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

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ABSTRACT

Calibration datasets based on the absolute amplitudes of a seismic signal require accurate knowledge of the seismometer-digitizer response. Body- and surface-wave magnitudes, moment estimation, multi-station source characterization, and attenuation model development all require digital seismic data to be corrected for the two components of a digital seismic system: the seismometer and digitizer. When the seismometer and digitizer characteristics are known, deconvolution of the digital system response is relatively straightforward (e.g., transfer command in Seismic Analysis Code [*SAC*], Goldstein et al., 2003). 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. Thus, for the nuclear explosion monitoring mission, the seismic response of the seismometer-digitizer system is essential.

Weston Geophysical Corporation proposes to develop a software toolbox that will recover the seismometer response for recorded seismic data. The toolbox will include 1) a database of known seismometer and digitizer responses with all possible gain settings; 2) methods for estimating response “transfer” functions between stations with and without known responses; 3) techniques for using synthetic seismograms for response validation; and 4) advanced methods for timing and polarity quality control. The toolbox will provide nuclear test monitoring scientists with a valuable asset to characterize datasets that can improve their ability to detect, locate, and discriminate underground nuclear explosions.

OBJECTIVES

We are developing a software toolbox to estimate, assess, and chronicle the seismometer and digitizer response from recorded seismic data. The specific technical objectives will include developing a comprehensive database of known seismometer and digitizer responses with all possible gain settings. Next, we will assemble a set of seismic analysis tools (Figure 1) to iteratively recover the instrument response using two approaches. First, we will estimate a station response transfer function by fitting the seismic data at an unknown station to the background noise and recorded signals from nearby stations with known responses. Second, we will perform variable-period body, coda modeling, and surface-wave modeling to fit the observed data at a station with unknown response to predicted synthetics.

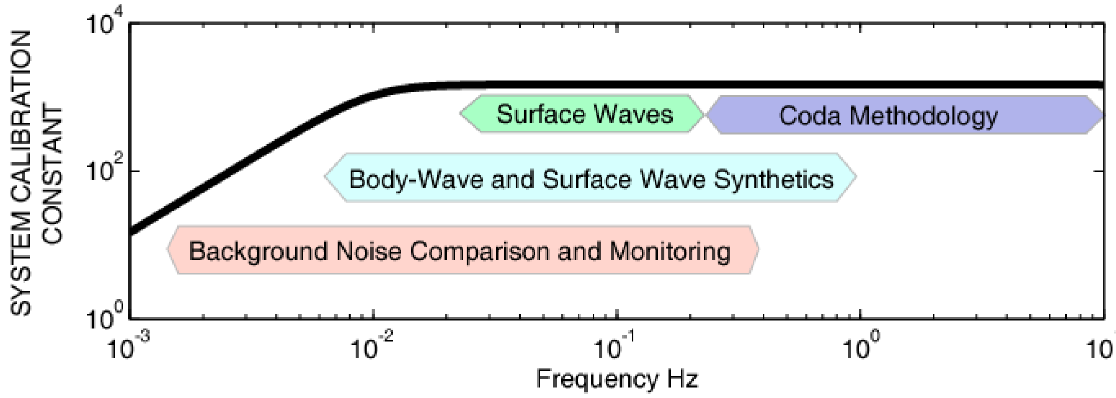

Figure 1. Schematic showing our planned methods for recovering the seismometer-digitizer response for recorded seismic data. The methods include developing transfer functions using surface wave and coda methods, developing synthetics for comparison to the observed data, and monitoring broadband background noise for timing and gain changes.

RESEARCH ACCOMPLISHED

Database Development

We are compiling a comprehensive, current database of seismometers and digitizers currently used (or in development) to monitor global earthquakes and explosions. The objective of this database will be to serve as a starting point when trying to recover a seismometer-digitizer response.

System Response Estimation

We are assembling a set of seismic analysis tools to recover the instrument response by 1) developing a response transfer function that fits the seismic data to the background noise and recorded signals from nearby stations with known responses, and 2) using variable-period body and surface wave modeling to fit the observed data to predicted synthetics. To demonstrate our research plan, we include a recent example of acquiring a test dataset for which both seismometer and digitizer response information were not available. We developed a working seismometer-digitizer response for these data using various seismic methods.

Seismic Data. Hundreds of new seismic stations have been deployed in Eurasia over the past few years, and many of these data are available for download. A problem often encountered with these new data involves compiling the correct seismometer and digitizer responses as well as information concerning the data quality. One such network (designated in this paper the “test network”) provides the waveform data from their 10–20 stations that record regional events and also provides the seismometer calibration sheets (Figure 2). The sheets provide information on the type of seismometers that comprise the stations of this network, including CMG-3T instruments with a nominal velocity output of approximately 2 x 750 V/m/sec. The pole-zero table representative of a flat velocity response between 100 seconds and 50 Hz (Figure 3) was also available on the website. While this was important information, it was not complete. The digitizer least significant bit, which is needed in order to convert the data from counts to ground motion velocity in *m/sec*, remained unknown.

CMG-3T CALIBRATION SHEET

WORKS ORDER:	0515	DATE:	16.02.96
SERIAL NUMBER:	T3347	TESTED BY:	SDG

	Velocity Output V/m/s (Differential)	Mass Position Output (Acceleration output) $V/m/s^2$	Feedback Coil Constant $Amp/m/s^2$
VERTICAL	2 x 750.7	1866	0.02828
NORTH/SOUTH	2 x 758.0	1677	0.03106
EAST/WEST	2 x 750.9	1749	0.03239

Power Consumption: 66 mA @ 12 V input
Calibration Resistor: 51K

NOTE: A factor of 2 x must be used when the sensor outputs are used differentially (also known as push-pull or balanced output). Under no conditions should the negative outputs be connected to the signal ground. A separate signal ground pin is provided.

Figure 2. Seismometer calibration sheet downloaded from the seismic network operator's webpage.

POLES AND ZERO TABLE

WORKS ORDER NUMBER: 0515

SENSOR SERIAL NO: T3345

Velocity response output, Vertical Sensor:

POLES (HZ)	ZEROS(HZ)
$-7.07 \times 10^{-3} \pm j\, 7.07 \times 10^{-3}$	0
$-80.5 \pm j\, 30.8$	0
	+ 150.5

Normalizing factor at 1 Hz: A = - 49.5

Sensor Sensitivity: See Calibration Sheet.

NOTE: The above poles and zeros apply to the vertical and the horizontal sensors and are given in units of Hz. To convert to Radian/sec multiply each pole or zero with 2π. The normalizing factor A should also be recalculated.

Figure 3. Poles and zeroes table for a seismometer in a test seismic network.

Guralp System Investigation. We searched the seismometer manufacturer's webpage and obtained specific information about their equipment. Since this manufacturer often sells their sensors and digitizers in combination, we assumed that the analog data from the CMG-3T were digitized using a DM24 digitizer, which has an input voltage range of ±10 volts. The point of this exercise was to develop an "initial" estimate of the response. For a 24-bit digitizer, this would correspond to a least significant bit of 1.19 μVolts/count assuming unity gain. Combining this assumed bit weight with the velocity output obtained from the seismometer calibration sheets (e.g., 2*750 V/m/sec), we estimated an "initial" digital sensitivity of 7.9E-10 m/sec/count. At this stage in our response recovery, we assumed that the downloaded data were in counts, but ultimately, our technique will not rely on this assumption.

Developing a Response Transfer Function. We now had an "initial" working estimate for the seismometer-digitizer response, based on actual sensor calibration data from the network operator's website together with generic information about the digitizer obtained from the manufacturer's website. We then applied this total system response to convert the velocity data from counts to displacement in nanometers.

The next stage in our response recovery was to compare the noise and signals from one of the unknown stations with the noise and signals from a nearby station with a known system response, $R_2(\omega)$. This method essentially develops a transfer function $T(\omega)$ between the response at a known station and the response at the station of interest $R_1(\omega)$, where

$$R_1(\omega)=R_2(\omega)*T(\omega). \qquad (1)$$

Because our techniques consider certain bands of the response, the recovered response $R_1(w)$ may not be continuous across the entire frequency band.

For example, an m_b=5.7 event occurred and its data from the Global Seismograph Network (GSN) and the test network were available for download. We compared the response-corrected signal and noise at station GNI (a GSN station in Armenia) and a nearby station in the test network (referred to as "Station M1") with unknown response given their similar propagation paths and epicentral distances. We then estimated the period-dependent surface wave magnitudes (Russell, 2006; Bonner et al., 2006) for the GNI and Station M1 data. The results are shown in Figure 4a. The figure shows the surface-wave magnitudes (solid lines) based on amplitudes between periods of 8 and 40 seconds. Also shown are the noise estimates (dashed lines) for the two stations at these same periods. Given the similarity in epicentral distance, propagation paths, and backazimuths to the event, we would not expect a significant difference in the surface-wave magnitudes for these two stations. However, there is a 0.5 magnitude unit (m.u.) difference (amplitude factor > 3x) between the GNI- and Station M1-based estimates, which is far greater than would be expected based on source or station effects. Also discouraging is that the noise estimates for the two stations are also offset by ~0.5 m.u. We decided that our initial estimate at the digitizer LSB was incorrect or that the sensor was operating at a different gain setting.

We note that the shapes of the noise estimates at the two stations are similar except for a static offset. By increasing the noise estimates at Station M1 to match the GNI noise data, we were able to estimate a new potential digitizer LSB for Station M1 of 4.0 μVolts/count (compared to our original estimate of 1.19 μVolts/count). Figure 4b shows that there is essentially no difference between the GNI surface wave magnitude estimate and the Station M1 estimate based on the new "calibrated" response (e.g., 6.72 versus 6.75). The GNI path samples part of the South Caspian Basin, and the surface wave amplitudes at periods < 20 secs have been attenuated while being less affected at longer periods.

At a later date than the analysis shown in Figure 4, we were able to obtain a copy of the digitizer calibration sheets for Station M1 and others in its network. These sheets provided the actual digitizer LSB for the instruments: 3.5 μVolts/count. When this value was used to correct the data for the instrument response, we obtained similar magnitudes (6.75 vs. 6.70) to our "calibrated" estimate (Figure 4b).

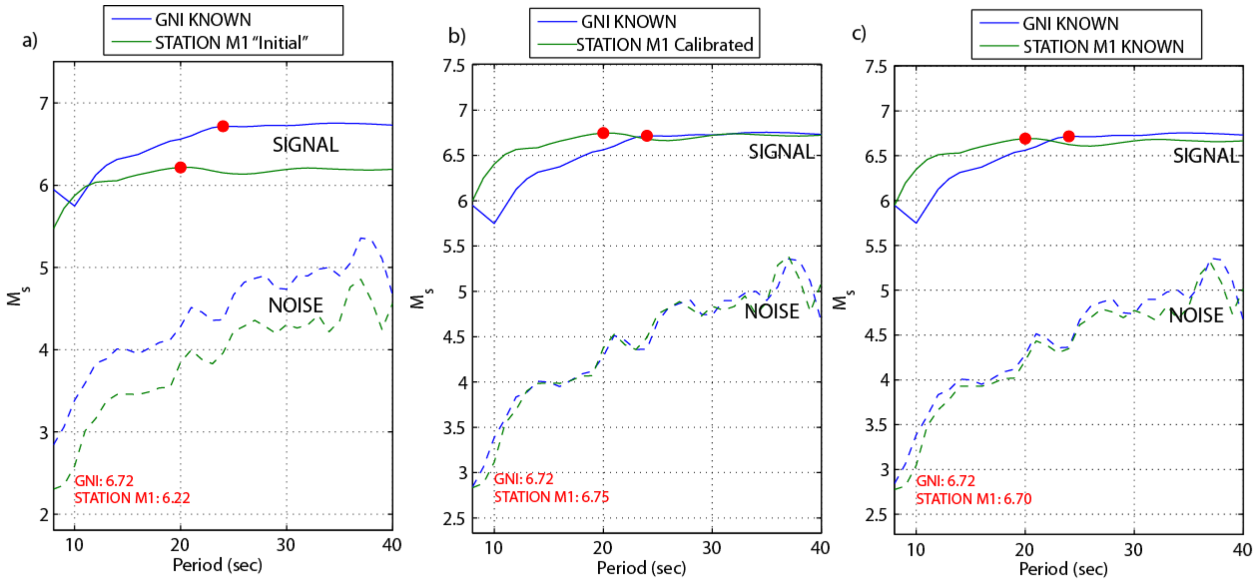

Figure 4. Evaluating different digitizer constants in terms of signal magnitudes and noise levels at GNI and Station M1--a seismic station with unknown response. a). Initial "guess" LSB of 1.19 µVolts/count. b) "Calibrated" LSB estimate of 4.0 µVolts/count based on fitting the long-period noise levels. c) Actual LSB of 3.5 µVolts/count based on digitizer calibration sheet.

Testing with Synthetics. Synthetic seismograms can be used to evaluate response estimates. This exercise requires the waveforms of an event large enough to be modeled, and also large enough to be independently tested and evaluated. We obtained the recordings of an M_w=7.9 earthquake on the same test network discussed in Figures 2–4. Since the epicentral distances ranged from 36 to 49 degrees, waveform modeling is not very sensitive to the upper mantle. In work for the USGS, Herrmann et al. (2008) implemented a detailed procedure for rapid moment tensor inversion using teleseismic *P*, *SV* and *SH* waves (see http://eqinfo.eas.slu.edu/Earthquake_Center/MomentTensor.html). A simple modification of that procedure created a forward modeling procedure for seismic network quality control (QC). Given a moment tensor solution, the teleseismic waveforms are lowpass filtered in such a way that the source time function does not have to be specified in detail. A direct comparison can then be made between observed and predicted signals.

The example shown in Figure 9 is for test network broadband stations with the derived broadband response for the systems (e.g., Figure 4). The *P*-wave comparisons are good, although the Station Z may have a timing problem. The peak amplitudes are generally within 50% of each other for the assumed response. The comparison of the SH components (Figure 5) may be affected by the assumptions of a point source for this large earthquake as much as the assumption that the horizontal components are correctly oriented.

For the network discussed in Figures 5 and 6, the number of posted teleseismic recordings is very small. However, the recordings of M > 4 earthquakes are often available. Forward modeling can be performed if the velocity and attenuation models are known along the source-receiver path and if the moment tensor is known. Such modeling will illustrate component orientation and timing problems. Of course the same data can be inverted for the moment tensor using velocity models for the path that are derived from the knowledge base. An approach here would be to start with larger events, seen by other nearby broadband stations to build confidence in the velocity models and the component orientation, followed by modeling of the smaller earthquakes to track the history of the data channels.

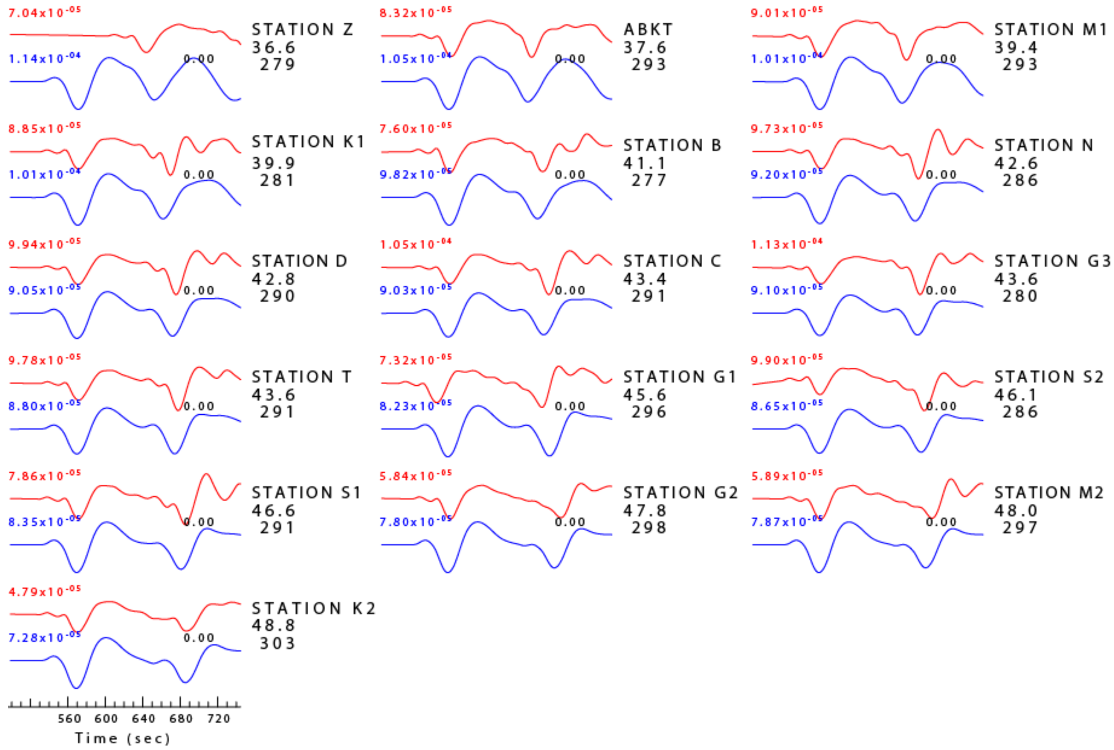

Figure 5. *P*-wave Vertical Component Comparison: Comparison of the observed traces (red) corrected with our calibrated system response and predicted traces (blue) ordered in terms of increasing epicentral distance. Each pair of traces is annotated with a station name, epicentral distance in degrees, source to station azimuth in degrees. Each pair of traces is plotted with the same scale and the peak amplitudes are indicated at the left of each trace. Finally the time shift between the *P*-wave first arrival picked and the theoretical *P*-wave first arrival in the predicted trace is indicated, with a positive sign indicating that the predicted trace has been shifted to the right by the given number of seconds as a function of source to station azimuth in degrees.

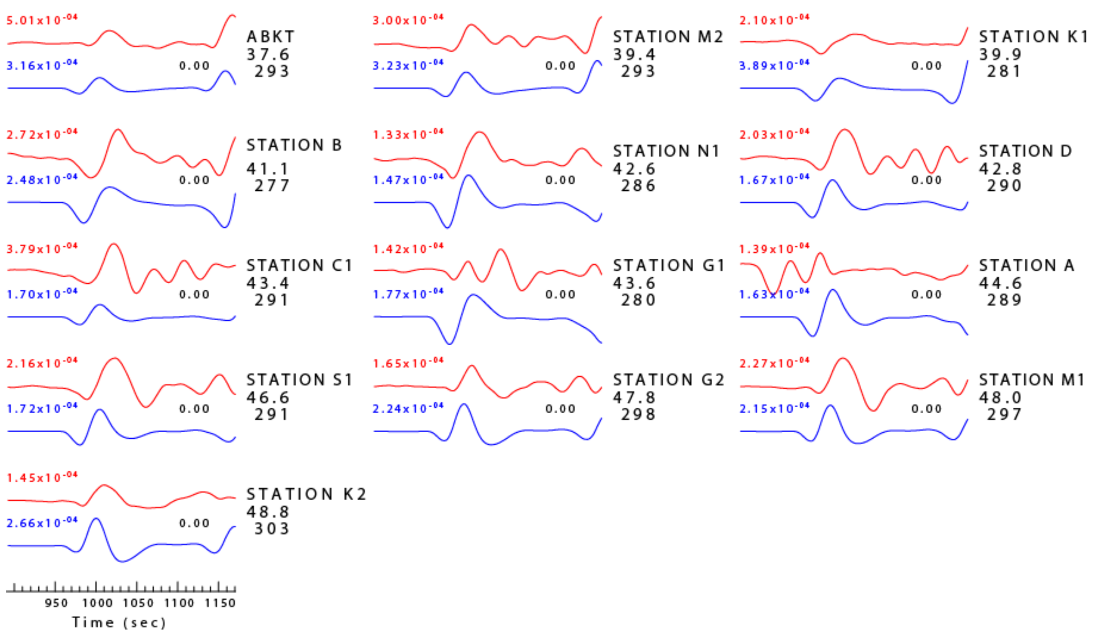

Figure 6. SH-wave T Component Comparison. See Figure 5 caption for details.

Advanced Data Quality Control

In addition to the recovery of the instrument response, the methods in this proposed toolbox could also provide other network QC features such as timing problems and polarity reversals. While examining the test network data using long period synthetic modeling, we determined several components had reversed polarity. Additionally, continuous monitoring of background noise levels will highlight possible network/station operator gain adjustments. Timing problems will also be illuminated by analyzing the noise field through the cross correlation of station pairs (Figure 7). During this project, we will address the possibility of incorporating these additional QC features in the toolbox.

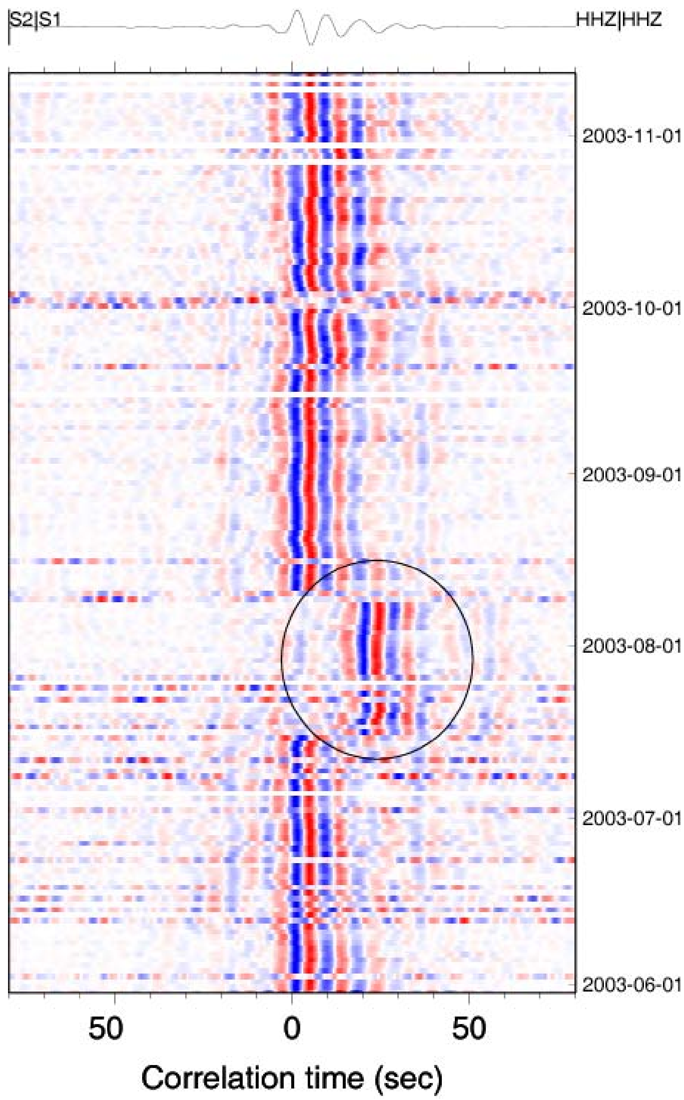

Figure 7. Two-station continuous correlation functions for a 5.5 month period for two nearby stations in the test network. Each row of the image represents a daylong correlation function, although only 100 seconds are displayed. Data processing includes spectral whitening prior to cross correlation followed by filtering to 0.08 - 0.15 Hz. The station pair is separated by 32 km. The anomalous time shift (black circle) in the dominant signal starting in mid-July and lasting approximately 1 month indicates a timing problem with one of the stations.

CONCLUSIONS AND RECOMMENDATIONS

We have just initiated the development of this software toolbox for recovery of seismometer-digitizer responses, and there are many questions that remain before we can determine its effectiveness. We hope the toolbox will be included in future versions of the *Seismic Analysis Code (SAC)*, which is a preferred seismic software analysis tool for many scientists. As a SAC module, the toolbox would provide nuclear test monitoring scientists with a valuable asset to characterize and improve calibration datasets. Products derived from these calibration datasets will improve their ability to detect and locate seismic events. In addition, the toolbox could highlight changes in instrument behavior in seismic networks that are used to monitor earthquakes for global seismic hazard prediction and assessment.

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