STABLE AND TRANSPORTABLE REGIONAL MAGNITUDES BASED ON CODA-DERIVED MOMENT-RATE SPECTRA

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Sponsored by National Nuclear Security Administration
Office of Nonproliferation Research and Engineering
Office of Defense Nuclear Proliferation

Contract No. W7405-ENG-48,[1] DE-FC03-01SF22416,[2] and DE-FC03-01SF22417[3]

ABSTRACT

We describe an empirical method of calibrating stable seismic source moment-rate spectra derived from regional coda envelopes using broadband stations. The main goal is to develop a regional magnitude methodology that has the following properties: 1) it is tied to an absolute scale and is thus unbiased and transportable; 2) it can be tied seamlessly to the well-established teleseismic and regional catalogs; 3) it is applicable to small events using a sparse network of regional stations; 4) it is flexible enough to utilize S_n-coda, L_g-coda, or *P*-coda, whichever phase has the best signal-to-noise ratio. The results of this calibration will yield source spectra and derived magnitudes that are more stable than any other direct-phase measure to date. Our empirical procedure accounts for all propagation, site, and *S*-to-coda transfer function effects. The resultant coda-derived moment-rate spectra are then used to provide any traditional band-limited magnitude (e.g., M_L, m_b etc.) as well as an unbiased, unsaturated magnitude (moment magnitude, M_w) that is tied to a physical measure of earthquake size (i.e., seismic moment). We validate our results by comparing our coda-derived moment estimates with those obtained from long-period waveform modeling. In order to demonstrate the usefulness and transportability of our method, we chose the Eastern Mediterranean region as our study area in general, and Turkey and adjacent areas in particular. Most importantly, using those observations of broadband stations in Turkey we demonstrate that the inter-station magnitude scatter is significantly reduced when using the coda-based magnitudes (i.e., M_w(coda) and m_b(coda)). Once calibrated, the coda-derived source spectra provide stable, unbiased magnitude estimates for events that are too small either to be reliably waveform modeled or to be seen at far-regional and teleseismic distances. Using broadband observations of events in the Gulf of Aqaba we found that our source amplitude estimates were nearly insensitive to the source radiation pattern and exhibited roughly a factor of 4 to 5 less inter-station scatter when compared against coda duration and conventional direct-phase measurements (e.g., P_g, L_g).

OBJECTIVE

Magnitude estimation forms an integral part in any seismic monitoring endeavor. For sparse local and regional seismic networks a stable and unbiased magnitude is of utmost importance for establishing accurate seismicity catalogs and assessing seismic hazard potential. In the context of underground nuclear explosion monitoring, magnitudes are used to construct detection threshold curves, differentiate between earthquakes and explosions (e.g., seismic discriminants such as m_b:M_s, m_b:M_o), and estimate nuclear explosion yield. In addition to magnitude, regional short-period discriminants for small-to-moderate sized events using P_n, P_g, S_n, and L_g all suffer from source and path heterogeneity. The coda spectral ratio discriminant, however, which compares high frequencies ($f \sim 6$ Hz) with low frequencies ($f \sim 1$ Hz), has been shown to be a more stable discriminant than L_g spectral ratios (Walter *et al*., 1995, Hartse *et al*., 1995). As a consequence of the direct wave variability, multi-station averaging is necessary to reduce the amplitude scatter. If the average station spacing is large (~1500 km), such as the International Monitoring System (IMS) network, the ability to measure a stable magnitude and/or source amplitude for small-to-moderate sized events becomes difficult because of limited number of regional stations over which to average direct-phase variability. Since these events cannot be measured teleseismically we require a stable, regional measure of source size from as little as one station.

The theoretical background of coda generation and empirical observations has been the subject of extensive study during the last four decades (e.g., see a review by Sato and Fehler, 1998). The coda stability stems from a time-domain measurement made simultaneously over a large portion of the seismogram, thereby averaging over the scattered wavefield. Unlike conventional narrowband regional magnitudes, which are relative measurements that often have regional biases (e.g., $m_b(P_g)$, $m_b(P_n)$, $m_b(L_g)$, M_s, M_L, M_d), magnitudes formed from our coda-derived moment-rate spectra are unbiased and not as sensitive to the undesirable effects of source radiation pattern, 3-D path heterogeneity, constructive/destructive interference near the recording site, and phase blockage. Furthermore, unlike teleseismic *P*-based magnitudes, the regional coda-based M_w is absolute and will not suffer from biases introduced by upper mantle variations beneath the source region. These biases can cause source size and explosion yield estimation errors if they are not accounted for properly. The coda methodology can provide a universal and transportable magnitude based on source spectra derived from *P* and/or *S* coda envelopes. These source spectra can be used to estimate a stable single-station M_w from the long-period levels (which by definition is absolute and transportable). Alternatively, we can convolve our source spectra with a short-period instrument response and define a regional or local magnitude, which can be tied to already established local and teleseismic catalogs (e.g., M_L, m_b etc.). For small regions such as the Nevada Test Site (NTS) (see Mayeda, 1993) and aftershock zones we find that a single-station coda magnitude is equivalent to roughly a 16-station network average using direct waves (e.g., $m_b(P_n)$, $m_b(P_g)$ and $m_b(L_g)$). For larger regions (such as earthquakes distributed throughout the western U.S.) the crustal averaging properties of the coda are equivalent to a 64-station network (Mayeda and Walter, 1996). Another important advantage of the method is that we are not restricted to using one type of coda. For example, Mayeda (unpublished) has applied the approach to paths between Novaya Zemlya and Fennoscandia using *P*-codas, and S_n-codas because of L_g blockage.

This study differs in a number of ways from recent coda source studies (e.g., Mayeda, 1993; Hartse *et al*., 1995; Mayeda and Walter, 1996). First, Mayeda (1993) used the simple analytic scattering formulation of Aki (1969) to measure the late L_g coda (measured after twice the L_g travel time) for NTS explosions recorded at Lawrence Livermore Natioanl Laboratory's four regional broadband stations. This approach simply demonstrated that an m_b based on ~1 Hz regional coda envelopes were significantly more stable (factor of 3 to 5) than those based on P_n and L_g. There was no need to incorporate path corrections since all the events came from the small region of NTS. Hartse *et al*. (1995) stacked narrowband envelopes for small local earthquakes in and around the NTS region to construct 'type curves' which could be used to match subsequent events for source amplitude measurements. By assuming that the local coda was homogeneously distributed in the region they did not need to incorporate a distance correction. Both methods were perfectly adequate for these specific monitoring scenarios, but were not applicable to events that were widely distributed. To measure coda-derived source spectra over regional distances, Mayeda and Walter (1996) used a 2-D, distance-dependent multiple scattering model to generate synthetic envelopes for earthquakes distributed throughout the western United States. However, the use of the scattering model did not account for all the path effects and additional 'ad-hoc' path corrections had to be made. The approach described in the current study expands upon the previous studies described above. Our strictly empirical formulation accounts for distance-dependent changes in coda envelope shape, spanning both local and regional distances. In addition, our path corrections are empirically based, without assumption of any scattering model and applicable over a wide distance range. We use the same approach of Mayeda and Walter (1996) in tying our coda amplitudes to an absolute scale.

RESEARCH ACCOMPLISHED

The first part of this project included refining the coda methodology using broadband data from events along the Dead Sea rift region. We found that our source amplitude estimates were nearly insensitive to the expected source radiation pattern and exhibited roughly a factor of 3 to 5 less inter-station scatter when compared against coda duration and conventional direct-phase measurements (e.g., P_g, L_g). We also found that the coda stability, as measured by the inter-station scatter for common events, reached a minimum value beyond a certain critical measurement window length. For example, at 6-8 Hz, the inter-station standard deviation was less than 0.08 provided the coda measurement was at least ~60 seconds in duration, whereas at 1.5-2.0 Hz the critical window length was 150 seconds. For all frequency bands, as the coda window becomes shorter the standard deviation increases, asymptotically approaching the direct wave scatter. The next phase of our project is still on-going, but has resulted in the collection of over 250 events from the NEIC catalog that were recorded by regional broadband stations ISP, ISK, MALT, and VANB in Turkey, as well as KIV and GNI in neighboring countries to the east (see Figure 1).

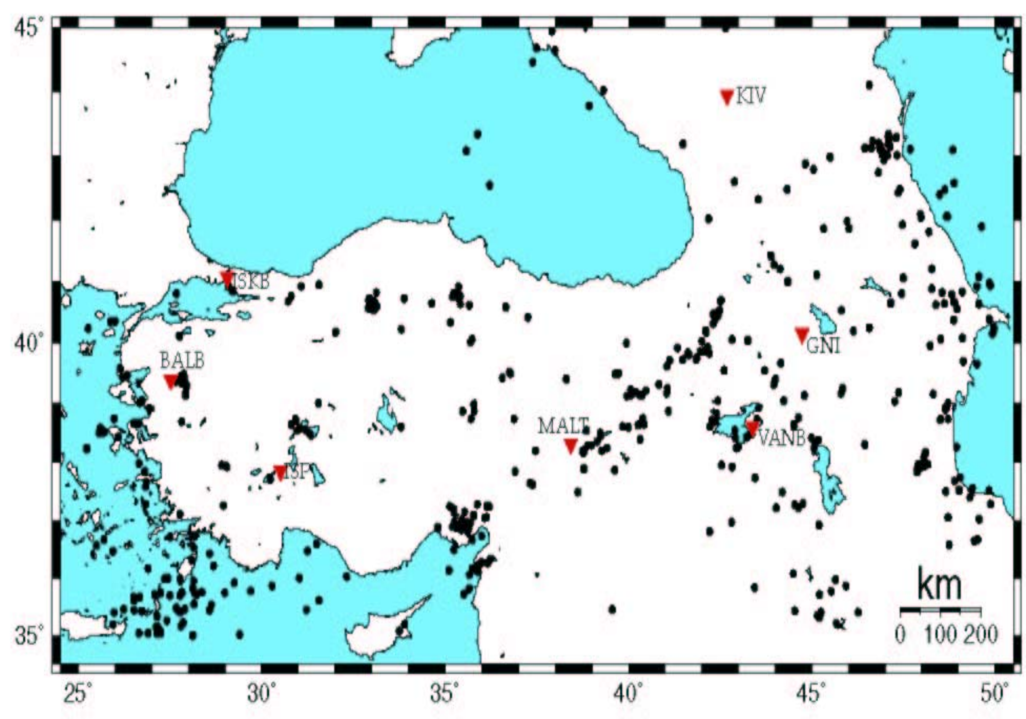

Figure 1. The collection of more than 250 events from the NEIC catalog. These events were recorded by regional broadband stations ISP, ISK, MALT and VANB in Turkey, as well as KIV and GNI in neighboring countries to the East.

Our preliminary results are very encouraging especially since this region is significantly larger and more tectonically complicated than the Dead Sea rift region.

Using common events recorded at two stations separated by roughly 800 km (MALT and ISP), we applied the coda methodology by forming narrowband envelopes using frequencies ranging between 0.02 and 1.0 Hz. We next formed velocity vs. distance curves for each frequency band, then found coda shape parameters as a function of distance. As a first attempt, we applied a grid-search approach to find the distance corrections that minimized the inter-station standard deviation. Figure 2 shows comparisons of distance-corrected coda amplitudes for two frequency bands as well as distance-corrected direct waves for comparison.

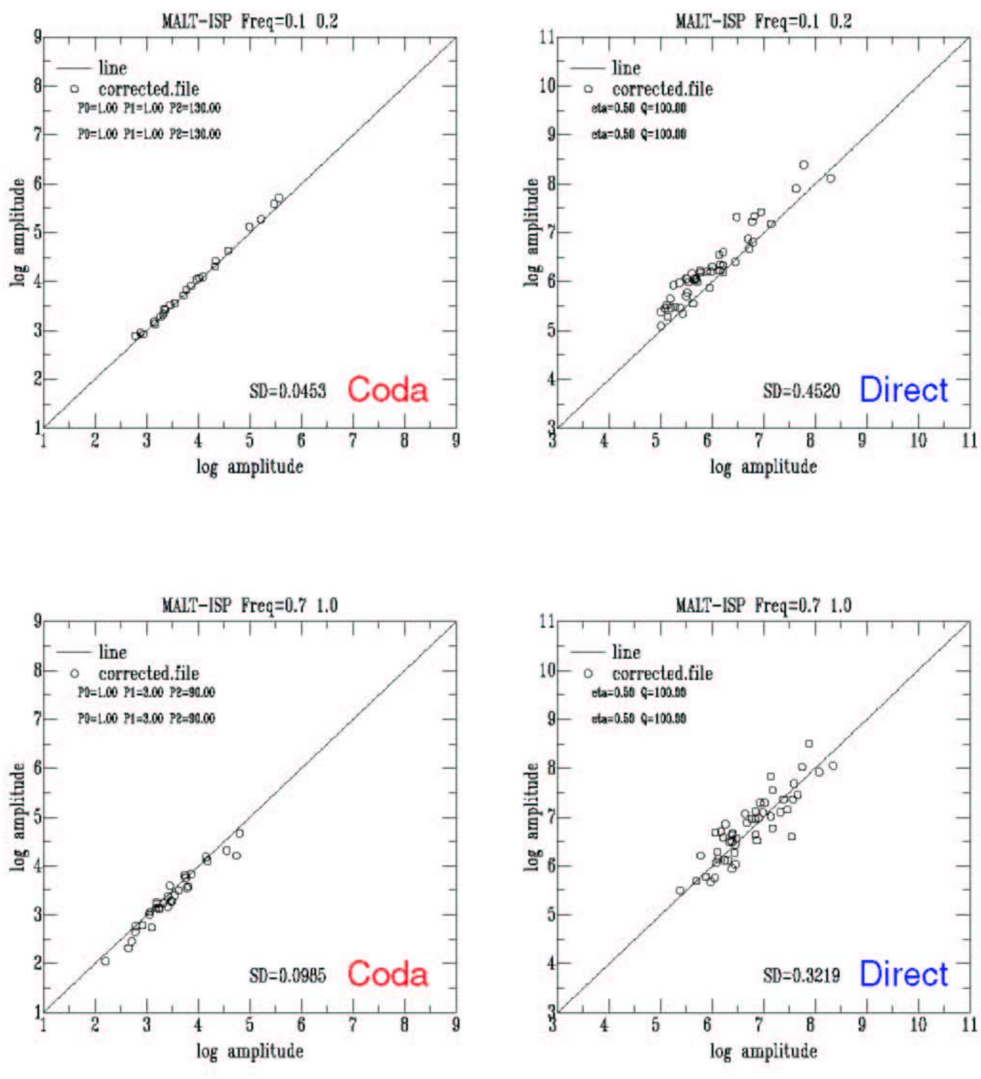

Figure 2. Comparisons of distance-corrected coda amplitudes for two frequency bands, as well as distance-corrected direct waves.

The coda results are surprisingly good for these wavelengths considering the lateral geologic complexity in Turkey. Our next steps will be to compute moment magnitude for selected earthquakes in the region and use them to tie our measurements to an absolute scale. We expect at the higher frequencies the complicated geologic structure may require us to use a 2-D distance correction rather than a simple homogeneous 1-D radially symmetric model.

CONCLUSIONS AND RECOMMENDATIONS

This paper describes an empirical methodology to transform non-dimensional coda amplitudes into stable moment-rate spectra. Once calibrated, the coda-derived spectra can provide unbiased, absolute magnitude estimates for events that are too small either to be waveform modeled or to be seen teleseismically. Our empirical path and site corrections were verified by comparing our seismic moment estimates against independent estimates from long-period waveform modeling. We found that source amplitude estimates were virtually insensitive to the source radiation pattern and exhibited roughly a factor of 3 to 5 less inter-station scatter when compared against conventional direct-phase measurements (e.g., P_g, L_g) as well as coda duration. We are now applying the same approach to the broader, more complicated region of Turkey.

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