.00012 | Ratio |
| Mean self-noise 0.1–30 s period | BH0 | −165.52 | 0.4378 | dB |
| Mean self-noise 0.1–30 s period | BH1 | −165.8 | 0.121 | dB |
| Mean self-noise 0.1–30 s period | BH2 | −165.55 | 0.143 | dB |
| Mean PSD 0.1–30 s period | BH0 | −152.98 | 0.9932 | dB |
| Mean PSD 0.1–30 s period | BH1 | −153.88 | 0.884 | dB |
| Mean PSD 0.1–30 s period | BH2 | −153.95 | 0.8701 | dB |
| Mean self-noise 30–100 s period | BH0 | −160.43 | 1.98 | dB |
| Mean self-noise 30–100 s period | BH1 | −160.76 | 1.90 | dB |
| Mean self-noise 30–100 s period | BH2 | −160.25 | 2.13 | dB |
| Mean PSD 30–100 s period | BH0 | −158.81 | 3.55 | dB |
| Mean PSD 30–100 s period | BH1 | −157.47 | 4.28 | dB |
| Mean PSD 30–100 s period | BH2 | −158.85 | 2.87 | dB |
| Relative orientation | BH1/2 | 0.0171 | 0.784 | ° |

All dB units are relative to $1(\mathrm{m/s}^2)^2/\mathrm{Hz}$. PSD, power spectral density.

## Sensor Self-Noise

We estimate the incoherent self-noise of the sensors using the three-sensor coherence analysis technique (Sleeman *et al.*, 2006). Our cross-power estimates use the same parameters as our PSD estimates. First, we remove the coherent signal by way of the Sleeman 3-sensor analysis technique (Sleeman *et al.*, 2006). We then convert our self-noise PSD estimates to acceleration by removing the nominal instrument response through ObsPy (Krischer *et al.*, 2015). From these PSD and self-noise estimates, we estimated the mean and standard deviation in two bands from 0.1–30 s and 30–100 s periods. Of course, when looking at the self-noise of a seismometer, one should consider the self-noise across the entire frequency band of interest and not simplify the measurement into a single number. However, for this experiment the self-noise variability was relatively constant across these bands (Fig. 2).

## Relative Orientation

To estimate the relative orientation between sensors, we minimize a cost function using a Levenberg–Marquardt minimization algorithm (Marquardt, 1963). Let $x_i(n)$ and $y_i(n)$ denote $n$th sample of the north–south and east–west time series of sensor $i$, respectively. Let $x_i'(n)$ and $y_i'(n)$ denote the $n$th sample of the time series after rotation by an angle $\theta$. We then find the relative angle $\theta$ between sensor $i$ and sensor $j$ by minimizing the following cost function for $\theta$ for $N$ points in our time series:

$$\min_{\theta}\left|\sum_{n=1}^{N}\frac{x_i'(n)x_j(n)}{\sqrt{(x_i'(n))^2(x_j(n))^2}}-1\right|.$$

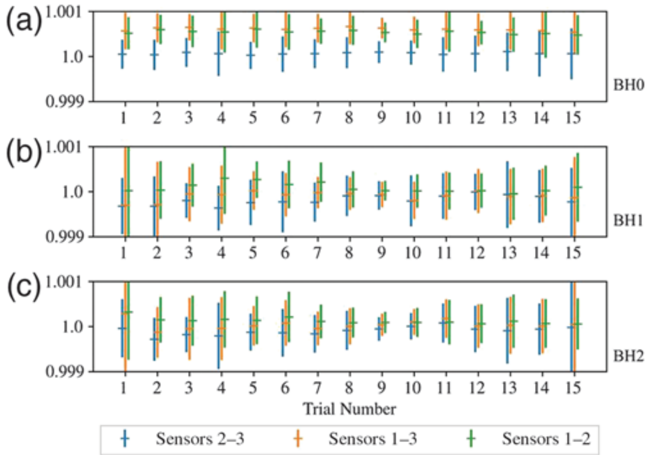


**Figure 3.** Mean ratios from 4 to 8 s period of estimated PSD between pairs of sensors of the 15 trials in this study for (a) the vertical (channel BH0), (b) the north–south (channel BH1), and (c) the east–west (channel BH2). The error bars represent ±2.5 standard deviations. Sensor 3 was the sensor that was reinstalled, whereas sensors 1 and 2 were the references.

To avoid long-period noise contaminating our estimates, we remove the mean, use a fourth-order band-pass filter from 1 to 10 s period, and apply a 5% cosine taper. This method assumes that the sensor's components are orthogonal and are similar to the cost function used to estimate orientation errors in the USArray (Ekström and Busby, 2008). It should be noted that each orientation estimate only makes use of two sensor pairs.

## Results

### Sensitivity

Using our relative amplitude estimates, we are able to give a bound on our ability to estimate the sensitivity of one sensor relative to another. *Q*–*Q* plots (Ⓔ Figs. S1–S4) show the distribution of our results and indicate that we can estimate confidence intervals assuming a standard normal. This holds true for each of the result categories below. Our trials suggest that with a 99th percentile confidence we can estimate the sensitivity to within 0.04% (Table 1). For this estimate, we are using all three-component estimates for each of the 15 trials (45 estimates in total). The 99th percentile confidence ratio is $1.000 \pm 0.0007$ (Taylor and Kuyatt, 1994). This suggests that once the absolute sensitivity of one sensor is found we may use it along with the relative sensitivity to estimate the absolute sensitivity of another sensor, making it possible to calibrate sensors to well within 1% of their actual sensitivity. In all of the trials, we found the relative sensitivity to be extremely stable and were able to give a very robust estimation of the amplitude in the 4–8-s-period band (Fig. 3).

### Self-Noise

The vertical self-noise estimates (BH0 channel) show that with a 99th percentile confidence, the self-noise is repeatable to within ±1.12 dB in the 0.1–30-s-period band (standard deviation 0.38; Table 1). Additional self-noise and PSD estimates in the 0.1–30-s-period band are included in Ⓔ Figure S5. Looking at the long-period band, we see that our 99th percentile confidence is ±5.10 dB (BH2 channel; standard deviation 2.13; Table 1). We also see that in the long-period band we are unable to systematically characterize the self-noise of the sensors relative to one another to certainties beyond ±5.6 dB, with a 99th percentile confidence (Table 1). In contrast, we see that the standard deviation of our PSD estimates in the long-period band can be as much as 4.28 dB (Fig. 4; BH1 channel). In certain cases, there can be nonobvious common noise signals (e.g., trials 2 and 7; Fig. 4). In these cases, the self-noise estimates remove the common signal, but noncoherent signals can still remain (e.g., sensors with different sensitivity to thermal changes in the vault).

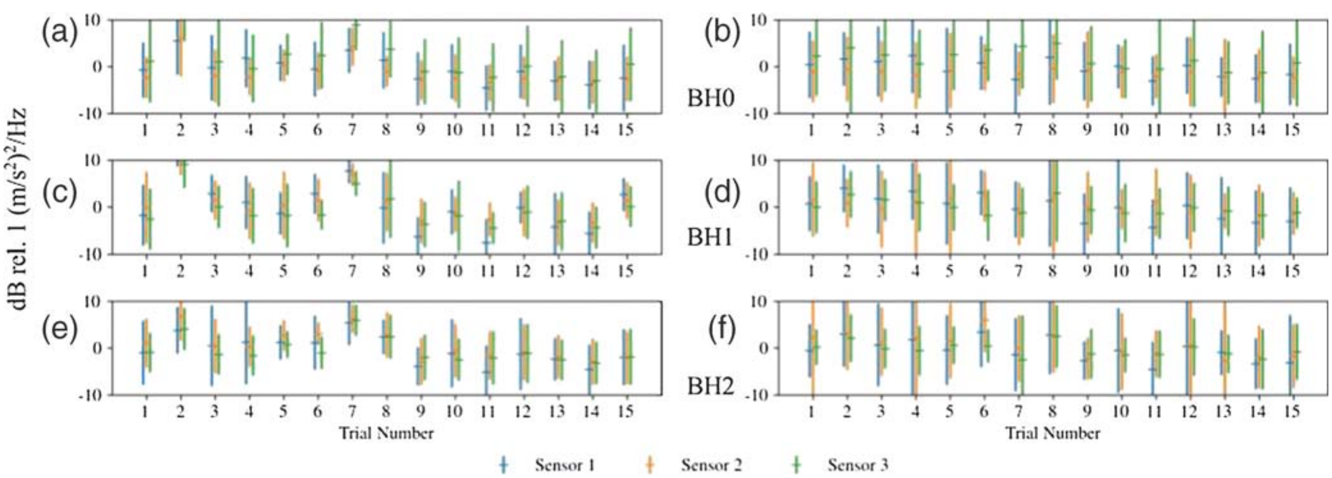


**Figure 4.** Mean removed (common mean from all trials and components) estimated (a,c,e) PSD and (b,d,f) self-noise from 30 to 100 s period of the 15 trials for (a,b) the vertical (channel BH0), (c,d) the north–south (channel BH1), and (e,f) the east–west (channel BH2). Error bars represent ±1 standard deviation.

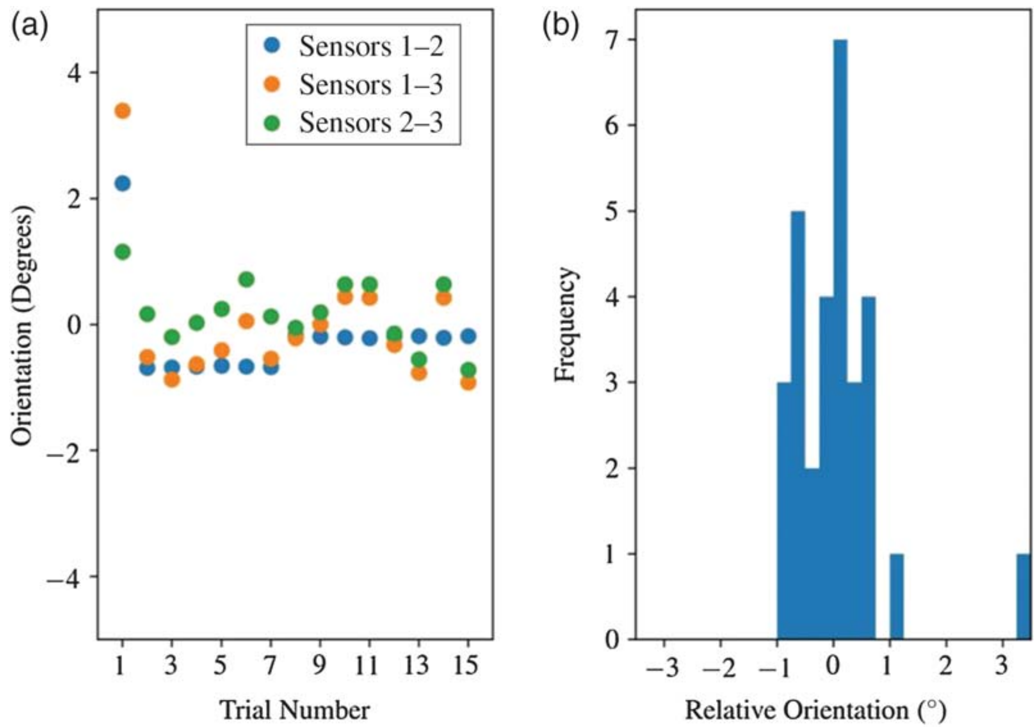


**Figure 5.** Relative orientations between sensor pairs for (a) the 15 trials and (b) a 0.5° bin histogram of all relative orientations. Only the sensors 1–3 and sensors 2–3 orientations have been included in the histogram.

Orientation

For each trial, we estimated the relative orientation between each pair of sensors. We found that the mean relative orientation difference between all three sensors was 0.0171° with a standard deviation of 0.784° (Fig. 5). Our first trial showed a large deviation from later trials and was likely caused by the thermal isolating box being bumped. The difference in the relative orientation of sensors 1–2 in trials 7 and 8 was possibly caused by one of the cables moving and causing a slight change in the orientation of one of the sensors. This required the sensors to be reinstalled. Our 99th percentile confidence is $0.0171° \pm 2.0196°$.

## Discussion

By reinstalling the same Nanometrics Trillium Compact sensor, we looked at the repeatability of estimating the self-noise, midband sensitivity, as well as the relative orientation between sensors. This examines the reproducibility of estimating various sensor parameters using different sensors of the same model type as well as different test conditions (e.g., vault conditions, installation methods used, and other nonseismic noise sources in the vault).

Our 15 trials suggest that we are able to repeat the relative sensitivity of a sensor with a very high precision that is well within 0.04%. This suggests that manufacturers are able to produce sensors with midband sensitivities that are well within desired specifications (Lay *et al.*, 2002), but our methods for estimating the sensitivity of a seismometer, without a known reference, is a limitation in sensor calibration. The relative sensitivity of the sensors is well within the manufacturer's stated accuracy of 0.5%, and our ability to repeat the relative amplitude measurement is an order of magnitude lower still, indicating the repeatability of the sensitivity estimate is extremely well constrained.

From our self-noise estimates, we see considerable variability among the sensors in the long-period band, even though the vault noise in the ASL cross tunnel is well below the sensor self-noise of the Trillium Compact for periods of 30 s and greater (Ringler and Hutt, 2010). This suggests that the sensor self-noise calculation is variable, with a standard deviation of ~2 dB, making us unable to characterize the self-noise in the 30–100-s-period range to better than ±5.5 dB with a 99th percentile confidence (Fig. 4). Of course, there are a number of potential sources of error that limit this repeatability. The sensor's sensitivity to nonseismic noise sources, variability in the repeated reinstallations, the sensor's variability in the self-noise, as well as variability in the testing conditions all could contribute. For this experiment, there are several possible nonseismic noise sources that may add to the variability of the self-noise estimates (Fig. 4). These include relatively poor thermal isolation and poor sensor coupling to the ground, which could remove long-period noise. The small size of these instruments relative to their cable connector could have also introduced excess strain that coupled as long-period tilt (Fig. 1). This suggests that a single number should not characterize that sensor self-noise without an uncertainty attached to the estimate. This relatively large variance in the long-period noise also suggests that in many cases our test conditions or the sensor's sensitivity to nonseismic noise sources could be the fundamental limiter, and the sensor's self-noise might not be what is limiting our ability to resolve long-period signals.

We suspect our study on the repeatability of the self-noise of the Trillium Compact shows the best-case scenario for broadband seismometers because we limited the study to periods no greater than 100 s. It is likely that sensor self-noise estimates at very long periods are even less repeatable. For example, Sleeman and Melichar (2012) saw a standard deviation of ~5 dB in the sensor self-noise of three Streckeisen STS-2s at 1000 s periods. Their study was with three fixed sensors, so we would expect the variability to be even larger when the sensors were reinstalled multiple times. Their study also focused on a sensor with self-noise well below that of the vault noise. In contrast, our tests used a sensor with self-noise levels that are above the typical vault noise levels at periods greater than 30 s. This suggests that in many situations researchers could be falsely estimating a sensor's self-noise as installation noise, site noise, or the sensitivity of a sensor to nonseismic noise sources, giving a falsely elevated self-noise estimate. By not considering these situations, we could be attributing variability in incoherent sensor self-noise to local site conditions or installation methods. The 30–100-s-period 99th percentile confidence interval of the self-noise is ±5.6 dB. This variability in self-noise levels represents a potentially nontrivial contribution to studies that focus on sensor installations (e.g., Aderhold *et al.*, 2015; Wolin *et al.*, 2015).

Our study indicates that the relative orientations see a fairly reliable mean estimate but significant scatter (Fig. 5). These estimates of orientation differences are consistent with previous orientation error estimate studies (Ekström and Busby, 2008; Ringler *et al.*, 2013), which suggest that we are able to visually orient seismometers to within ~2°. However, the small size of the Trillium Compact could introduce some level of error in our orientation.

## Conclusions

In this repeatability study, we have shown:

1. The ability to repeat relative midband sensitivity calculations is extremely well constrained, allowing calculation of differences an order of magnitude smaller than the manufacturer's stated sensitivity accuracy.
2. Self-noise calculations show significant variability, particularly at long periods, suggesting that in many situations calculated self-noise may include installation noise, site noise, or other nonseismic noise sources. In these cases, calculations may give a falsely elevated self-noise estimate, and the associated calculation errors should also be considered.
3. Estimated orientation of repeated installations show variability similar to that seen in other sensor orientation studies. This may indicate a fundamental lower limit in the ability to visually align sensors, suggesting a more complex method for sensor orientation may be warranted.

## Data and Resources

All data were collected at the Albuquerque Seismological Laboratory (ASL). All code used in the analysis is freely available on github at https://github.com/aringler-usgs/RepeatTest.git (last accessed October 2016). The data used in this study are available at the Incorporated Research Institutions for Seismology (IRIS) Data Management Center under network code GS. The IRIS Nominal Response Library (NRL) is available at http://www.iris.edu/NRL (last accessed January 2017).

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Any use of trade, product, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

## References

Aderhold, K., K. E. Anderson, A. M. Reusch, M. C. Pfeifer, R. C. Aster, and T. Parker (2015). Data quality of collocated portable broadband seismometers using direct burial and vault emplacement, *Bull. Seismol. Soc. Am.* **105,** no. 5, 2420–2432.

Anthony, R. E., R. C. Aster, D. Wiens, A. Nyblade, S. Anandakrishnan, A. Huerta, J. P. Winberry, T. Wilson, and C. Rowe (2015). The seismic noise environment of Antarctica, *Seismol. Res. Lett.* **86,** no. 1, 89–100.

Berger, J., P. Davis, and G. Ekström (2004). Ambient Earth noise: A survey of the global seismographic network, *J. Geophys. Res.* **109,** no. B11307, doi: 10.1029/2004JB003408.

Ekström, G., and R. W. Busby (2008). Measurements of seismometer orientation at USArray Transportable Array and backbone stations, *Seismol. Res. Lett.* **79,** no. 4, 554–561.

Holcomb, L. G. (1989). A direct method for calculating instrument noise levels in side-by-side seismometer evaluations, *U.S. Geol. Surv. Open-File Rept. 89-214*, 34 pp.

Hutt, C. R., J. R. Evans, F. Followill, R. L. Nigbor, and E. Wielandt (2009). Guidelines for standardized testing of broadband seismometers and accelerometers, *U.S. Geol. Surv. Open-File Rept. 2009-1295*, 60 pp.

Krischer, L., T. Megies, R. Barsch, M. Beyreuther, T. Lecocq, C. Caudron, and J. Wassermann (2015). Obspy: A bridge for seismology into the scientific Python ecosystem, *Comput. Sci. Discov.* **8,** no. 1, 014003.

Lay, T., J. Berger, R. Buland, R. Butler, G. Ekström, C. R. Hutt, and B. Romanowicz (2002). *Global Seismic Network Design Goals Update 2002*, IRIS, Washington, D.C.

Marquardt, D. W. (1963). An algorithm for least-squares estimation of nonlinear parameters, *J. Soc. Ind. Appl. Math.* **11,** no. 2, 431–441.

Oppenheim, A. V., and R. W. Schafer (1975). *Digital Signal Processing*, Prentice-Hall, Englewood Cliffs, New Jersey, 585 pp.

Peterson, J. (1993). Observations and modeling of seismic background noise, *U.S. Geol. Surv. Open-File Rept. 93-322*, 94 pp.

Ringler, A. T., and C. R. Hutt (2010). Self-noise models of seismic instruments, *Seismol. Res. Lett.* **81,** no. 6, 972–983.

Ringler, A. T., C. R. Hutt, R. Aster, H. Bolton, L. S. Gee, and T. Storm (2012). Estimating pole-zero errors in GSN-IRIS/USGS network calibration metadata, *Bull. Seismol. Soc. Am.* **102,** no. 2, 836–841.

Ringler, A. T., C. R. Hutt, and K. Persefield (2013). Seismic station installation orientation errors at ANSS and IRIS/USGS stations, *Seismol. Res. Lett.* **84,** no. 6, 926–931.

Sleeman, R., and P. Melichar (2012). A PDF representation of the STS-2 self-noise obtained from one year of data recorded in the Conrad Observatory, Austria, *Bull. Seismol. Soc. Am.* **102,** 587–597.

Sleeman, R., A. van Wettum, and J. Trampert (2006). Three-channel correlation analysis: A new technique to measure instrumental noise of digitizers and seismic sensors, *Bull. Seismol. Soc. Am.* **84,** no. 1, 222–228.

Tasič, I., and F. Runovc (2013). Determination of a seismometer's generator constant, azimuth, and orthogonality in three-dimensional space using a reference seismometer, *J. Seismol.* **17,** no. 2, 807–817.

Taylor, B. N., and C. E. Kuyatt (1994). Guidelines for evaluating and expressing the uncertainty of NIST measurement results, *NIST Technical Note, 1297*, 25 pp.

Tsai, V. C. (2011). Understanding the amplitudes of noise correlation measurements, *J. Geophys. Res.* **116,** no. B9, doi: 10.1029/2011JB008483.

Widmer-Schnidrig, R. (2003). What can superconducting gravimeters contribute to normal-mode seismology? *Bull. Seismol. Soc. Am.* **93,** no. 3, 1370–1380.

Wielandt, E. (2012). Seismic sensors and their calibration, in *New Manual of Seismological Observatory Practice 2 (NMSOP-2)*, P. Bormann (Editor), GeoForschungsZentrum, Potsdam, Germany, 1–139.

Wilson, D., J. Leon, R. Aster, J. Ni, J. Schlue, S. Grand, S. Semken, S. Baldridge, and W. Gao (2002). Broadband seismic background noise at temporary seismic stations observed on a regional scale in the southwestern United States, *Bull. Seismol. Soc. Am.* **92,** 3335–3341.

Wolin, E., S. van der Lee, T. A. Bollmann, D. A. Wiens, J. Revenaugh, F. A. Darbyshire, A. W. Frederiksen, S. Stein, and M. E. Wysession (2015). Seasonal and diurnal variations in long-period noise at SPREE stations: The influence of soil characteristics on shallow stations' performance, *Bull. Seismol. Soc. Am.* **105,** 2433–2452.

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