DEVELOPING MULTIPLE-FREQUENCY DISCRIMINANTS FOR USE WITH REGIONAL CODA-AMPLITUDE MEASUREMENTS

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ABSTRACT

This paper investigates the feasibility of employing local to near-regional coda-wave amplitude measurements, in multiple, narrow bands, for the purpose of discriminating small seismic events. The motivation comes from previous studies that have shown that regional, single-station coda-magnitude estimates are more stable and accurate than any direct phase measure to date (e.g., Mayeda et al., 2003). Typically, the source amplitude estimates derived from the coda have interstation variances on the order of 0.07 log amplitude units; hence, the method is excellent for regions with sparse station coverage. The method has been thoroughly tested over large geographic regions spanning both local and regional distances for the purpose of magnitude estimation. In terms of discrimination, only a preliminary study using coda waves was performed on Nevada Test Site (NTS) explosions and earthquakes in the study by Walter et al., (1995). Since this time, however, no additional studies have been conducted, in spite of the coda's successful application for moment magnitude (M_W) estimates in the broad areas of Eurasia and the Middle East. Due to the nature of the scattered energy comprising the coda, path and azimuthal source-radiation effects are averaged over, making coda amplitudes insensitive to local structure, in sharp contrast to direct regional phases such as *Pn, Pg*, and *Lg*. Calibrated with respect to seismic moment (M_0) or M_W, coda-derived source spectra provide a means to obtain moment estimates from seismograms of smaller or more distant events that cannot be analyzed with conventional waveform or spectral source-inversion techniques because of signal-to-noise limitations. Tying coda magnitude to *Mw* also provides a physical measure of event size that is unbiased and therefore transportable. We have completed a new path and site calibration for frequencies ranging between 0.3 and 8.0 Hz using openly available Incorporated Research Institutions for Seismology (IRIS) and Korea Meteorological Administration (KMA) stations for small to moderate-sized regional events within the Korean Peninsula. This involved tying the coda measurements to independently determined seismic moments for earthquakes in the region (R. Herrmann, pers. comm., 2007). Our next step will be to test seismic discrimination performance using coda spectral ratios and comparing their stability with those derived from direct Lg.

OBJECTIVE

The objective of this proposal is to test the performance of a high-frequency spectral ratio discriminant that uses regional Lg coda from explosions and earthquakes in the Korean peninsula. Over the past decade, significant advances have been made in regional monitoring that take advantage of stable amplitude measurements derived from narrowband coda envelopes. For example the Department of Energy (DOE) laboratories, with guidance from the Air Force Technical Applications Center (AFTAC) Seismic Review Panel, have developed a regional coda wave methodology to obtain the lowest variance estimate of the seismic source spectrum (e.g., Mayeda et al., 2003). Thus, regional M_W derived from Sn and Lg coda are very stable, even when only a single station is used. For the case of the current study region, we have performed a preliminary one-dimensional (1-D) calibration for Korean peninsula earthquakes using openly available stations from IRIS and KMA and then have formed spectral ratios. Our plan is to apply the same path and site corrections to explosions in the region and compare the spectral ratio performance against direct Lg.

RESEARCH ACCOMPLISHED

Currently within the explosion monitoring research community, there is interest in identifying and locating small underground nuclear explosions from sparsely instrumented networks. The most successful teleseismic discriminant compares the 20-second period surface wave magnitude (M_S) with the ~1-Hz body wave magnitude (m_b). However for smaller events that are deficient in long-period surface wave energy, the only alternative is to use high-frequency discriminants from the regional phases such as Pn, Pg, Sn, and Lg. However, because of strong lateral heterogeneity in the crust at short length scales, single-station direct phase measurements have high variance.

First, we have collected waveform data from both IRIS and KMA Web sites (Figure 1). Of these, a large fraction have been waveform modeled (*R. Herrmann*, pers. comm., 2007, http://www.eas.slu.edu/Earthquake_Center/MECH.KR/) and estimates of *Mw* were used to calibrate the coda-derived source spectra using the methodology outlined in Mayeda et al. (2003).

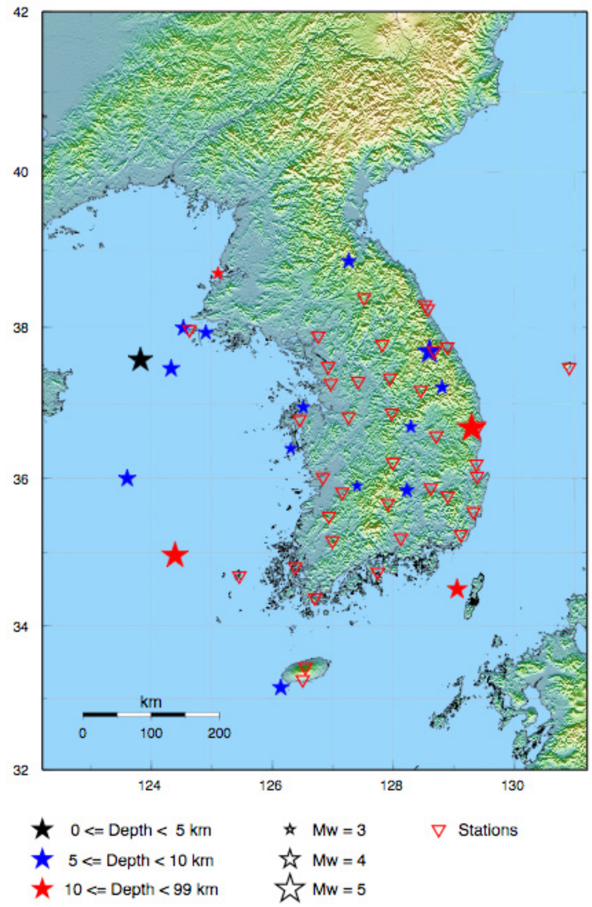

Figure 1. Map of calibration events and stations available in the current study.

We formed $\log_{10}$ averaged envelopes from the two horizontal components for consecutive narrow frequency bands ranging between 0.5 Hz to 8.0 Hz. The coda envelopes for each frequency band can be idealized with the following equation,

$$A_c(f, t, r) = W_o(f) \cdot S(f) \cdot T(f) \cdot P(r, f) \cdot H(t - t_s) \cdot (t - t_s)^{-\gamma(r)} \exp\left[-b(r) \cdot (t - t_s)\right], \qquad (1)$$

where f is the center frequency, r is the epicentral distance in kilometers, t is the time in seconds from the origin time, t_s is the S-wave travel time in seconds, W_o represents the S-wave source, T represents the S-to-coda transfer function, S is the site effect, P includes the effects of geometrical spreading and attenuation, H is the Heaviside step function, $\gamma(r)$ and $b(r)$ are the distance-dependent coda shape factors that control the coda envelope shape. However for the purpose of generating synthetics we set W, T, S, and P to unity. Following the methodology outlined in Mayeda et al. (2003), the coda shape parameters and velocity of the peak S/L_g-wave arrival were fit using the form of a hyperbola.

Unlike direct waves, the local to near-regional coda appears to be homogeneously distributed in the crust behind the expanding direct wave front and thus requires a different formulation for the attenuation (see Figure 2).

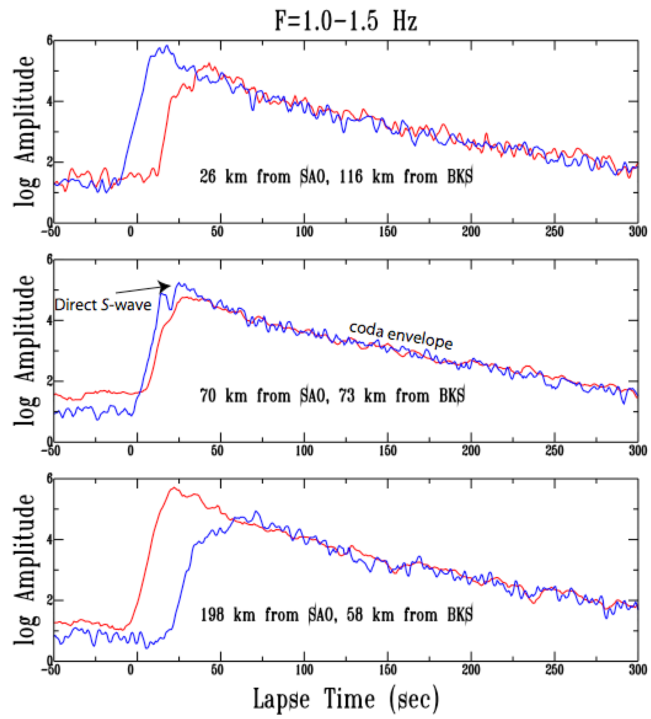

Figure 2. Example envelopes (*f*=1.0-1.5 Hz) for three local earthquakes located in the San Francisco Bay region recorded at stations SAO (blue) and BKS (red), part of the Berkeley Digital Seismic Network (BDSN). These two stations are separated by roughly 140 km. Irrespective of the events' distance to each station, the coda envelopes attain the same amplitude level, in sharp contrast with the direct arrivals. At this range of distances, the scattered *S*-waves or 'coda' are homogeneously distributed in the crust (figure taken from Mayeda et al., 2005).

For each narrowband envelope in our data set, raw coda amplitudes were determined by generating synthetics at the appropriate distance and using a source of unity then DC shifting using an L-1 norm to fit the observed envelope. The amount of the DC shift is the nondimensional raw coda amplitude. Next, we use the following empirical equation for coda path correction of Mayeda et al. (2003).

$$P(r,f) = \left[1 + \left(\frac{r}{p_2}\right)^{p_1}\right]^{-1} \qquad (2)$$

Using common recordings at each station pair, we then grid searched over p_1 and p_2 and tabulated the interstation scatter for each frequency band. The choice of frequency-dependent path correction for the entire region was based upon the path parameters p_1 and p_2, which gave the lowest average interstation standard deviation between station pairs. In general, the interstation standard deviation ranged between 0.07 and 0.15, whereas the scatter for distance-corrected Lg and surface waves resulted in an interstation scatter of 0.27-0.45, roughly a factor of 3 to 4 times larger. These results confirm our initial hypothesis that the coda can effectively average over the effects of both source and path heterogeneity.

Next, we use the independent *Mw* estimates to calibrate the coda-derived source spectra. (See Mayeda et al. [2003] for calibration details.) Figure 3 shows example source spectra for a range of stations after all frequency-dependent path and site corrections were applied to each station. In general, the coda-derived spectra are very stable, in good agreement with previous published applications of the coda methodology.

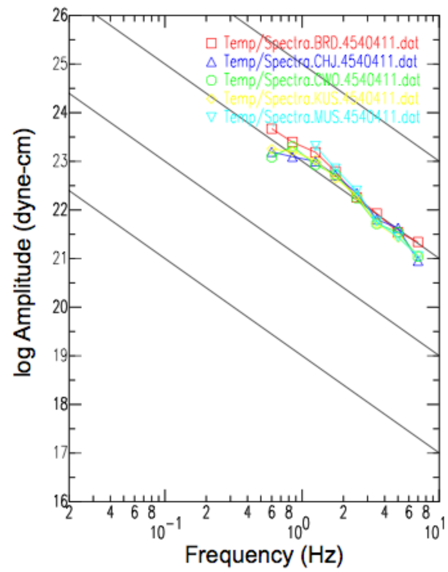

Figure 3. Example coda-derived source spectra for a range of stations. In general, the coda spectra are stable; however, our path calibration is preliminary, and we expect further improvement by reducing the amplitude scatter.

To validate the results, Figure 4 shows coda-derived *Mw* estimates (y-axis) are in good agreement with independent estimates (x-axis). We use roughly 10 events to perform the moment-rate calibration, then apply the same site-transfer corrections to all the events in our data set.

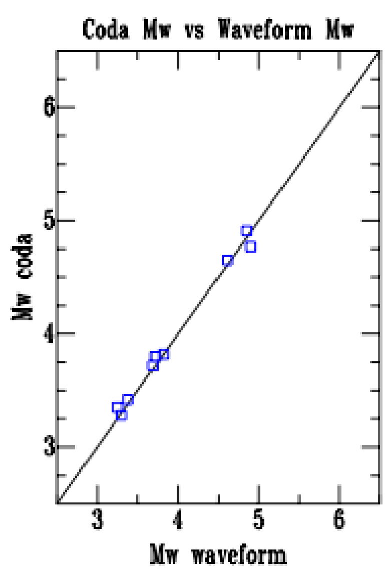

Figure 4. ***Mw*** **derived from the low-frequency level of the coda spectra plotted against independent** ***Mw*** **from waveform modeling.**

Next, using the spectra like the one shown in Figure 3, we form amplitude ratios for all earthquakes in our calibration data set (Figure 5). For each range of pass bands, a consistent trend is observed that is expected due to corner-frequency changing as a function of magnitude. In general the data scatter is small and suggests that the coda spectral ratios are reducing the variance associated with source radiation pattern and path heterogeneity. The next part of the project will be to process a training explosion data set that will consist of mining-related explosions, single-fired explosions, and the recent North Korean nuclear test.

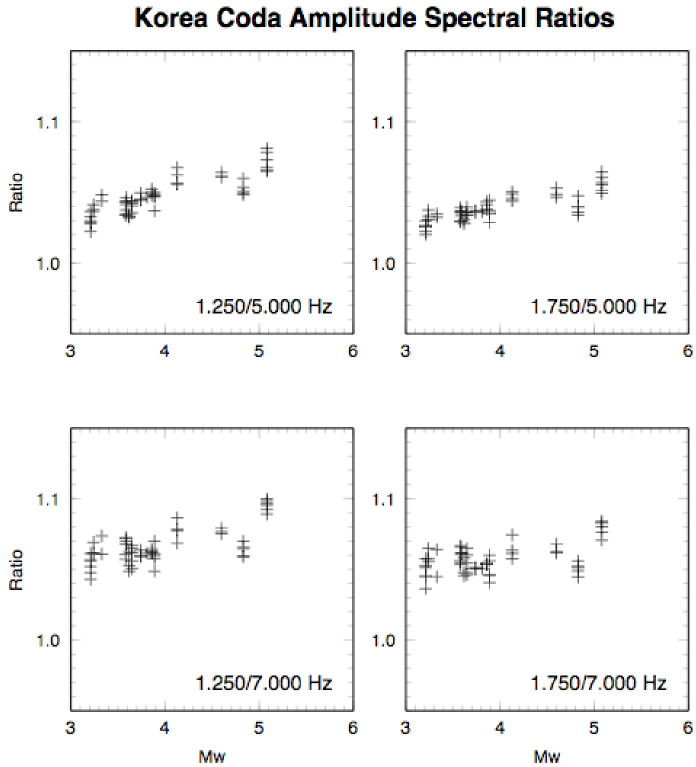

Figure 5. Single-station coda spectral ratios for the 15 calibration earthquakes distributed in and around the Korean peninsula for a range of different pass bands.

CONCLUSIONS AND RECOMMENDATIONS

We have performed a preliminary coda calibration for openly available stations in and around the Korean peninsula for 15 earthquakes ranging between *Mw* 3.2 and 5.1. In general, the 1-D coda calibration is performing well, and we expect future refinements to further reduce the data variance. The coda path and site calibrations will be improved in the next phase of the project, and we will begin processing of explosion data. At that point, we will also compute direct Lg spectral ratios to compare the discriminant performance against the coda spectral ratios.

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