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Short Note

Broadband Sensor Nonlinearity during Moderate Shaking

by Andrew A. Delorey, John Vidale, Joseph Steim, and Paul Bodin

Abstract We observe that broadband seismometers may produce artifact long-period signals that resemble impulse responses, similar to a step in acceleration, in the presence of shaking as moderate as 0.2%*g*. This observation accords with recent observations in Europe and elsewhere with similar instruments (e.g., Zahradnik and Plesinger, 2005). We present two case studies. For both the 8 October 2006 *M* 4.5 earthquake near Mt. Rainier in the Pacific Northwest and an *M* 5.0 event on 29 September 2004 in southern California, artifact signals, possible step tilts, and apparent sensor problems are observed as far as about 200 km from the epicenters. Such long-period artifacts, if not recognized, complicate and degrade estimation of source parameters of moderate and larger earthquakes on regional networks. The exact cause of the artifacts currently remains obscure, but may require alterations to instrument installation and/or design strategies.

Introduction

Regional seismic networks (RSNs) monitor local seismic activity, provide information for hazard assessment, and support basic research. RSNs provide hypocenter locations, determine source parameters for small- and medium-sized earthquakes, estimate local velocity structure, and estimate ground-motion levels from larger earthquakes. While contributing to several RSN data products, the primary role of broadband sensors in RSN operations is often to provide critical data used to determine earthquake source characteristics accurately and quickly. This information is contained particularly in the longer-period signals. This environment of operation differs from that found in global network operations, chiefly because at teleseismic distances, ground motions are usually extremely small, and high frequencies have been stripped from the signal by attenuation over long paths. At regional distances, in contrast, peak ground motions can be moderate to strong at stations within a few hundred kilometers of small- to medium-sized earthquakes, and the spectrum of ground motion may be rich in high frequencies. It is, nevertheless, necessary for broadband instruments to behave linearly under these conditions. In the wake of EarthScope's Transportable Array, many regional networks in the United States are being augmented by broadband instruments, and it is within that context that we consider the suitability of these instruments to the needs of regional networks, in this case, the Pacific Northwest Seismic Network.

We first noted apparent signal irregularities within regional records of a moderate regional earthquake. In the process of investigating the cause of apparent artifact signals, suspecting limitations in the recording system, we discovered documentation of similar problems in another article (Zahradnik and Plesinger, 2005). Then we verified that similar problems are present in a third regional network with similar instrumentation (the California Integrated Seismic Network, CISN) and then explored why these problems arise.

The observed artifact signals are similar to the expected response to a step in the acceleration. If the baseline deviations we observe are solely the product of a transient elastic seismic wave at the instrument, then it would represent a nonlinear response. Alternatively, the sensors may be experiencing motion that is not simply caused by an elastic wave; the sensor may be producing the correct response to a quasi-static tilt. We examine these two possibilities: the instrument is producing a nonlinear response to an elastic wave, or the instrument is recording a ground motion that is not linear and elastic, as would be the case for permanent deformation.

Observations

We collect the three-component broadband data from instruments within 150 km of the 8 October 2006 *M* 4.5 event near Mt. Rainier from the Cascadia Array for Earth-Scope (CAFE) experiment and the EarthScope Transportable Array. The transportable array uses a mix of Guralp CMG3T and Streckeisen STS-2 instruments recording at 40 samples per second, and the CAFE experiment uses Guralp CMG3T instruments recording at 50 samples per second (Simpson, 2006; K. Creager, personal comm., 2007; Fig. 1). For each trace, we remove the mean, remove the trend, deconvolve the instrument response, convert to displacement, and apply a low-pass filter with a corner frequency of 0.1 Hz. Then

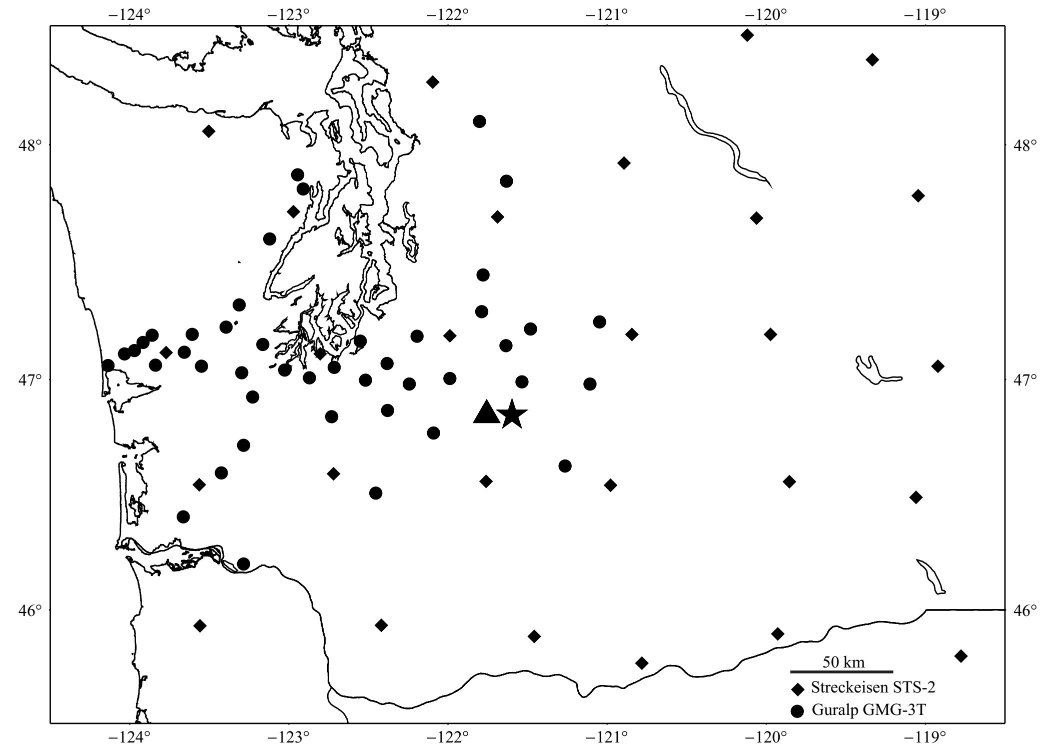

Figure 1. Stations of the EarthScope Transportable Array and CAFE experiment. Diamonds represent the locations of Streckeisen STS-2 instruments, and circles represent the locations of Guralp CMG3T instruments. The star represents the location of the Mount Rainier event, and the triangle represents the location of Mount Rainier.

all traces are manually inspected for the presence of suspect transient signals. In some cases, we use alternative signal-processing techniques to highlight suspect signals, including inspecting acceleration and velocity in addition to displacement, or modifying the corner frequency on the low-pass filter. A typical nonlinear waveform is distinguished by a step in the acceleration followed by a recovery with a period of a hundred seconds or more (Fig. 2). From the point of view of RSN operations, the long-period transient is noise that could lead to the incorrect analysis of an earthquake's source char-

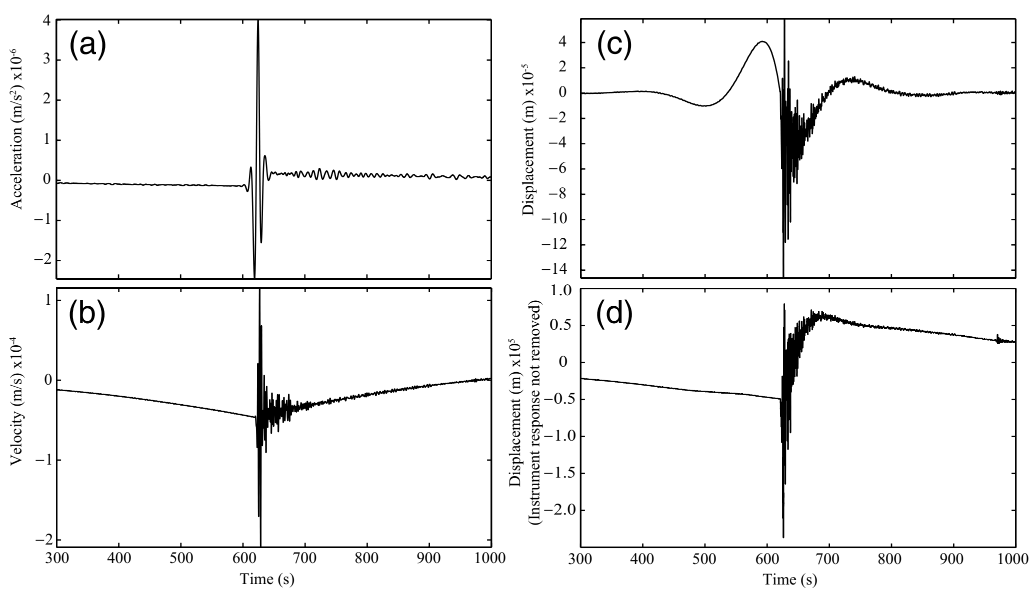

Figure 2. Station N110, component BHN. Typical nonlinear behavior is identified by a step in the acceleration (a), followed by a recovery with a period of hundreds of seconds. Nonlinear behavior can also be seen in velocity (b), in displacement (c), and in raw displacement (integrated velocity response) (d). The data have been low-pass filtered with corner frequencies of 0.1 Hz for acceleration, 0.5 Hz for velocity, and 1 Hz for displacement. The location of station N110 is indicated by a square on Figure 3.

acteristics unless either corrected or recognized and the recording eliminated from further analysis. However, this type of noise is not stationary, but rather is signal generated, and so we proceeded to try to recognize under what conditions it is introduced into the data.

Our analysis indicates that data from at least 32 of the 75 stations we examined were contaminated by artifact transients. This number is a lower bound because at some stations high levels of ambient noise may have obscured long-period transients. The relative displacement amplitudes of horizontal artifacts processed as described previously are shown in Figure 3. Figure 4 reveals the polarizations of horizontal excursions. Stations closer to the earthquake (e.g., S090, S100) tend to have larger excursions, but there are several exceptions. We can identify no strong patterns in the direction of polarization of the horizontal excursions but note a weak tendency for them to point away from the earthquake epicenter and a stronger tendency for nonlinear behavior on the north component than the east component. Some stations show excursions on the vertical component, and most of these are close (<75 km) to the earthquake epicenter. The time of the nonlinear excursions corresponds roughly with the strongest shaking, which is during the arrival of the *S* wave. In Figures 5 and 6, we examine the relationship between artifact transients and spectral acceleration. There appears to be no precise threshold for nonlinearity, but stations tend to go nonlinear for spectral accelerations between 10^{-6} and 10^{-7} m/sec^2. We note that this representation of the accelerations is limited to the passband below the Nyquist frequency of the sampled data (either 20 or 25 Hz). The sensor and its active feedback circuitry may be exposed to, and respond to, frequencies higher than this passband if present in the seismic wave field.

We observe similar artifacts on at least 22 broadband stations in southern California due to an *M* 5.0 event on 29 September 2004 (Figs. 7 and 8). The distance between the event and the most distant station identified as exhibiting nonlinear behavior is 249 km, farther than that observed for the Rainier event and consistent with the greater magnitude of the California event. Peak ground acceleration is 2.2%*g* for the closest station, and some of the stations show evidence of clipping. Like the Rainier event, there is no clear pattern to the polarization of the horizontal excursions, and stations close to the event are more likely to show nonlinear behavior than more distant stations.

Causes

We investigate the causes of nonlinear behavior in broadband instruments during moderate shaking. At least two of the closest instruments, S090 and N120, have clipped in the digitizer and probably in the seismometer as well during peak accelerations of 1%*g* and 0.25%*g*, respectively.

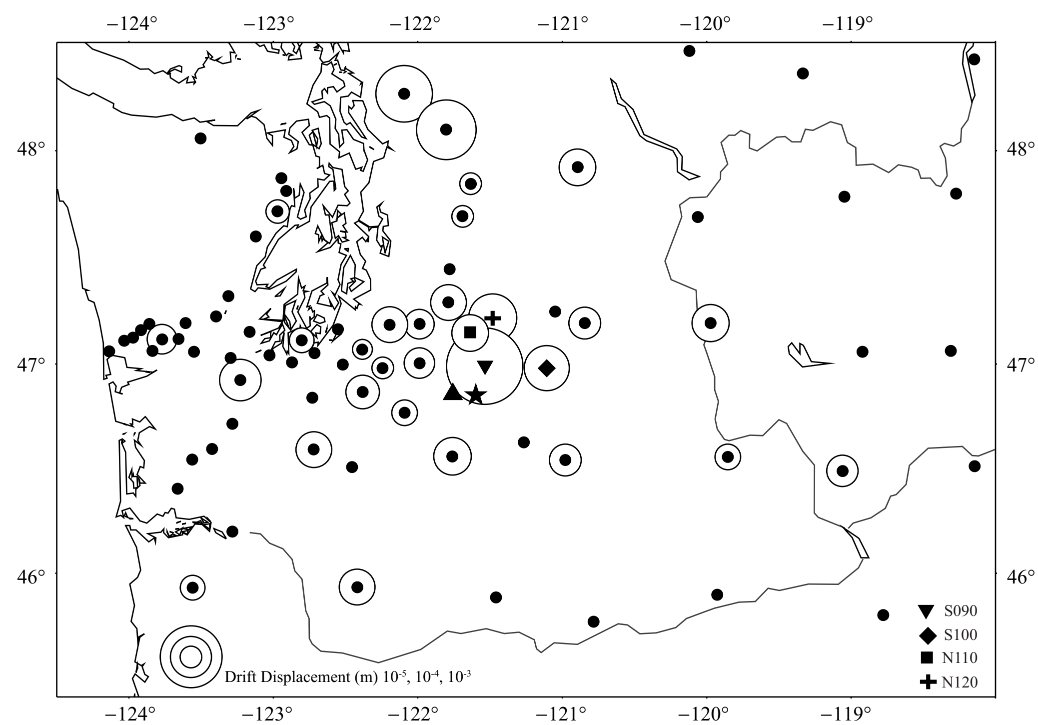

Figure 3. CAFE and Earthscope stations near the Mount Rainier event with drift displacements. Drift displacement is determined by viewing the displacement response and determining how much the mean of the signal drifts from zero. See Figure 2c for an example. The star represents the location of the Mount Rainier event, and the triangle represents the location of Mount Rainier. The upside-down triangle represents the location of station S090, the diamond represents the location of station S100, and the square represents the location of station N110. Circle size indicates the relative drift magnitude using a log scale.

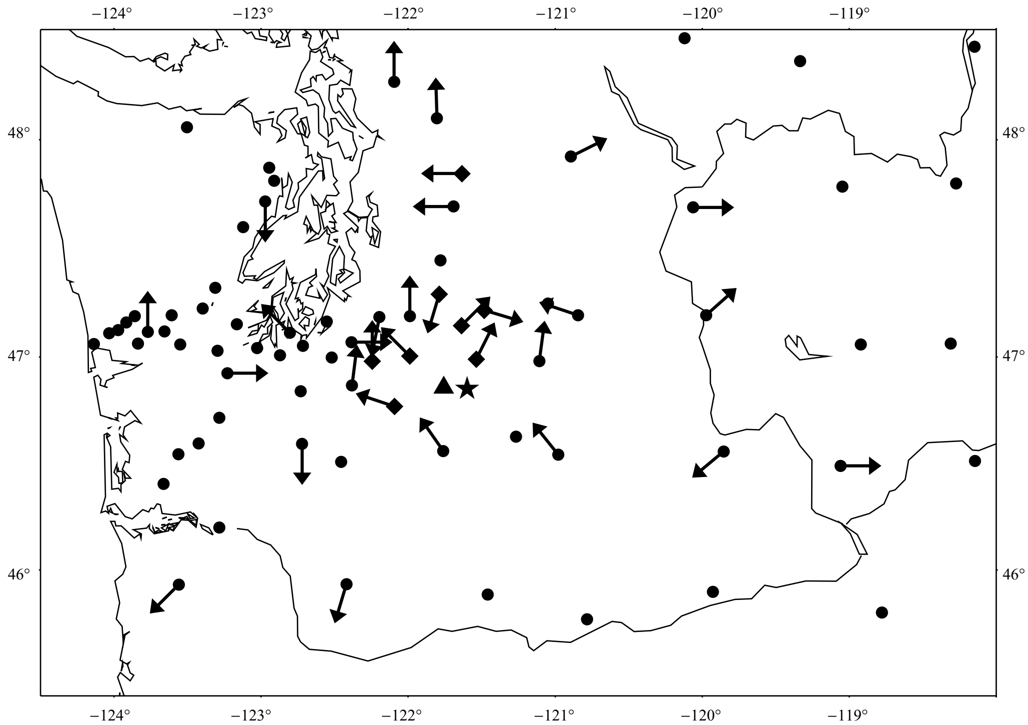

Figure 4. Horizontal drift polarization. The triangle is the location of Mount Rainier. The star represents the location of the Rainier event. The arrows indicate the polarization direction of the horizontal instrument drifts. The stations plotted as diamonds are stations that had drifts on the vertical component.

However, clipping, which occurs at ~1 cm/sec for the Guralp CMG3T and 1.3 cm/sec for the Streckeisen STS-2, is not a widespread problem for this event. Measured peak velocities for the two clipped stations are 1.7 cm/sec for S090 and 0.86 cm/sec for N120.

In the absence of clipping, the most commonly supposed cause of nonlinear behavior is tilting of the instrument (Zahradnik and Plesinger, 2005). A small step in acceleration, caused by a permanent tilt, can explain the observed velocity excursions in the raw data. It should be noted that

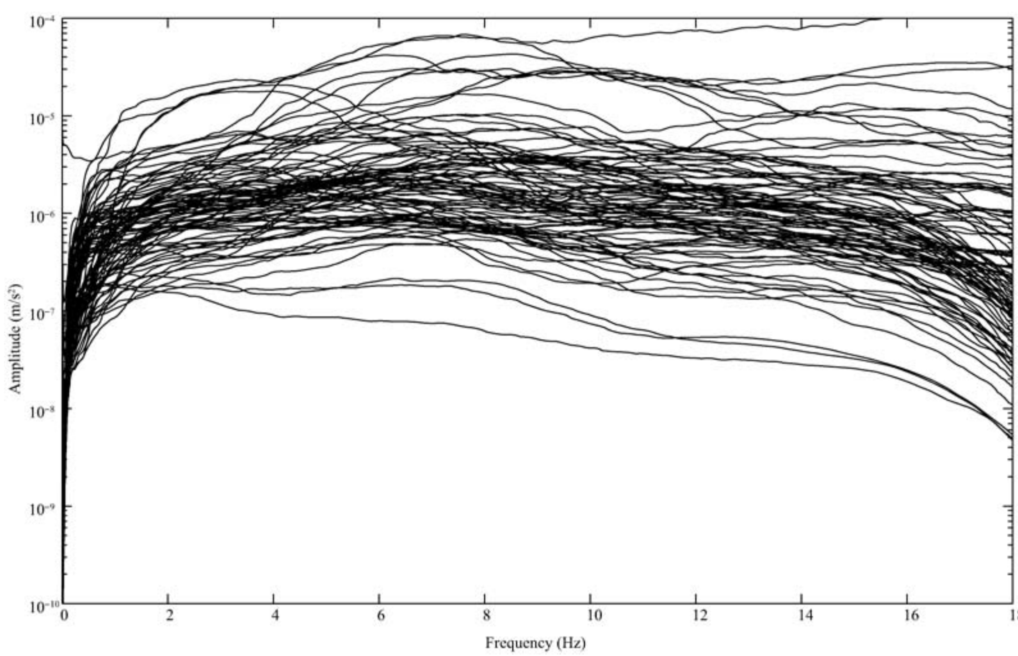

Figure 5. Acceleration as a function of frequency for stations recording the Rainier event. Only stations that show nonlinear behavior are shown.

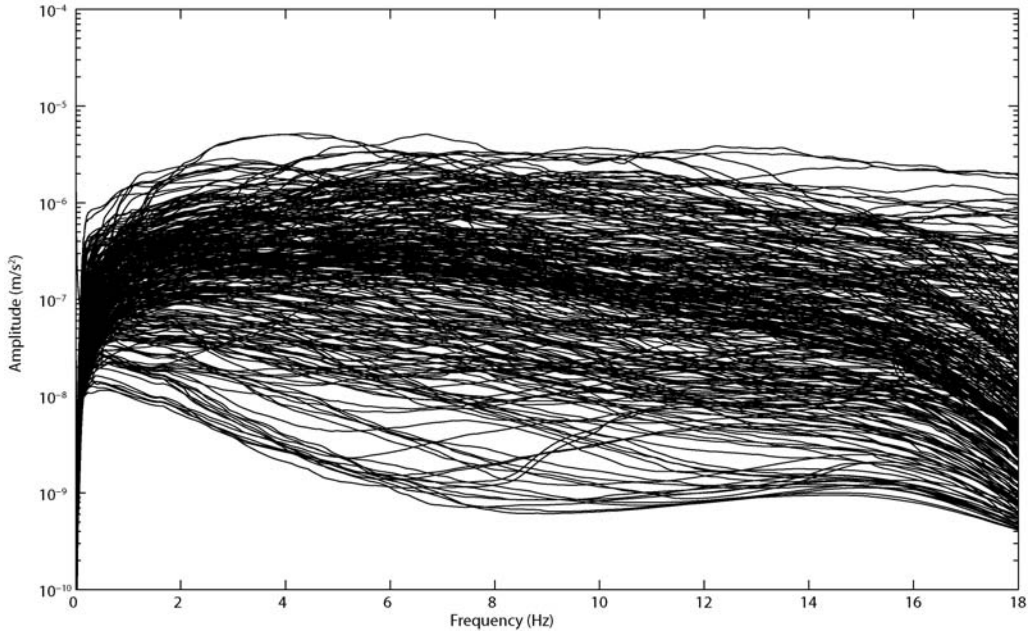

Figure 6. Acceleration as a function of frequency for stations recording the Rainier event. Only stations that do not show nonlinear behavior are shown.

a step in acceleration on a horizontal component could be caused by both an impulsive and permanent horizontal displacement and a permanent tilt around the appropriate horizontal axis, but not by a vertical displacement. The response to a tilt could be compared to an equivalent displacement, the horizontal displacement that would be required to produce the same signal. In general, quasi-static tilts could arise from ground deformation of tectonic origin, from instabilities in instrument installation, or from local failures within the instrument pier (e.g., crack formation caused by shaking or

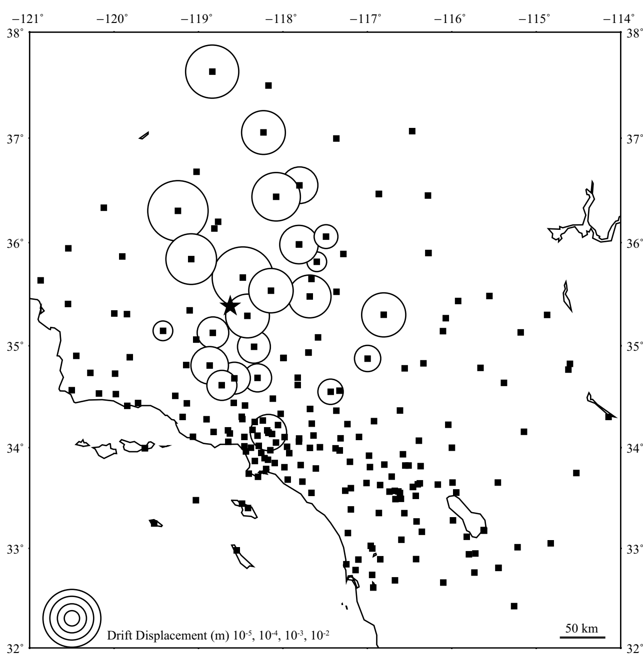

Figure 7. Drift Displacement for California event (29 September 2004, *M* 5.0). Drift displacement is determined by viewing the displacement response and determining how much the mean of the signal drifts from zero. See Figure 2c for an example. The earthquake location is indicated a star. Circle size indicates the relative drift amplitude using a log scale.

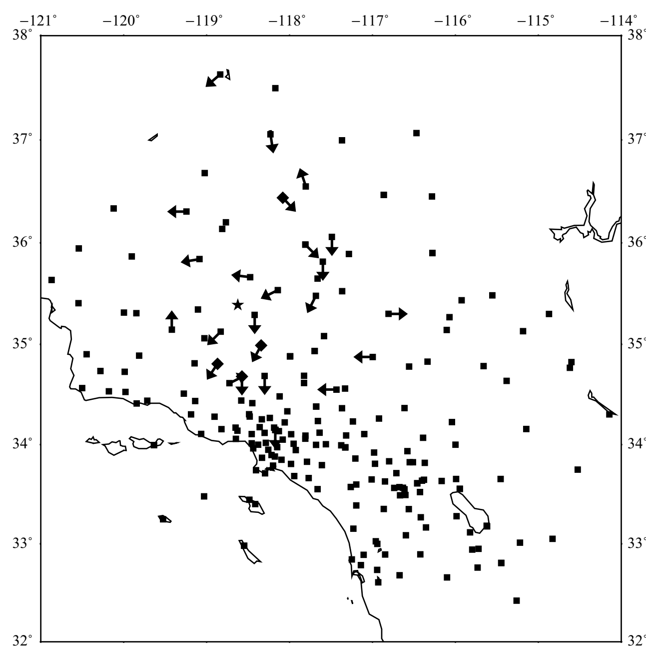

Figure 8. Polarization direction of the horizontal instrument drifts for California event (29 September 2004, *M* 5.0). The earthquake location is indicated by a star. The arrows indicate the polarization direction of the horizontal instrument drifts. The stations plotted as diamonds are stations that had drifts on the vertical component.

shifting in objects surrounding the sensor). In fortunate cases, seismograms can be separated into ground motion and tilt (Wielandt and Forbriger, 1999; Battaglia *et al.*, 2000; Boore *et al.*, 2002; Wiens *et al.*, 2005; Graizer, 2006). We show that the nonlinear signal recorded on station S100 (BHN) can be modeled as the response to a step in acceleration as would be expected for instrument tilt (Fig. 9). Our case differs from most of these cited in that we are using a broadband sensor undergoing moderately strong shaking; these other cases have either strong motion sensors or tilting in the absence of strong shaking.

We perform an experiment using a Streckeisen STS-2 instrument, successively lifting each leg a controlled amount to produce controlled tilts. This produces acceleration steps and resulting calibration pulses in the expected ratios on north and east components with no vertical signal. It is clear from this experiment that vertical movement on one of the three feet would not cause the observed dominant north polarization, suggesting that more than one of the three legs of the instrument is affected. On both the Guralp CMG3T and the Streckeisen STS-2 instruments, there is a foot at the westerly compass direction and the three feet are at an ~120° distance from each other. This experiment does not explain observations of the behavior of the vertical component.

Because of the incoherence of the patterns in the apparent tilt direction, and the vastly greater amplitude than expected from the earthquake's moment release, the evidence suggests that any tilting is local, perhaps as local as within the instrument vault. In the presence of moderate shaking, there could be some settling of the instrument platform. For transportable array and CAFE stations, after the instruments are installed, the vaults are filled with sand to reduce long-period noise. Jostling at the peak 3–4-Hz motions and a small fraction of *g* may be sufficient to shift the sand, causing small tilts in the instrument. If events like this happened once per week and the occurrence of such artifacts diminished over time, it would be evidence that the installations really were settling. However, this behavior is observed at southern California stations that have experienced many moderate earthquakes, including an event on the previous day to the one presented here. Some of the same stations show nonlinear behavior of a similar magnitude for both events.

Some instruments show excursions that are almost exclusively on one of the horizontal components (Fig. 4) with a preference for the north–south component. While it is possible that east–west excursions could be the result of an elevation change in one foot, a purely north–south excursion due to sensor-foot settlement would require elevation changes in at least two feet. Additionally, it is more likely for a foot to settle than to be elevated, and we observe excursions in the east–west component in both east and west directions. So we must consider causes other than ground tilt affecting only one or two feet to explain at least some of the excursions.

Another possible cause of the artifacts is an inherently nonlinear response of the sensors to ground motion. Higher frequency signals observed at regional distances might be rectified or distorted, resulting in apparent low-frequency

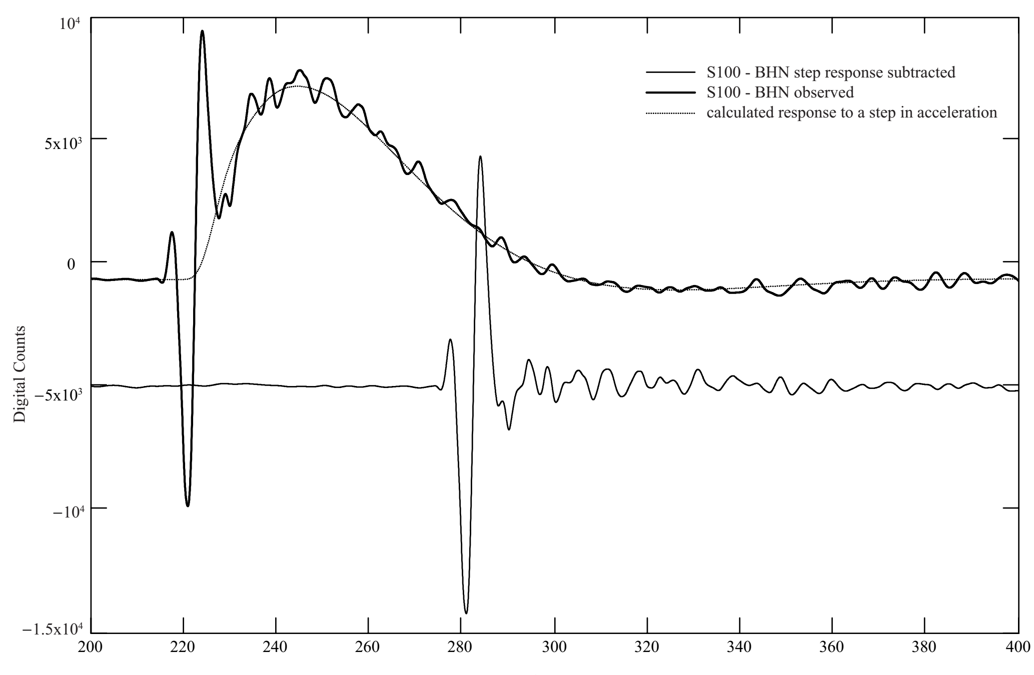

Figure 9. Modeling a step response in acceleration. The signal recorded on station S100 (BHN) is almost an ideal acceleration step response—so much so that an analytic step expression does an excellent job of removing it, resulting in a corrected, interpretable seismogram. The signals are shifted in time for clarity. The location of station S100 is indicated by a diamond on Figure 3.

products. The impulsiveness of the signal might be important in generating spurious long-period offsets, leading to further variation between stations and apparent ground-motion levels at which the artifacts are generated. Both types of instruments have similar active feedback circuits and therefore could be susceptible to the same problems without resorting to external explanations. However, in the case of the Streckeisen STS-2 instruments, the three output components (north, east, and up) are electronically generated from three cube-cornered sensors. It seems unlikely that nonlinear responses of the sensors would manifest themselves on the horizontal output components but not as frequently on the vertical output component. Also, the Guralp instruments resolve the three output components mechanically and show the same variation of behavior in the output components as the Streckeisen instruments, supporting the argument that the cause of artifacts is external to the instruments.

Impacts

The introduction of transient long-period artifacts into regional broadband ground motion data for moderate to large earthquakes is a problem of grave concern to RSNs. Analyses that depend on accurate ground motions at periods of 10–100 sec, such as waveform-matching moment-tensor estimates, become fraught with uncertainty. As illustrated in Figure 9 (see also Zahradnik and Plesinger, 2005), if the artifact can be understood well enough to be modeled theoretically, it may be removed and its impact mitigated. At a minimum, if the conditions under which they may affect data can be adequately understood, automatic processing systems may be able to flag data with potential artifact problems and not use it in automatic analyses. Also, many applications of seismic data filter out long-period data (>100 sec) and therefore will not be negatively impacted by the long-period nonlinear behavior we describe. Applications that use long-period data, like the broadest-band calculation of source parameters, are prone to error if nonlinear behavior at these periods is not identified. Thus it is important to keep in mind the instrument limitations identified in this article. Future generations of broadband sensors should be thoroughly tested to ensure that any long-period data they record are actually the result of ground motions at those frequencies. To the extent that seismic vaults and/or installation techniques are found to be at fault, these will have to be amended for use at regional distances and moderate earthquakes.

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Earth and Space Sciences
University of Washington
Johnson Hall 070, Box 351310
4000 15th Avenue NE
Seattle, Washington 98195-1310
(A.A.D., J.V., P.B.)

Quanterra, Inc.
325 Ayer Rd
Harvard, Massachusetts 01451
(J.S.)

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