

An application of the coda methodology for moment-rate spectra using broadband stations in Turkey

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[1] A recently developed coda magnitude methodology was applied to selected broadband stations in Turkey for the purpose of testing the coda method in a large, laterally complex region. As found in other, albeit smaller regions, coda envelope amplitude measurements are significantly less variable than distance-corrected direct wave measurements (i.e., L_g and surface waves) by roughly a factor 3-to-4. Despite strong lateral crustal heterogeneity in Turkey, we found that the region could be adequately modeled assuming a simple 1-D, radially symmetric path correction. After calibrating the stations ISP, ISKB, and MALT for local and regional distances, single-station moment-magnitude estimates (M_w) derived from the coda spectra were in excellent agreement with those determined from multi-station waveform modeling inversions, exhibiting a data standard deviation of 0.17. Though the calibration was validated using large events, the results of the calibration will extend M_w estimates to significantly smaller events which could not otherwise be waveform modeled. The successful application of the method is remarkable considering the significant lateral complexity in Turkey and the simple assumptions used in the coda method. **INDEX TERMS:** 7205 Seismology: Continental crust (1242); 7215 Seismology: Earthquake parameters; 7219 Seismology: Nuclear explosion seismology. **Citation:** Eken, T., K. Mayeda, A. Hofstetter, R. Gök, G. Örgülü, and N. Turkelli (2004), An application of the coda methodology for moment-rate spectra using broadband stations in Turkey, *Geophys. Res. Lett.*, 31, L11609, doi:10.1029/2004GL019627.

1. Introduction

[2] Local and regional coda envelopes are generally thought to be composed of scattered waves that sample some volume surrounding the earthquake source. The first and simplest model to describe the coda was the single-scattering model of Aki [1969] where the volume sampled is an ellipsoid with the station and source at the foci. A number of observational studies have shown that the volume averaging of the coda waves samples the entire focal sphere and renders them virtually insensitive to any source radiation pattern effect, in contrast to direct waves [e.g., Aki, 1969; Aki and Chouet, 1975; Rautian and Khalurin, 1978].

Since the earliest studies on coda, advances in the theoretical background of coda generation and empirical observations have been the subject of extensive study during the last several decades and is reviewed thoroughly by Sato and Fehler [1998].

[3] Mayeda and Walter [1996] studied the seismic source parameters such as energy, moment, and apparent stress drop by using amplitude measurements derived from narrowband coda envelopes for earthquakes in the western United States. More recently Mayeda et al. [2003] developed a completely empirical calibration method for obtaining stable seismic source moment-rate spectra derived from local and regional coda envelopes using broadband stations. Their empirical method accounts for path, S-to-coda transfer function, site effect, and any distance-dependent changes in coda envelope shape for frequencies ranging between 0.02 and 8.0 Hz.

[4] In the current study we apply the method of Mayeda et al. [2003] to the large and tectonically complex region of Turkey, a laterally heterogeneous region that experiences intensive seismic activity [e.g., Bozkurt, 2001; Barka and Kadinsky-Cade, 1988], responsible for numerous destructive earthquakes. However, since the method assumes a simple 1-D radially symmetric path correction, this study region was a good test of the hypothesis that the coda averages over lateral crustal complexity as well as source heterogeneity (e.g., source radiation pattern and directivity).

2. Data

[5] The Kandilli Observatory and Earthquake Research Institute (KOERI), Bogaziçi University, operates a nationwide seismic network for monitoring the seismic activity in and around Turkey. Magnitude calculation plays an important role in KOERI's activities and currently they report duration magnitude (M_d), local magnitude (M_L), and moment magnitude (M_w). In this study, we calibrated three broadband stations, ISKB, ISP, and MALT (Figure 1) for coda-derived moment magnitudes, $M_w(\text{coda})$ and compare against independent moments. We selected over 250 earthquakes recorded at three broadband stations, spanning a distance range of roughly 30 to 1400 km that generally samples the entire country of Turkey (Figure 1). The majority of these events were used to calibrate the coda envelope shapes and derive path corrections. Of these, 88 events had independent seismic moment estimates that were previously derived from long-period waveform modeling. Approximately 15 of these events were used to derive frequency-dependent site and S-to-coda transfer function corrections that transformed the path-corrected coda spectra to an absolute scale. The remaining events were used to validate

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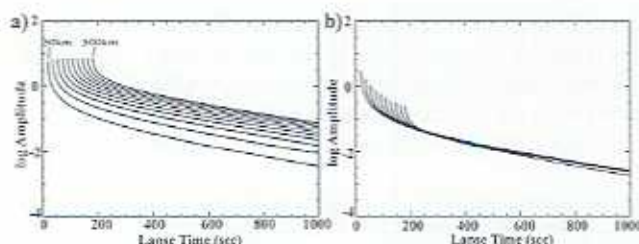


Figure 3. a) Synthetic envelopes at 0.1–0.2 Hz at equal intervals ranging between 50 and 500 km using the coda shape and velocity values listed in Table 1 and a source of unity. Notice that the envelope levels are not the same due to changes in the coda shape parameters as a function of distance; b) Same as (a) but after distance corrections were applied. Notice that the calibrated synthetics have the same behavior as the observed data in Figure 2.

narrowband envelope in our dataset, 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 non-dimensional raw coda amplitude. Next, we use the following empirical equation for coda path correction of *Mayeda et al.* [2003],

$$P(r, f) = [1 + (r/p_2)^{p_1}]^{-1} \quad (2)$$

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 (see Table 1). With path parameters determined, we can transform the synthetics in Figure 3a to path-corrected envelopes that also account for the distant-dependent bias. The resultant calibrated synthetics exhibit similar coda envelope levels irrespective of distance (e.g., Figure 3b), in good agreement with the example data shown in Figure 2. After applying the distance corrections to all the raw coda amplitudes we checked the consistency of distance-corrected coda amplitude measurements for common events observed at a station pair. In general, the interstation standard deviation ranged between 0.07 and 0.15 (e.g., Figure 4b) whereas the scatter for distance-corrected L_g and surface waves resulted in an interstation scatter of 0.27–0.45, roughly a factor of 3-to-4 larger (e.g., Figure 4a). These results confirm our initial hypothesis that the coda can effectively average over the effects of both source and path heterogeneity.

4. Results

[8] Although the coda amplitudes are corrected for frequency-dependent path effects, they still carry the S -to-coda transfer function as well as site effects and must be removed in order to obtain a moment-rate spectrum that has absolute units (e.g., dyne-cm). We used the moment calibration and empirical Green's function procedure outlined by *Mayeda et al.* [2003], which uses a handful of independently derived seismic moments to tie the low frequency

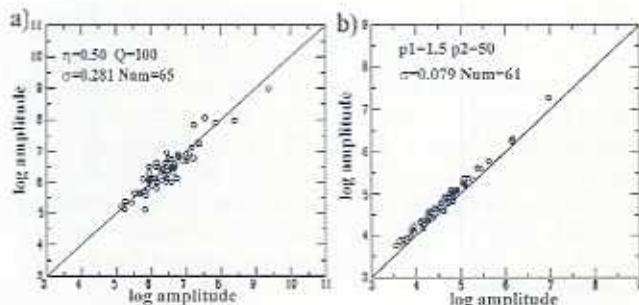


Figure 4. a) Distance-corrected direct waves for common events at station ISKB and ISP for the 0.1–0.2 Hz band using the formulation of *Street et al.* [1975] where critical distance is 100 km, $\eta = 0.5$ and $Q = 100$; b) Distance-corrected coda amplitudes for roughly the same events as in (a) where the standard deviation is a factor of 4 times smaller. The total number of events is denoted as Num and σ is the data standard deviation. Note that the small DC offset is a result of relative site effect between the two stations.

($f < \sim 0.7$ Hz) coda amplitudes to an absolute scale and smaller events as empirical Green's functions to derive corrections for the higher frequencies. In our case, we chose roughly 15 events that had independent moment estimates ranging between $3.9 < M_w < 6.5$ to derive the "site-transfer" corrections (i.e., combined site effect and S -to-coda transfer function corrections, see Table 1). Next, we applied the path and site-transfer corrections to all the raw coda amplitude data to form moment-rate spectra. Figure 5a demonstrates the consistency between the coda-derived source spectra for earthquakes recorded at the three stations.

[9] We validate our source calibration by comparing against independent seismic moment estimates of roughly 70 earthquakes ($\sim 4.0 < M_w < 7.4$) that generally sampled the entire country of Turkey (see Figure 1). In addition to seismic moment tensors performed in this study, we also took estimates from *Örgülü and Aktar* [2001] as well as those from the Harvard CMT catalog. For events recorded at multiple stations, their coda-based source spectra were

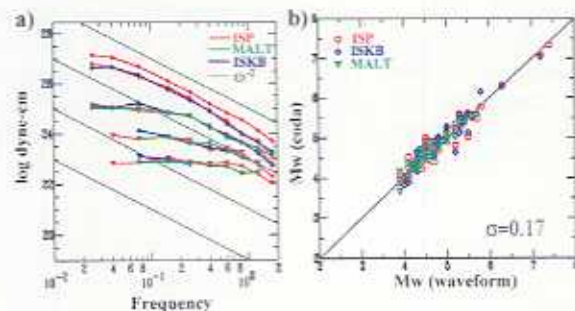


Figure 5. a) Examples of coda-derived source spectra computed at stations ISP, ISKB, and MALT. We note that for those events with multiple station recordings, their source spectra are quite similar between the stations; b) Single-station coda-derived moment magnitudes agree with the long-period waveform modeled estimates with a data standard deviation of 0.17.

Nuclear Explosions Monitoring Final Report

ROA No. or Contract No.: *DE-FC03-01SF22416/A000*

Research Title: *A Stable Regional Magnitude Methodology: Application to IMS Stations in the Eastern Mediterranean Region*

Name: Prof. Dr. Niyazi Türkelli

Institution: Bogazici University, Kandilli Observatory and Earthquake Research Institute (KOERI).

The main objective of the project is to calibrate IMS stations in the Eastern Mediterranean Region using coda envelope measurements to obtain a stable regional magnitude.

During the project, a recently developed magnitude methodology based on coda envelope amplitudes was applied to selected broadband stations in Turkey in order to test the coda method in a large and laterally complex region. Previous studies (e.g., Mayeda and Walter, 1996; Malagnini *et al.*, 2003; Morasca *et al.*, 2003; Mayeda *et al.*, 2003) which examined smaller and tectonically more stable regions has indicated that coda envelope amplitude measurements significantly showed 3 or 4 times less variation than the distance-corrected direct wave measurements (i.e., L_g and surface waves). Even though Turkey has a strong lateral crustal heterogeneity, we found that the region could be adequately modeled assuming a simple 1-D, radially symmetric path correction for 10 narrow frequency bands ranging between 0.02 to 2 Hz. We selected over 250 earthquakes recorded at three broadband stations, spanning a distance range roughly 30 to 1400 km that generally samples the entire country of Turkey (Figure 1). After the path corrections, we calibrated the stations, ISP, ISKB, and MALT for local and regional distances, using a handful of independently derived seismic moments to tie the low frequency ($f < 0.7$ Hz) coda amplitudes to an absolute scale and smaller events as empirical Green's functions to derive corrections for the higher frequencies. In this step, roughly 15 events that had independent moment estimates ranging between $3.9 < M_w < 6.5$ were chosen in order to derive the "site-transfer" corrections (i.e., combined site effect and S-to-coda transfer function corrections). Next, we applied our findings from the path and site-transfer corrections to all the raw coda amplitude data to form moment-rate spectra. Figure 2 presents a good example that shows the consistency between the coda-derived source spectra for earthquakes recorded at the three stations. The source calibration results were validated by comparing them against independent seismic moment estimates of roughly 70 earthquakes ($4.0 < M_w < 7.4$). In addition to seismic moment tensors performed in a part of the project, we also made use of the estimates from Örgülü and Aktar (2001) as well as those from the Harvard CMT catalog. For events recorded at multiple stations, their coda-based source spectra were almost identical, which confirms the path and site corrections used in the project. We used the low frequency levels of source spectra in determining the seismic moment values by averaging the measurements of the two lowest frequencies. The moment magnitudes, M_w (coda), were then estimated through the following equation,

$$M_w = 2/3 \log_{10}(M_0) - 10.73$$

(Hanks and Kanamori, 1979)

Figure 3 explains well that the single-station M_w (coda) estimates are in excellent agreement with M_w (waveform), with a data standard deviation of only 0.17 magnitude units. As a final validation, we have also computed M_w (coda) of several recent earthquakes (Figure 1) and the results agree very well with waveform-modeled results using the long-period waveform modeling approach of Dreger and Helmberger (1993).

In fact, our results at the end of the project are indicating a successful application of the empirical coda methodology to a broad and tectonically complex region such as Turkey. The followings are the main results:

- a) A radially symmetric attenuation model is consistent with the region for the frequencies between 0.02 to 2.0-Hz despite the lateral tectonic complexity;
- b) Coda-derived moment magnitudes, M_w (coda) obtained from a only one station shows a good agreement with agrees with multi-station inversions for M_w ;
- c) Compared to the direct wave measurements, coda envelope amplitude measurements are distributed in less variation by roughly a factor 3-to-4;
- d) The current calibration parameters can be used in estimating M_w (coda) for events that are too small to be waveform modeled as well as events with poor station coverage.

Observations from the inter-station scatter of distance-corrected coda amplitudes varied from 0.07 to 0.15 in a frequency range between 0.02 and 2.0-Hz, in good agreement with results obtained from previous applications of the methodology to the western United States, Italian Alps, and Dead Sea Rift regions (*e.g.*, Mayeda and Walter, 1996; Malagnini *et al.*, 2003, Morasca *et al.*, 2003, Mayeda *et al.*, 2003). We obtained additional validation by computing source spectra of 4 recent large earthquakes such as the M_w (coda) 6.3 Pölümür earthquake on January 27, 2003; the M_w (coda) 5.7 Urla earthquake on April 10, 2003; the 6.4 Bingöl earthquake on May 1, 2003; and the M_w (coda) 4.7 Bandırma earthquake on June 9, 2003. In figure 4, coda-derived source spectra and moment magnitude, M_w (coda) for Pölümür earthquake is given. Our plan is to incorporate these calibrations into a newly developed SAC command that will automatically compute stable, single-station estimates of coda-derived source spectra, moment, and radiated energy for use by KOERI. In addition, it is possible to extend the calibration to other broadband stations in the region by simply deriving empirical site effect corrections for the new stations and using the path corrections and coda shape parameters from the current study.

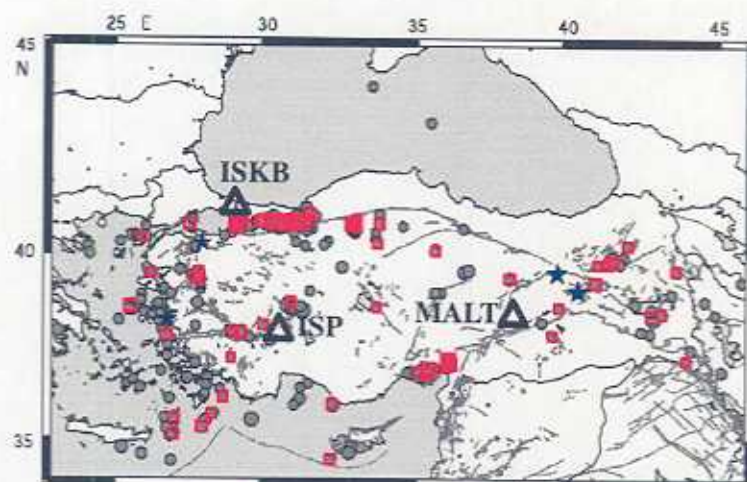


Figure 1. Map shows locations of the events and the stations used in this study. The earthquakes with gray circle were used in the coda calibration procedure. Red squares represent ground-truth earthquakes for which we have independent moment magnitudes. Blue stars show recent earthquakes used for further validation of the method.

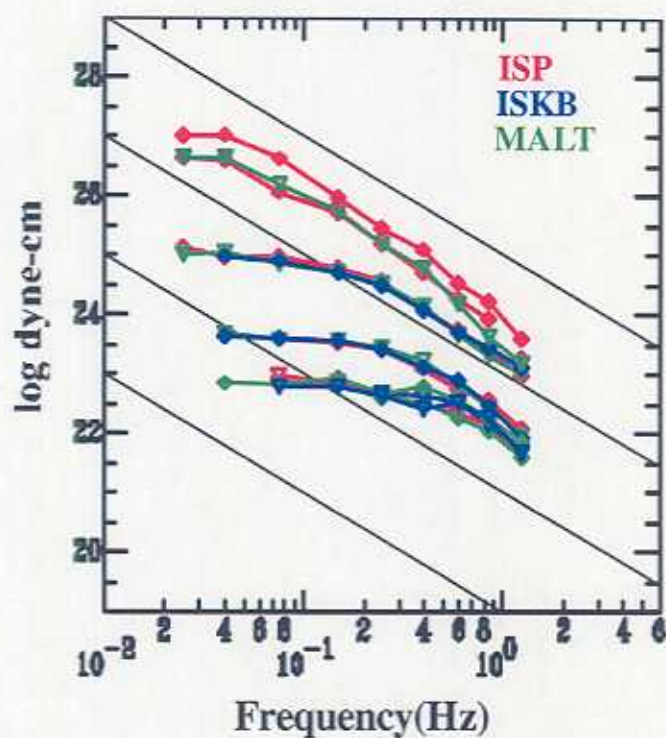


Figure 2. Coda-derived source spectra obtained at stations ISP, ISKB, and MALT. Note that the source spectra of those events recorded at three stations are virtually similar.

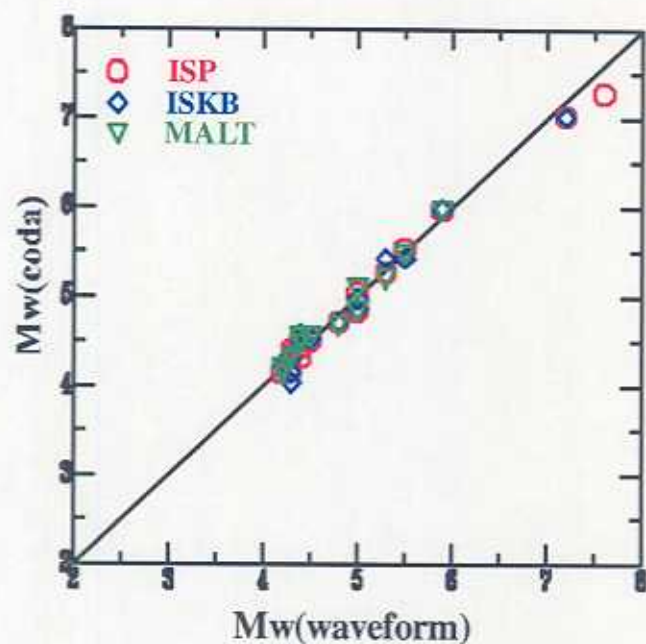


Figure 3. Single-station coda-derived moment magnitudes agree with the long-period waveform modeled estimates with a data standard deviation of 0.17.

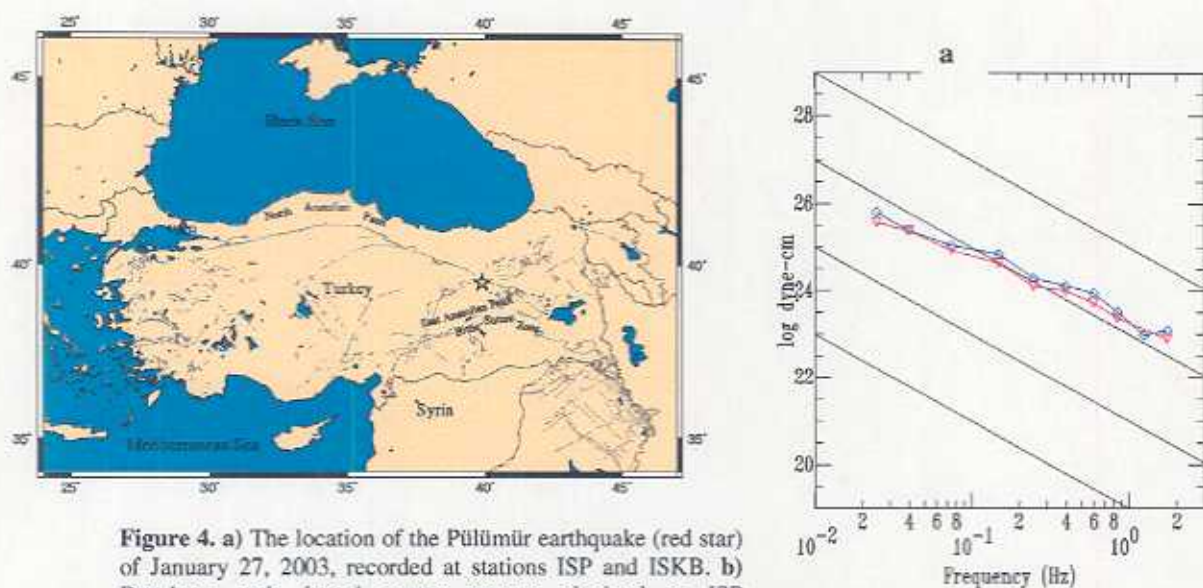


Figure 4. a) The location of the Pölümür earthquake (red star) of January 27, 2003, recorded at stations ISP and ISKB. b) Resultant coda based source spectra obtained at ISP (diamonds) and ISKB (triangles). Similarity between spectra at different stations is important in terms of showing the stability of coda methodology.

Activities conducted during the project:

A workshop was held in Rome, Italy between December 3, 2001 and December 6, 2001. Dr. Niyazi Turkelli and Tuna Eken from KOERI, Dr. Kevin Mayeda from LLNL and Dr. Abraham Hofstetter from GII (Israel) attended to the workshop.

Tuna Eken from KOERI went to Tel Aviv (Israel) to work with one of the our ROA collaborator (Dr. Abraham Hofstetter, Geophysical Institute of Israel - GII) for the period January 21 – February 6, 2002. Dr. Hofstetter and Tuna Eken examined the ISP and MALT broadband waveform data and they continued compilation of the catalogues.

The codes were implemented and tested to the workstation at KOERI during our ROA collaborators' s visit to Istanbul on May 2002, to several data of selected station pairs.

Dr. Kevin Mayeda one of the our ROA collaborator from LLNL invited Tuna Eken from KOERI to the U.S.A. to work with him. Tuna Eken learned how to use codes and complete whole process of the methodology between the dates August 17th 2002 and September 20th.

At the end of this collaboration, Dr. Kevin Mayeda and Tuna Eken also presented the findings of their work through a poster at the September SRR meeting in Florida, in 2002.

Dr. Gonca Orgulu from KOERI visited the LLNL from February 19, 2003 to March 31, 2003 in order to study on moment magnitude estimations of the earthquakes showing a broader epicentral distribution over Turkey.

Prof. Turkelli and Eken from KOERI with the ROA collaborators Dr. Mayeda from LLNL and Dr. Hofstetter from GII participated in the EGS-AGU-EUG Joint Assembly in Nice between the dates 6-11 April 2003 and presented a talk entitled "*An Application of the Coda Methodology for Moment-Rate Spectra Using Turkish Broad Band Stations*".

Final results of the project were presented during the SRR meeting in Tucson, Arizona in 2003.

Tuna Eken has completed and defended his master thesis successfully, entitled "*An application of the coda methodology for moment-rate spectra using broadband stations in Turkey*" in KOERI in June 2004.

A paper entitled "*An application of the coda methodology for moment-rate spectra using broadband stations in Turkey*" was published in the Geophysical Research Letters, vol.31, L11609, doi:10.1029/2004GL019627, 2004.