A SOFTWARE TOOLBOX FOR SYSTEMATIC EVALUATION OF SEISMOMETER-DIGITIZER SYSTEM RESPONSES

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ABSTRACT

Measurement of the absolute amplitudes of a seismic signal requires accurate knowledge of the seismometer-digitizer response. When the seismometer and digitizer characteristics are known, deconvolution of the digital system response is relatively straightforward. However, even with a known response, problems in timing and incorrect polarities can often contaminate any calibration parameters derived from these data. When either one or both components of the response for a seismometer system are unknown, the data are often not considered suitable for seismological tasks that require absolute amplitude measurements.

We have developed a set of software tools that can recover the sensor/digitizer response function from raw data when the response is either unknown or incorrectly known. These software tools include SACPSD, which estimates seismic noise power spectral densities, and NOISETRAN, which generates a pseudo-amplitude response (PAR) for a seismic station, based on background noise at a reference station.

During the first year of our Phase II project, we have focused on improving NOISETRAN and validating the method on multiple datasets. First, we estimate the PAR for a short-period seismometer (L-4C 3D) using a broadband station located 40 km away. The PAR was within a factor of 2 of the true response for the seismometer from periods between 0.1 and 3 Hz. Next we applied the method to USArray data from 2009–2011. Application to the 400+ stations of the Transportable Array (TA) deployed in the central United States and Rocky Mountains allowed us to understand spatial variations in the response error, which is the difference between the actual response and the PAR. For stations within 200 km of the reference station, the response error for all frequencies (0.01 to 10 Hz) is typically within less than ±0.3 log units (e.g., factor of ±2 difference between the actual and pseudo-response). The scatter in the error estimates for all frequencies increases to ±1.0 log units (e.g., order of magnitude) at great distances; however, much of that error is at frequencies above 1 Hz, where local cultural noise source differences between the reference and candidate stations are magnified. We also see geologic and population effects distributed in the response error maps. Lastly, we used the PAR files estimated from NOISETRAN to correct the TA data from the 11 March 2011 Tohuku earthquake. The error between maximum *P*-wave amplitudes estimated using the PAR files and the actual responses ranges from -0.3 log units (for frequencies below 0.5 Hz) to -1.0 log units (for frequencies above 0.5 Hz). The response error is consistently negative, meaning that the PAR files are overcorrecting the *P*-wave amplitudes.

During the final year of the project, we will package NOISETRAN and additional seismic tools into an easy-to-use graphical interface, conduct alpha testing of the toolbox, and then conduct beta testing at Los Alamos National Laboratory.

OBJECTIVES

We have developed a seismic software toolbox with the objective of estimating, assessing, and chronicling the seismometer and digitizer response of a seismic station when the actual response is unknown. During the first year of this Phase II project, we initiated development of an easy-to-use graphical user interface to assist the user in applying these tools to iteratively recover the response function of an unknown instrument. We have focused on continued development and validation of NOISETRAN, which estimates the seismic response of a station by comparing its background noise and recorded signals to noise and signals from nearby stations with known responses. In this paper, we provide an example of the NOISETRAN method using seismic data from Israel, estimate error and uncertainty in the method using the USArray stations, and then apply the NOISETRAN-estimated responses to recordings of the 2011 Tohoku earthquake.

RESEARCH ACCOMPLISHED

NOISETRAN: Noise Transfer Functions for Pseudo-Response Estimation

Important calibration datasets may be obtained in which no metadata (e.g., station information, such as location, instrument type, response, and gains) accompany the waveforms. We are examining methods that attempt to determine a rough order-of-magnitude (ROM) estimate of the seismometer-digitizer response by considering the background seismic noise at a nearby seismic station with a known response (e.g., the "reference" station). We refer to this method as NOISETRAN, as we attempt to estimate a *transfer function* $T(\omega)$ to convert the background seismic *noise* at a candidate station ($R_1(\omega)$) with unknown response (henceforth referred to as the "candidate" station) to the background noise levels at a reference station $R_2(\omega)$. The transfer function can be estimated using:

$$R_1(\omega)=R_2(\omega)*T(\omega)+e_r(\omega). \tag{1}$$

The response error (e_r) in this procedure is due mainly to differences in the noise fields between the two sites, which is frequency (ω) dependent. Once the ROM system response $R_1(\omega)$ has been recovered, we can then use waveform modeling techniques to further refine the system response.

Our assumption for attempting the NOISETRAN technique is that the actual noise field at certain periods should be the same or similar for a network covering a relatively small geographical area. McNamara and Buland (2004) showed the geographical distribution of noise in three different period bands (e.g., 0.125–0.0625 sec, 8–4 sec, and 64–32 sec) in North America. They observed the strongest geographical variations at periods smaller than 1 sec due to cultural noise, especially near large population centers. Proximity to oceans dominates the variations in the microseism band (8–4 sec). They note that at longer periods (64–32 sec) the geographic variations decrease and that the responses are largely a function of the installation characteristics (e.g., borehole vs. surface installation) instead of the actual seismic noise characteristics. Their results suggest that our best results for NOISETRAN will most likely occur at periods longer than 1 sec.

Applying NOISETRAN to a Seismometer in Israel

During Phase I of this project, we applied NOISETRAN only to broadband seismic stations, which have typical responses that are flat across a wide range of frequencies (e.g., 0.01 to 50 Hz). The first test for the Phase II project was to determine the applicability of the NOISETRAN method on instruments typically referred to as "short-period" seismometers (e.g., L4, L22, S6000) or "high-frequency" geophones (L28, etc). These instruments are typically flat to velocity at frequencies above 1, 2, or 4.5 Hz, but have a steep roll-off at lower frequencies.

In January 2011, Weston Geophysical Corporation (WGC) participated in the Sayarim, Israel, Ground Truth Zero (GT0) Calibration explosions (Gitterman and Hofstetter, 2011), which included a 102-ton surface explosion used for calibrating the International Monitoring System (IMS) network. WGC deployed six (6) Sercel L-4C 3D velocity seismometers within 10 km of the explosions. Although we already knew the response for the L-4C 3D instrument—the seismometer is flat to velocity above 1 Hz—we used NOISETRAN to recover the response of one of the stations (NS3) deployed for the Sayarim GT0 experiments. We selected a sample of nighttime noise for the candidate station for input into NOISETRAN. The next step in NOISETRAN is to select a reference station. The considerations for choosing a reference station should include (1) available data to establish a background noise model for the reference stations, (2) proximity to the stations of interest, and (3) whenever possible, similar expected background noise levels between the reference and unknown stations. The station that best matched these requirements for our candidate station was EIL (Eilat, Israel). We downloaded data from EIL from the Incorporated Research Institutions in Seismology (IRIS) for the same time period as our candidate station noise sample.

Figure 1 compares the power spectral densities (PSDs) for the candidate and reference station after the response file was repaired. We estimate the transfer function between the two PSDs as the difference in log units between the candidate and reference station PSDs. We convert the data from decibels into an amplitude factor that converts the candidate data, with units unknown, to the units of the reference data (e.g., acceleration). This amplitude factor is then output as a PAR file (two columns: frequency and amplitude) that can be used in a variety of seismic software (e.g., SAC, GSAC, Antelope, etc.) to remove the amplitude response for the reference station data.

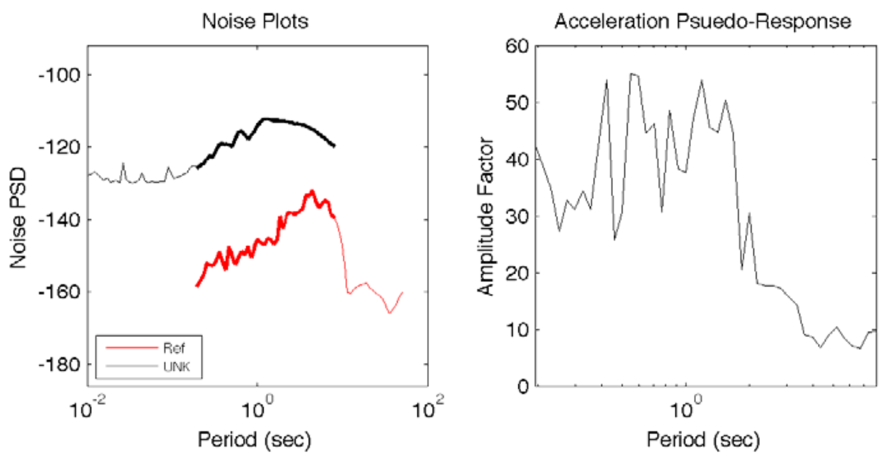

Figure 1. NOISETRAN analysis for a station in a temporary deployment in Israel. (Left) Candidate (black) and reference (red) station noise PSDs. (Right) The transfer function (as an amplitude factor) to correct the candidate PSD to the reference PSD.

Figure 2 compares the PAR obtained from NOISETRAN (using broadband reference station EIL) with the actual response for the short-period Sercel L4 instrument. NOISETRAN has successfully recovered the true instrument response for station NS3 between 0.1 and 3 Hz. The result is quite remarkable, considering that the NS3 was a temporary deployment buried just below the surface while EIL is a permanent station of the Israeli Seismic Network. The differences between the actual response and PAR at high frequencies is manageable, better than ROM, and could be tested in our toolbox's next stage, which includes examining signals from seismic events to further refine the response. These results suggest that NOISETRAN will work for short-period stations when corrected using a nearby broadband station with similar noise conditions.

Applying NOISETRAN to USArray Data

In the second test of the Phase II project, we used NOISETRAN to recover the response of both transportable and backbone stations of the USArray. We selected a one-hour sample of nighttime noise from 1 February and downloaded the data from IRIS for the years 2009, 2010, and 2011 to use as input for NOISETRAN. We applied NOISETRAN to each station available on 1 February 2009, 2010, and 2011; obtained PARs for each; and analyzed errors relative to the known responses. Figure 3 shows the station locations for the years 2011 (left) and 2009 (right). Results for the 2011 dataset, including error analysis, are presented within. As an example of the NOISETRAN procedure, Figure 4 shows PSD plots for a candidate station (N38A) and a reference station (Q34A). These stations are separated by 440 km. The difference between these two noise spectra in dB was converted into an amplitude factor. Then, a PAR was generated and compared to the known frequency response of station N38A (Figure 5). This is one of our best examples of the agreement between the NOISETRAN estimate and the true response for a station.

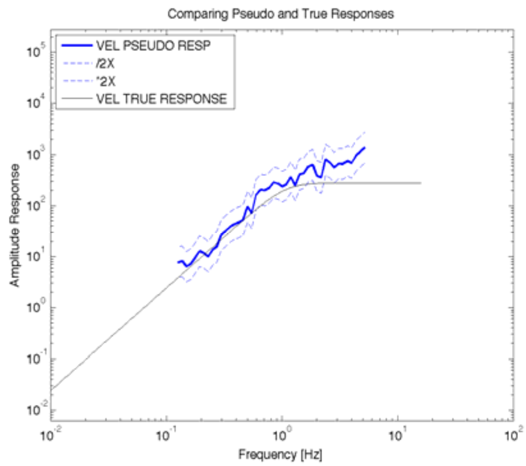

Figure 2. PAR for NS3 (±2× Error) from NOISETRAN and the true velocity response (black line).

In our tests of the data from 2011, we performed four separate analyses, in each case with a different reference station, in order to test the range of performance with different reference-candidate station geometries. The reference stations selected were Q34A (central), BGNE (off-center), BLA (eastern US), and R11A (western US). Station BLA is a US National Seismographic Network (USNSN) station, while the others are from the USArray. We compared the resulting PAR files obtained from NOISETRAN with the actual station responses for the stations shown in Figure 5. To evaluate the method's performance, we calculated mean response error e_r between the actual response (A_{true}) and the PAR (A_{PAR}) across a range of N frequencies (ω_1, ω_2, …ω_N) as

$$e_r = \frac{1}{N}\sum_{\omega 1}^{\omega N}(\log 10(A_{true}(\omega)) - \log 10(A_{PAR}(\omega))). \tag{2}$$

For frequencies between 0.01 and 10 Hz, the most centrally located station (Q34A) provided a significantly smaller amplitude response error (Table 1) for the mean of USArray station errors, while station BLA (USNSN) provided a significantly smaller error for the mean of USNSN station errors. Additional error analysis for reference station Q34A was performed to evaluate the accuracy of PARs at using lower-frequency bands, as shown in Figure 6 and summarized in Table 1.

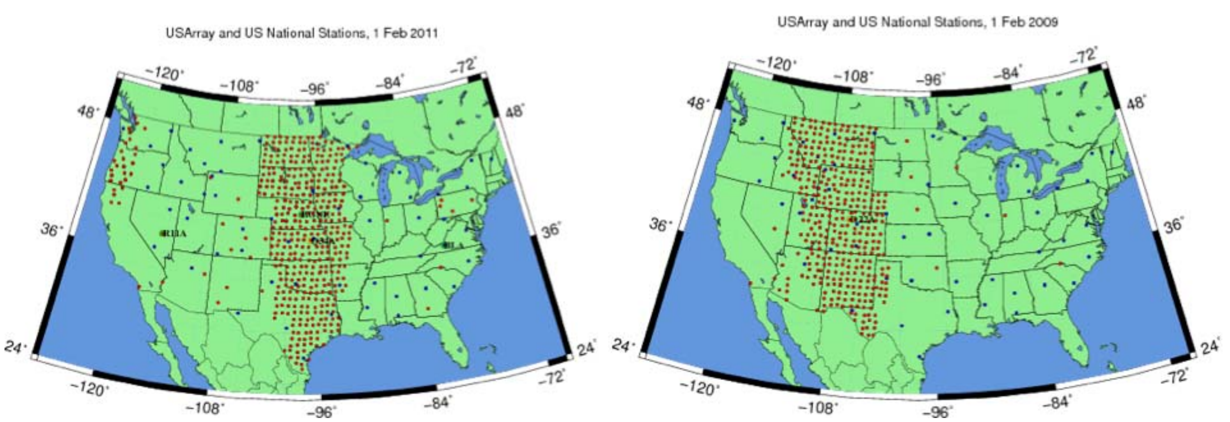

Figure 3. USArray stations (red) and USNSN stations (blue) on 1 February 2011 (left), and 1 February 2009 (right).

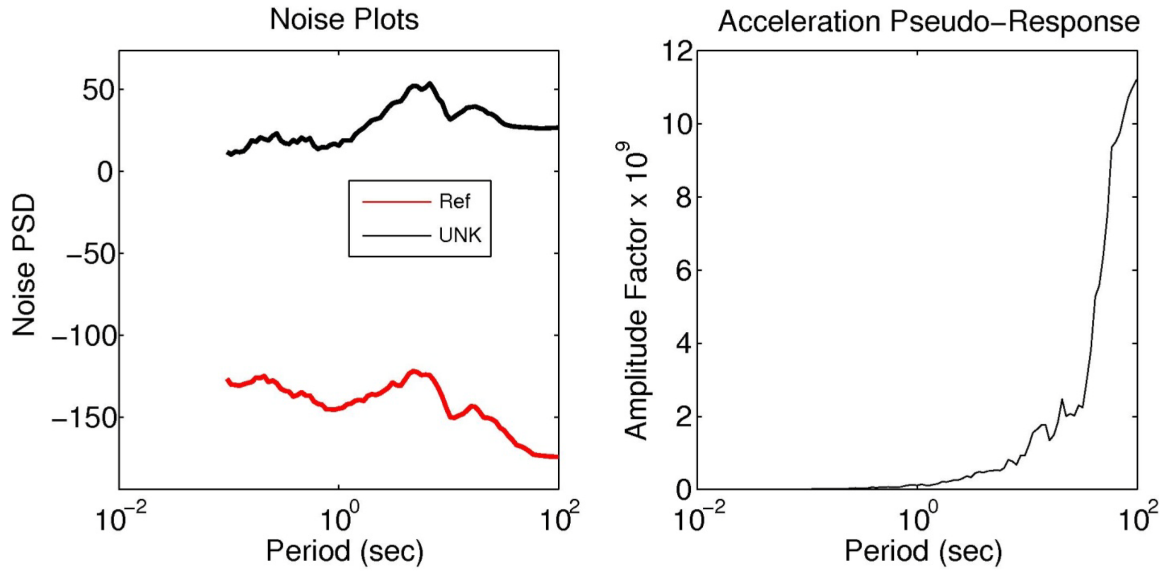

Figure 4. NOISETRAN analysis on USArray data. (Left) Candidate N38A (black) and reference (red) station Q34A noise PSDs. (Right) The transfer function (as an amplitude factor) to correct the candidate PSD to the reference PSD.

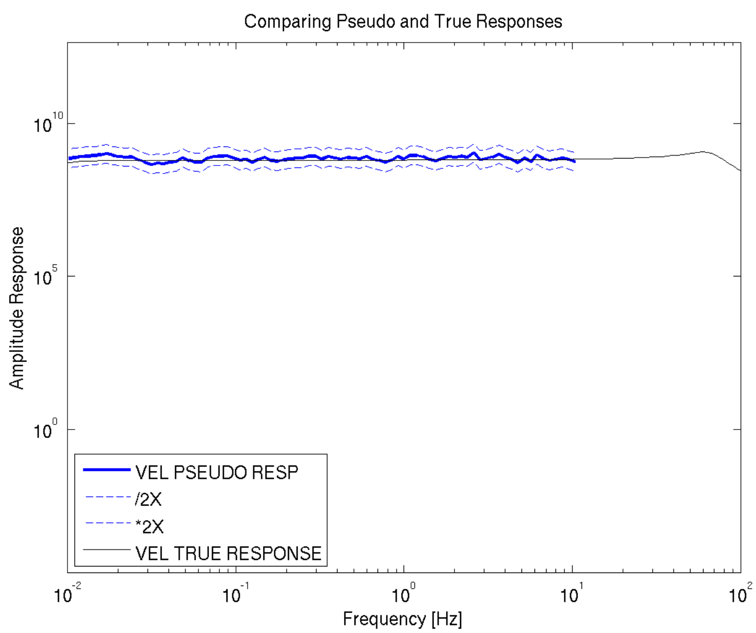

Figure 5. PAR for N38A (±2´ Error) from NOISETRAN and the true velocity response (black line)

Table 1. PAR error analysis (2011)

Reference Station	Frequency Band (Hz)	Mean Error USArray	Standard Deviation	Mean Error USNSN	Standard Deviation
BGNE	0.01 – 10	0.7390	0.4612	1.1400	0.6557
R11A	0.01 – 10	-1.3713	0.4615	-0.9609	0.6606
BLA	0.01 – 10	-0.5023	0.4542	-0.0968	0.6622
Q34A	0.01 – 10	-0.0554	0.4618	0.3476	0.6557
Q34A	0.1 – 1.0	-0.0857	0.2282	-0.0363	0.5045
Q34A	0.01 – 0.1	-0.0506	0.1438	-0.0348	0.4701

We plotted the PAR errors for each station versus distance from reference station Q34A for the USArray stations (Figure 6) and the USNSN stations. For stations within 200 km of the reference station, the response error for all frequencies is typically within less than ±0.3 log units (e.g., factor of ±2 difference between the actual and pseudo responses). A low-frequency band (0.01–0.1 Hz) gives even tighter error bounds that extend to distances of 800 km or more from the reference station. The scatter in the error estimates for all frequencies increases to ±1.0 log units (e.g., order of magnitude) at distances > 200 km; however, much of that error is at frequencies at which cultural noise differences between the reference and candidate stations are magnified.

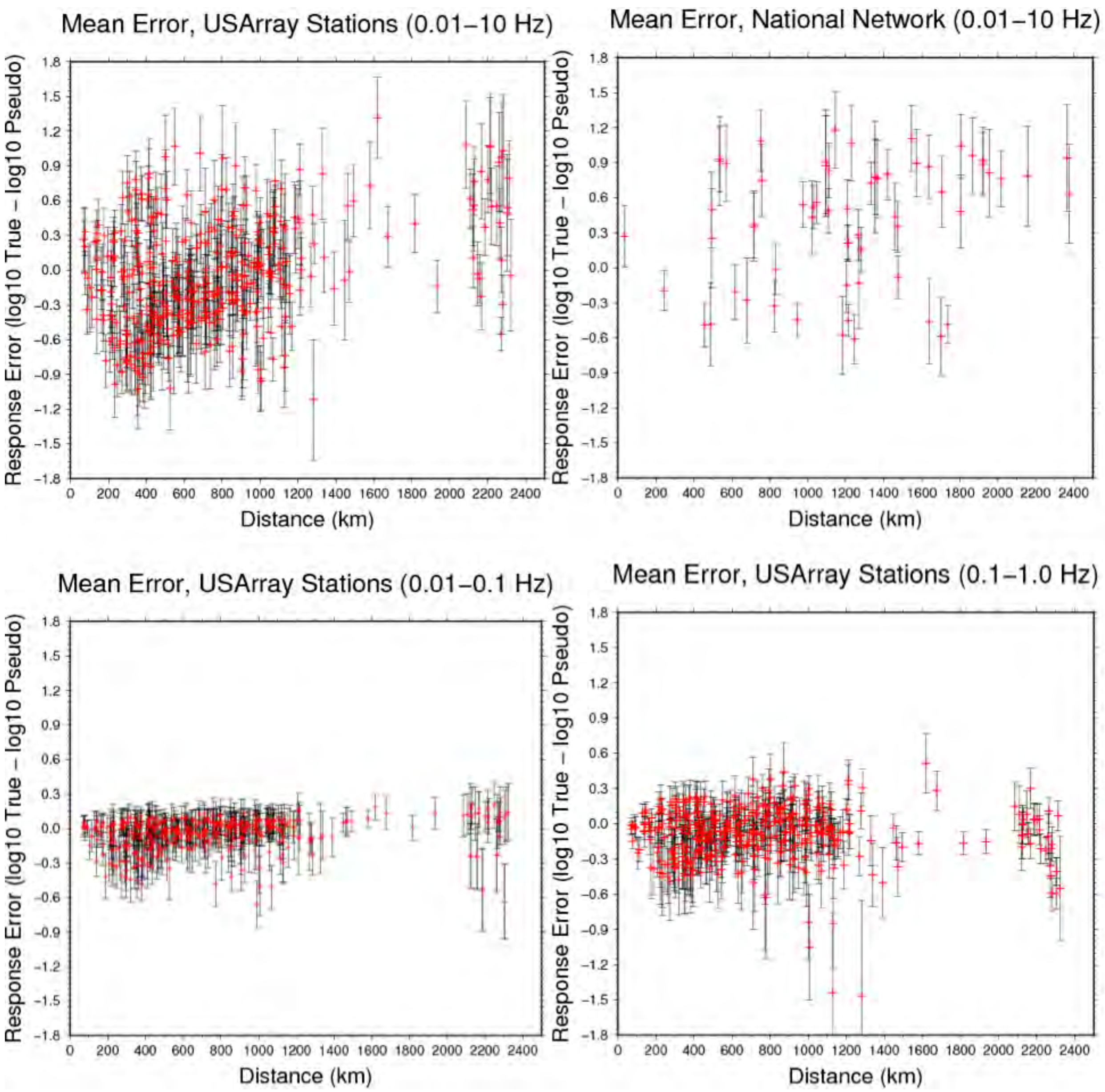

Figure 6. Mean response error (red crosses) and standard deviation (error bars) in different frequency bands at each station, plotted versus distance from reference station Q34A. Top-right shows results for USNSN stations. Top-left and bottom plots show errors for USArray stations with differing frequency bands, as indicated.

Next, we plotted the mean error at each station for select frequencies in map view (Figure 7) with an overlay of US Geological Survey (USGS) Generalized Geologic Map of the United States (http://pubs.usgs.gov/atlas/geologic/). The USGS map depicts the geology of the bedrock that lies at or near the land surface, but not the distribution of surficial materials such as soils, alluvium, and glacial deposits. The units are defined by sedimentary, volcanic, plutonic, or metamorphic rock types and by their geologic age. For this exercise, we plot only the unit boundaries as a guide. It appears that there are correlations between the amplitude response error and geology. We plan to analyze these plots further to better understand the contribution of geologic variations to response error. We also plan to investigate other possible error sources (e.g., topography and population centers) that may exist. Any correlations identified can help us to make more-appropriate reference station selections when there is more than one station under consideration. Additional data will be examined to determine whether observed correlations are consistent and can be used to develop a suitable error model or, alternatively, a correction to the pseudo-amplitude responses.

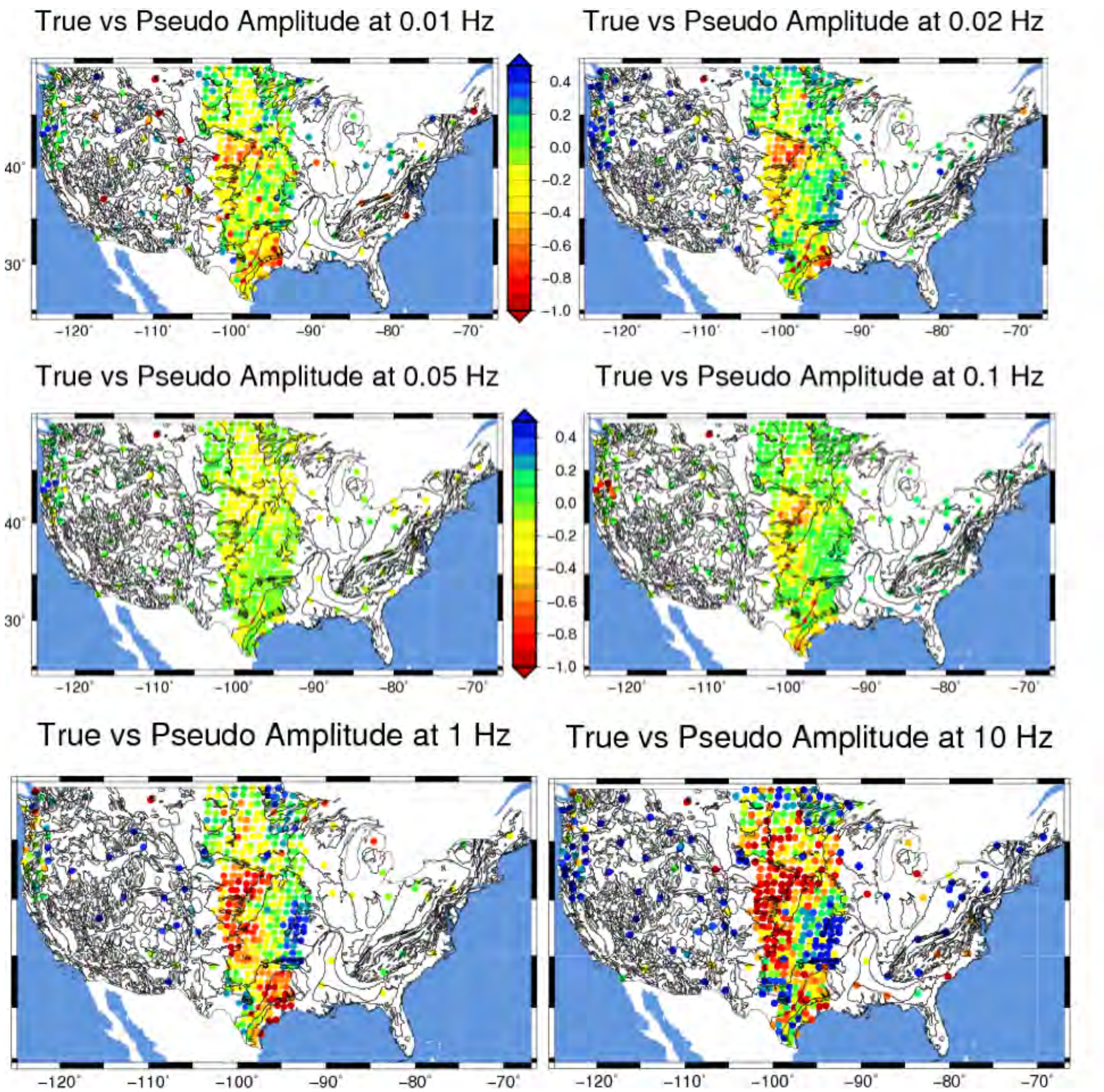

Figure 7. Mean response error at each station for data on 1 Feb 2011. Color scale is the same across all plots.

Testing NOISETRAN PARs: The 11 March Tohoku Earthquake

To further test the PAR files generated by NOISETRAN, we applied them to the USArray dataset for the M = 9.0 11 March 2011 Tohoku earthquake. PAR files were created for each station in the March 2011 TA network (~430 stations). Station Q34A was chosen as the reference.

In order to define a consistent *P*-arrival for the complex recordings of the Tohoku earthquake, the program TauP was used to calculate the *P*-wave arrival time using the velocity model AK135 (Kennett et al., 1995). Waveforms were windowed approximately 600–900 sec after the origin time of the earthquake (3/11/2011 05:45:23 UTC) to account for moveout across the array. The PAR files were converted to pseudo phase-amplitude response files for each station and used in seismic analysis code (SAC) to deconvolve the signal in the time-domain. The same procedure was followed for the true response files (e.g., RESP files from the IRIS SEED volumes), resulting in "true" and PAR corrected waveforms.

We slightly redefine the estimated response error, e_r, as

$$e_r = \log_{10}(\mathrm{A}_{\mathrm{p\_true}}) - \log_{10}(\mathrm{A}_{p\_PAR}), \tag{3}$$

where $A_{\mathrm{P\ true}}$ and $A_{\mathrm{P\ PAR}}$ are the log of the maximum *P*-wave amplitudes in the analysis window for the true and NOISETRAN-estimated responses, respectively. The response error is small for the unfiltered data, with an average -0.2 unit bias; however, there are a few stations that are clipping, which could be causing this low error estimate. For bandpass filtered data between 0.08 and 0.5 Hz, the error increases slightly to -0.3 log units but increases to an average -1.0 log units (e.g., order of magnitude) with a 0.5–2.0 Hz band pass filter. The bias is consistently negative, meaning that the PAR files are producing slightly larger *P*-wave amplitudes than the true response. The geographical distribution of the response error across the TA network using reference station Q34A is shown in the maps in Figure 8 for the 0.08–0.5 Hz and 0.5–2.0 Hz filter bands. There are clear geographic patterns observed in the response error that need to be further studied to understand the performance of our method. We are surprised by the large response error for periods near 1 sec, and this might suggest poor performance of the NOISETRAN method at higher frequencies or poor choice of a reference station. We will continue to examine this dataset in the coming months of the project, including using synthetic analysis of the event to iterate to an improved response function.

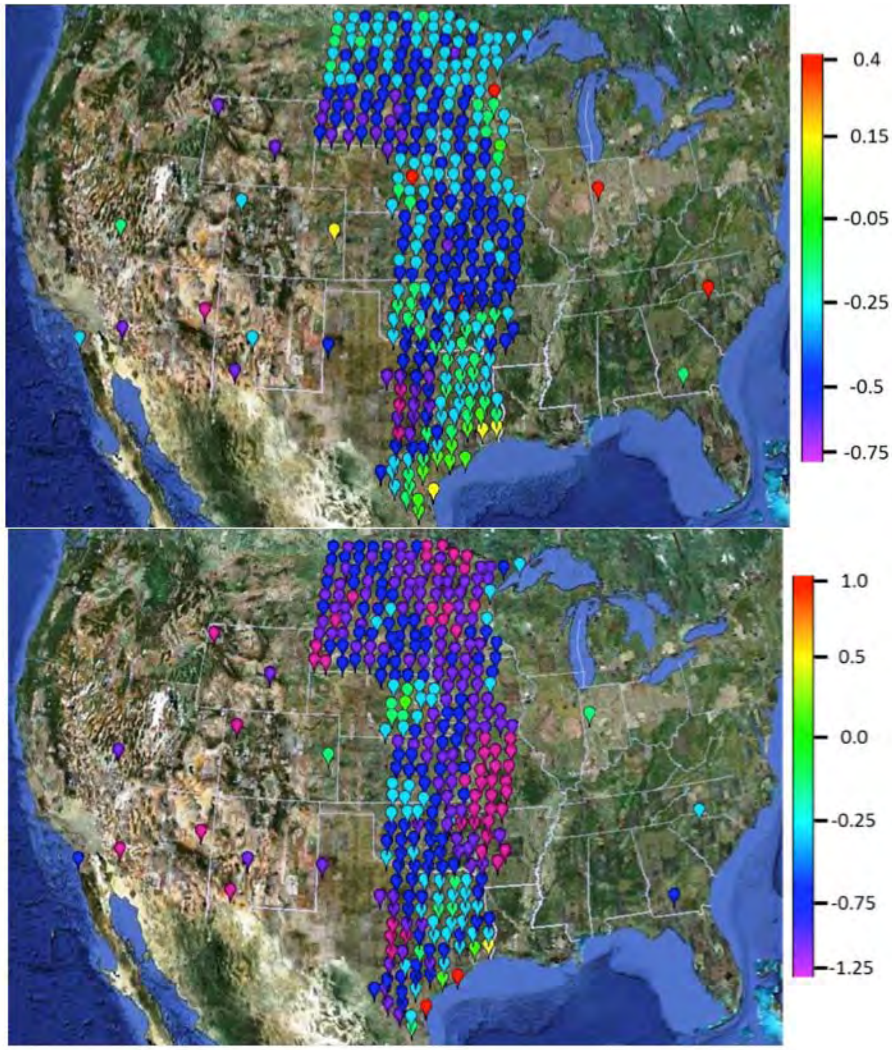

Figure 8. Geographic distribution of response error for Tohuku *P*-waves filtered at 0.08–0.5 Hz (top) and 0.5–2.0 Hz (bottom) using reference station Q34A.

CONCLUSIONS AND RECOMMENDATIONS

After the first nine months of the Phase II project, we have made significant progress in the application of SACPSD and the development of NOISETRAN, which are the major components of our response recovery toolbox. The progress includes the following:

- We now understand the distance requirements for the reference stations (e.g., < 200 km) and the magnitude of the response error that can be expected across a frequency band of 0.01–10 Hz. We also now have a better understanding of geological and other effects on the noise comparisons between the reference and candidate stations. For periods below 1 Hz, the reference station selection can be extended beyond 200 km.
- We have also developed a method for converting the PAR into an amplitude file that can be used in SAC, GSAC, Antelope, or other programs for easy seismometer response deconvolution. This allows us to correct real signals (e.g., *P*-waves from the Tohuku earthquake) using the PAR functions estimated from noise analysis.

- We have tested new ways for metadata evaluation and response error detection.
- We are currently working again on a graphical user interface for the toolbox.

During the final year of the project, we will package NOISETRAN and additional seismic tools into an easy-to-use graphical interface, conduct alpha testing of the toolbox, and then conduct beta testing at Los Alamos National Laboratory. We also need to examine possible phase recovery of the seismometer. Based on our initial presentation of these results to other seismic researchers, we believe this toolbox will have an important impact in many seismological communities where the characteristics of the recording system are either unknown or possibly erroneous.

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