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MOMENT MAGNITUDE CALIBRATION FOR THE EASTERN MEDITERRANEAN REGION FROM BROADBAND REGIONAL CODA ENVELOPES

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ABSTRACT

The following is an overview of results from ROA01-32 that focuses on an empirical method of calibrating stable seismic source moment-rate spectra derived from regional coda envelopes using broadband stations. The main goal was to develop a regional magnitude methodology that had 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 yield source spectra and derived magnitudes that were more stable than any other direct-phase measure to date. Our empirical procedure accounted for all propagation, site, and S-to-coda transfer function effects. The resultant coda-derived moment-rate spectra were used to provide 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 validated our results by comparing our coda-derived moment estimates with those obtained from long-period waveform modeling. We first tested and validated the method using events distributed along the Dead Sea Rift (*e.g.*, Mayeda *et al.*, 2003). Next, we tested the transportability of the method to earthquakes distributed across the entire country of Turkey and validated our results using seismic moments of over 50 events that had been previously waveform modeled using the method of Dreger and Helmberger, (1993). In both regions we demonstrated that the interstation magnitude scatter was significantly reduced when using the coda-based magnitudes (*i.e.*, M_w(coda) and m_b(coda)). Once calibrated, the coda-derived source spectra provided stable, unbiased magnitude estimates for events that were too small either to be reliably waveform modeled or to be seen at far-regional and teleseismic distances. In general coda-derived magnitudes are roughly a factor of 3 to 5 more stable than traditional regional magnitudes that use the direct-phases such as P_g and L_g. This appears to be a universal observation for all regions where the coda methodology has been applied.

OBJECTIVE

In this paper we review a method of calibrating a stable regional magnitude based on coda envelopes using a combination of International Monitoring System (IMS) and non-IMS seismic stations. The main goal was to develop a methodology for a universal regional magnitude that had 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 teleseismic catalog; 3) it is applicable to much smaller regional 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.

In order to demonstrate and test the usefulness of our method, we chose the Eastern Mediterranean region as our study area. Our paper, keeping in mind the above mentioned properties, has three main elements:

1) to prepare, outline and test our magnitude calibration procedure using a sub-region of the Eastern Mediterranean, specifically along the Dead Sea rift, as well as a portion of Eastern Turkey, using a variety of source types;
2) to extend and regionalize the procedure to IMS stations (*e.g.*, EIL, MRNI, KEG, GNI, KIV) throughout the broader, more complex regions of the Eastern Mediterranean using IMS and non-IMS data (*e.g.*, ISP, MALT, ISKB) for calibration;
3) to make the procedure and the code accessible for magnitude calibration of stations in any region.

For sparse local and regional seismic networks a stable magnitude is of utmost importance for establishing accurate seismicity catalogs and assessing seismic hazard potential. In the context of underground nuclear explosion monitoring, we need accurate magnitudes for construction of detection threshold curves, formation of discriminants and yield estimation. Unlike magnitudes such as M_L and m_b which are relative, narrowband measurements that often have regional biases, our approach can provide stable, absolute source spectra that are corrected for S-to-coda (or P-to-coda) transfer function, scattering, inelastic attenuation and site effects. In the small regions where this has been previously applied, we found that coda envelope amplitude measurements were not very sensitive to 3-D path heterogeneity and source radiation pattern. The resultant spectra were used to calculate stable moment estimates (and hence M_w), traditional short-period magnitudes (*i.e.*, m_b, M_L) and radiated seismic energy, E_R.

This research increases the IMS ability to compute stable magnitudes for small-to-moderate sized regional events using a sparse network and, consequently, contributes considerably to the improvement of seismic verification in the Eastern Mediterranean region. The resulting calibration methodology and software can be transferred to other observatories and groups of researchers to enhance the ability to monitor compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT). This research was funded under ROA01-01 Topical Area 1.3 and 1.4 and is distinct from the DOE Base Program in a number of ways: 1) we are compiling non-IMS broadband waveforms to help calibrate IMS stations for regional magnitude from "in-country" networks which may otherwise be difficult to obtain; 2) we are testing the methodology over a much larger, more complex region using P and S coda envelopes; 3) we are studying a variety of seismic source types and depths to better understand the methods performance. The need for non-IMS stations is simple. There are significant trade-offs if we were to solely use IMS stations for the magnitude calibration. For example, non-IMS stations are more numerous, better distributed, and have closer-in data that can be used for independent moment estimation, determination of coda shape factors, velocity and attenuation. Furthermore, these non-IMS stations are likely to have been operational for a larger period of time and therefore have an archive of waveform recordings, whereas many of the IMS stations are relatively new (or currently non-existent). All three institutions bring regional seismological expertise to the project as well as waveform data that would otherwise be difficult to obtain.

RESEARCH ACCOMPLISHED

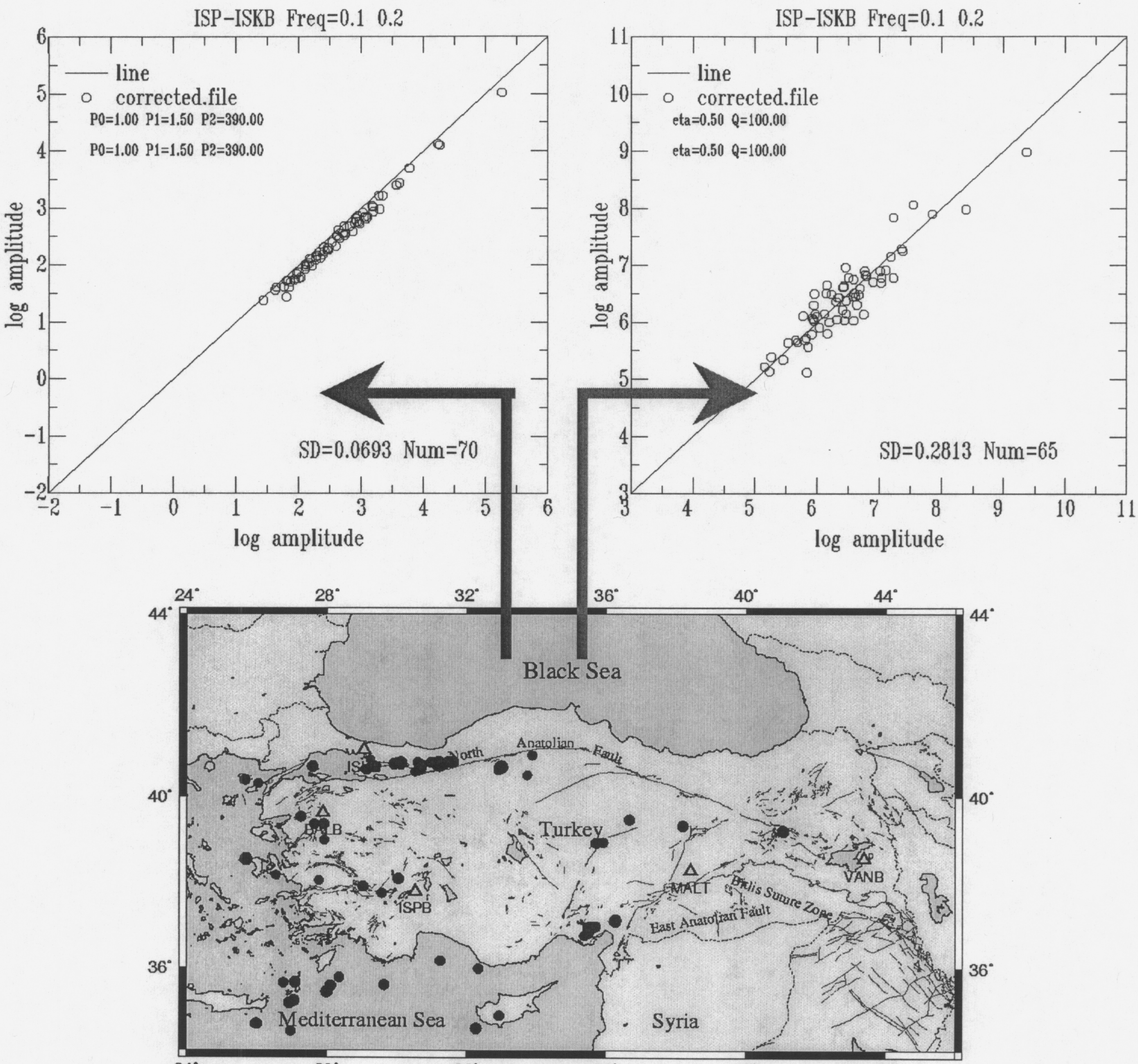
Dead Sea Rift Pilot Study:

In Mayeda *et al.* (2003) we described an empirical calibration method for obtaining stable seismic source moment-rate spectra derived from local and regional coda envelopes using broadband stations. This study was meant to be a pilot study to test the method in a small region using data essentially distributed along the strike of the Dead Sea fault. The results of applying this method provided source spectra that were more stable than any other direct-phase measure to date. The procedure accounted for all propagation, site, and S-to-coda transfer function effects. The resultant coda-derived moment-rate spectra were then used to provide traditional band-limited magnitudes (*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 validated our results by comparing our coda-derived moment estimates with those obtained from long-period waveform modeling. Most importantly, we demonstrated that the interstation magnitude scatter was significantly reduced when using long-window-length coda (*i.e.*, M_w(coda) and m_b(coda)). However, when we used short-window coda measurements of 5 seconds in length taken after twice the direct wave travel time, the scatter remained large, comparable to direct waves. Once calibrated, the coda-derived source spectra provided stable, unbiased magnitude estimates for events that were too small either to be reliably waveform modeled or to be seen at far-regional and teleseismic distances. This property makes it ideal for sparse local or regional networks. 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 interstation 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 interstation scatter for common events, reached a minimum value beyond a certain critical measurement window length. For example, at 6-8 Hz, the interstation standard deviation was less than 0.08 provided the coda measurement window was at least ~70 seconds in duration, whereas at 1.5-2.0 Hz the critical window length was ~90 seconds. For all frequency bands, as the coda window becomes shorter the standard deviation increases, asymptotically approaching the direct wave scatter. We defer the details of the calibration procedure to the paper of Mayeda *et al.* (2003) that describes in detail the methodology and addresses concerns related to choosing optimal measurement window lengths, estimating error, testing empirical path corrections, and tying coda amplitudes to an absolute scale.

Broad Area Calibration of Turkey:

To test the transportability of the coda method to a broader and more heterogeneous region we focused our attention to the country of Turkey. As of this writing we have successfully transported the coda methodology to broadband data distributed over the entire region of Turkey using only three broadband stations and roughly 50 earthquakes ranging between $4.0< M_w <7.6$ (see Figure 1). After determining and applying distance corrections to the raw coda amplitudes for the frequencies 0.02 and 2.0 Hz, we looked at the consistency of the common events at stations ISP and ISKB for distance-corrected coda amplitude measurements. The interstation standard deviation of our distance-corrected coda amplitudes ranged between 0.07 and 0.2 (*e.g.*, see Figure 1). In addition to correcting coda amplitudes for distance, we also applied a grid search technique, which minimized the interstation scatter to the direct L_g waves in order to solve for the attenuation and geometrical spreading using the formulation of Street *et al.* (1975). We observed that the direct waves amplitudes showed scatter in the range of 0.27-0.45 for the same events. This proved that the interstation scatter results of distance-corrected coda amplitudes were remarkably 3-to-4 times lower than those obtained from distance-corrected direct wave amplitudes. Similarly, we observed that coda-based amplitudes between stations ISP and MALT had similar reduction in scatter when compared against direct waves. After all parameters were determined (*i.e.*, velocities, coda shape factors, and path corrections) we generated synthetic envelopes for a hypothetical source for a wide distance range. Considering the previous studies on coda waves (*e.g.*, Mayeda and Walter, 1996), the generation of the calibrated synthetics envelopes in this methodology represents a major change since they are purely empirical and do not depend on any assumption about the scattering mechanism and attenuation.

For the calibration of ISP-ISKB, we used independently derived seismic moment solutions of 39 earthquakes in the ISP-ISKB dataset to transform the coda amplitudes to absolute source spectra in dyne-cm. Seismic moment solutions were taken from Örgülü and Aktar (2001) as well as from the Harvard CMT catalog. The magnitudes of these events ranged between M_w 4.0 and 7.6. These new coda-based source spectra obtained at two stations, ISP and ISKB showed a consistent behavior for almost for all events (Figure 2). Coda-derived seismic moment values were determined by averaging the coda amplitudes for the two lowest frequencies. Coda-derived moment magnitudes, M_w(coda), were estimated from the equation developed by Kanamori and Hanks (1979), $M_w = 2/3\log_{10}(M_o) - 10.7$. The comparison made between M_w(coda) and waveform modeled moment magnitudes, M_W(waveform), showed excellent correspondence with a standard deviation of 0.2, comparable to results from the Dead Sea rift region (*e.g.*, Mayeda et al., 2003) and the western United States (*e.g.*, Mayeda and Walter, 1996). Figure 3 shows examples coda-derived source spectra observed at ISP and ISKB and the relation between our M_w(coda) and M_w(waveform). Likewise, we calibrated the ISP-MALT station pair by using independently derived moment estimates of 49 earthquakes in the ISP-MALT data-set. Compared to 39 earthquakes used for the calibration of ISP-ISKB station pair, these 49 earthquakes nearly sampled the entire region of Turkey. The magnitudes of these 49 earthquakes ranged between M_W 4.0 and 6.3. Following the same



Events distribution between 0.1_0.2 Hz.

Figure 1. Comparison of distance-corrected coda amplitudes at 0.1-0.2 Hz with the amplitudes of direct L_g arrival for ISP-ISKB. Inter-station standard deviation results show that coda amplitudes at this frequency band are 4 times more stable than distance corrected direct waves for the common events whose locations are shown on the map.

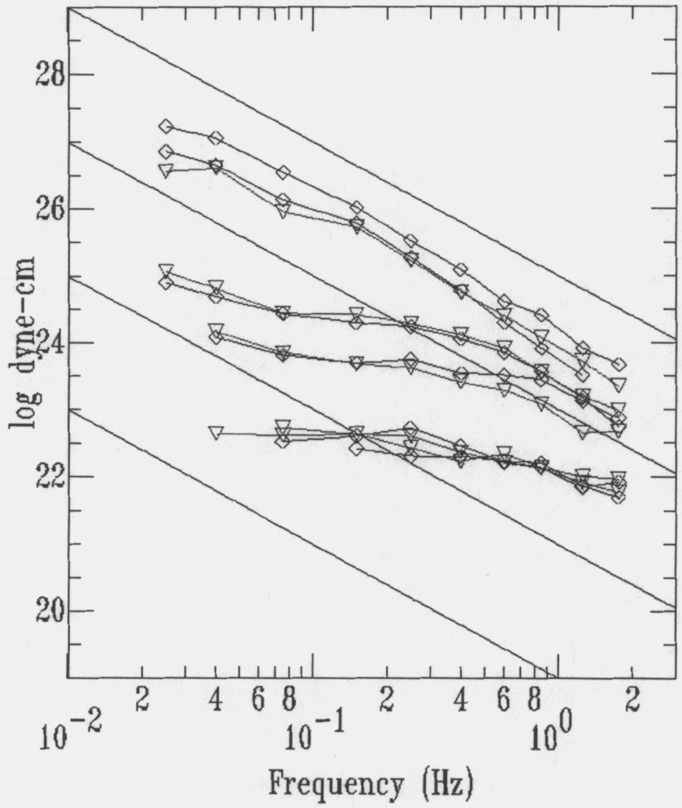


Figure 2. Example source spectra of common events from ISP (diamonds) and ISKB (triangles). Note that source spectra of each event are quite similar between the stations.

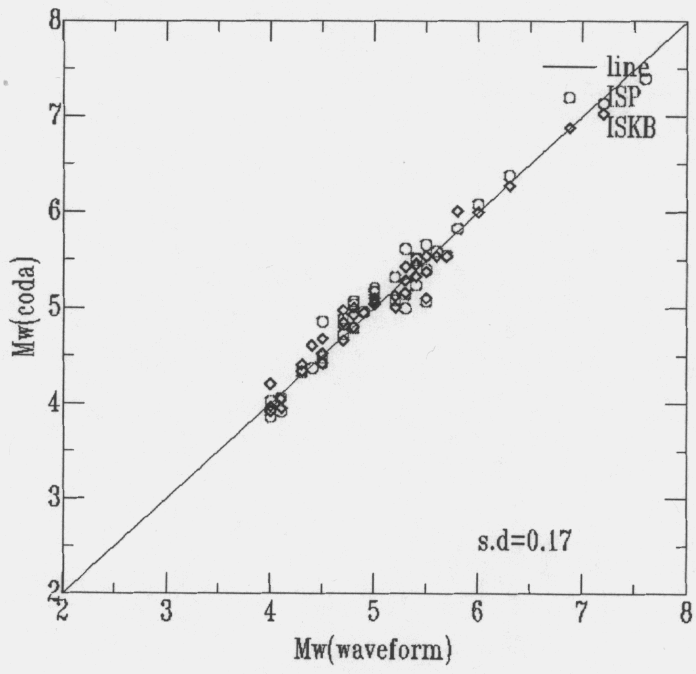


Figure 3. Comparison of M_W(coda) of 39 events estimated at stations ISP (circles) and ISKB (diamonds) with those obtained from long-period waveform modeling. There is a good correspondence with a standard deviation of 0.17 between two types of moment magnitude.

technique, we found the frequency dependent moment-rate constants for ISP-MALT station pair. After we applied these moment-rate constants to uncorrected coda amplitudes at each frequency, we observed that resultant coda-based moment rate spectra generated at each station for a given event showed good agreement. These source spectra, again, were then used to calculate M_w(coda) of the events for entire data set. Similar to the results from ISP-ISKB dataset, M_w(coda) estimated from the long-period levels of coda-derived source spectra indicated a consistent relation with independently derived M_w(waveform). Applying moment rate constants, we have computed coda-derived source spectra and then obtained M_w(coda) of some recent earthquakes, which we have not used during the calibration process without any knowledge of independently derived seismic moment, and moment magnitude. Some of major earthquakes that have been recently studied are the Pülümür earthquake of January 27 with M_w(coda)~6.3, the Urla earthquake of April 14, 2003 with M_w(coda)~5.7, the Bingol earthquake of May 1, 2003 with M_w(coda)=6.4, and the Bandirma earthquake of June 9, 2003 with M_w(coda)=4.7. Our estimates again showed that the M_w(coda)'s found for these earthquakes were very consistent with moment magnitude estimates derived from long period waveform modeling.

CONCLUSIONS AND RECOMMENDATIONS

This paper reviews progress-to-date on ROA01-32 that focused on an empirical methodology to transform non-dimensional coda amplitudes into stable moment-rate spectra. The initial pilot study in the Dead Sea rift (Mayeda *et al.*, 2003) showed unequivocally that the coda methodology provides the most stable estimates of the source spectra of any local or regional method to date. Once calibrated, the coda-derived spectra 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 interstation scatter when compared against conventional direct-phase measurements (*e.g.*, P_g, L_g) as well as coda duration. The typical interstation scatter ranged between 0.07 to 0.1 for the coda measurements for frequencies between 0.02 and 8.0 Hz. This means that a single coda amplitude measurement is equivalent to a 9- to 25-station network average of direct wave amplitudes. Results of our calibration procedure can be used as ASCII input into the latest version of SAC (Goldstein *et al.*, 2002), which has a new command to produce coda-derived source spectra, energy, and moment.

In this study, an empirical regional calibration methodology was applied to two different datasets in Turkey consisting of earthquakes that occurred in a tectonically complex region with dominant lateral heterogeneities. During the calibration process two different datasets were compiled from three Turkish broadband stations (ISP, ISKB, and MALT) to obtain stable moment magnitude estimates. The events in the first dataset (ISP-ISKB) are distributed mostly over the western Anatolia region while the second dataset (ISP-MALT) samples the entire country. For both datasets, in a frequency range between 0.02 and 1.0 Hz, the interstation scatter of distance corrected-coda amplitudes varies from 0.07 to 0.15, in good agreement with results obtained from previous applications of the methodology to the western United States and Dead Sea Rift regions (*e.g.*, Mayeda and Walter, 1996; Mayeda *et al.*, 2003). This result is very encouraging because it demonstrates that the method can also be applied over larger and complex regions ranging between local and far-regional distances. As found in other regions, comparison to the direct waves (*i.e.*, L_g , P_g, and surface waves), shows that the interstation scatter for the coda is a factor of 3-to-4 smaller. For this region, this appears to be a robust methodology for frequencies at least up to 1 Hz because the coda waves provide roughly 3-to-4 times more stable amplitude measurements relative to the direct waves. In other words, a single coda measurement is approximately equivalent to a 9-to-16 station network average using direct waves. Observational results with regard to the standard deviation between distance-corrected coda amplitude measurements at different pairs of stations also showed that even a single, frequency dependent coda attenuation function was enough to explain the coda envelope amplitude over the entire country. After correcting our coda amplitudes for propagation effects, we tied our non-dimensional measurements to an absolute scale using independently derived moments. In other words, we transformed distance corrected coda amplitudes into a source spectra by making frequency dependent corrections for both the site and *S*-to-coda transfer function effects. The validation of this empirical approach is proven by observing identical spectra for the same event at two stations separated by roughly 500 km. The stable source spectra also confirm that the coda is averaging over any source radiation pattern as well as any lateral crustal heterogeneity. As a final validation, these selected source spectra were used to estimate coda-derived moment magnitudes, M_W(coda). Upon comparing our M_W(coda)'s with those from long-period waveform modeling, M_W(waveform), we observed a standard deviation of 0.17 for ISP-ISKB and 0.14 for ISP-MALT. These observations prove the stability of coda waves at regional distances and furthermore can be used for small events that cannot be reliably waveform modeled due to poor signal to noise ratio for long period surface waves.

In conclusion, we transported a newly developed regional magnitude methodology based on coda envelopes to estimate stable source spectra and hence moment magnitudes for earthquakes in Turkey. We calibrated the broadband stations ISKB, ISP and MALT and our results strongly suggest that they can be used to estimate M_W(coda) for waveforms that are clipped and/or too small to be waveform modeled. With the use of the calibration results, we successfully estimated M_W(coda)'s of three recent earthquakes, the January 27, 2003, Pülümür, the April 4, 2003, Urla, the May, 1, 2003, Bingöl, and the June 9 Bandirma, that occurred in Turkey. We also proved that; a) the application of the methodology is successful in a tectonically complex and laterally heterogeneous region, b) it is convenient for a sparse local and regional seismic networks, c) the magnitude estimation is unbiased, c) it is transportable and universal, d) it does not saturate, e) it is insensitive to source radiation pattern. With the use of calibration results, we are now able to estimate M_W(coda) for events that are too small to be reliably waveform modeled.

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REFERENCES

Aki, K. (1969). Analysis of seismic coda of local earthquakes as scattered waves, *J. Geophys. Res.*, 74, 615-631.

Biswas, N. N. and K. Aki (1984). Characteristics of coda waves: Central and south central Alaska, *Bull. Seism. Soc. Am.*, 74, 493-507.

Dewey, J. F. and A.M.C. Sengör (1979). Aegean and surroundings regions: Complex multiplate and continuum tectonics in a convergent zone, *Geolog. Soc. Amer. Bull.*, 90, 84-92.

Dewey, J.F., M.R. Hempton, W.S.F. Kidd, F. Saroslu and A.M.C. Sengör (1986). Shortening of continental lithosphere: the neotectonics of Eastern Anatolia-a young collision zone, in *Collision Tectonics,* edited by M. P. Coward, and A.C. Ries, pp. 3-36, Geol. Soc. London, London.

Goldstein, P., D. Dodge and M. Firpo (2001). SAC2000: Signal processing and analysis tools for seismologists and engineers, UCRL-JC-135963, Invited contribution to the IASPEI, International Handbook of Earthquake and Engineering Seismology, Academic Press, London, U.K.

Mayeda, K. (1993). m_b(Lg Coda): A stable single station estimator of magnitude, *Bull. Seism. Soc. Am.*, 83, 851-861.

Mayeda, K. and W. R. Walter (1996). Moment, energy, stress drop, and Source spectra of western United States earthquakes from regional coda envelopes, *J. Geophys. Res.*, 101, 11195-11208.

Mayeda, K., A. Hofstetter, J. O'Boyle and W. R. Walter (2003). Stable and Transportable Regional Magnitudes Based on Coda-Derived Moment-Rate Spectra, *Bull. Seism. Soc. Am.*, 93, 224-239.

McKenzie, D. P. (1972). Active tectonics of the Mediterranean region, *Geophy. J. Roy. Astr. Soc.*, 30, 109-185.

McKenzie, D. P. (1978). Active tectonics of the Alpine-Himalayan Belt: The Aegean Sea and surrounding regions, *Geophy. J. Roy. Astr. Soc.*, 55, 217-254.

Örgülü, G. and M. Aktar (2001). Regional Moment Tensor Inversion for Strong Aftershocks of the August 17, 1999 Izmit Earthquake (M_W-7.4), 28, 371-374.

Reilinger, R.E., S.C. McClusky, M.B. Oral, R.W. King, M.N. Toksöz, A.A. Barka, I. Kinik, O. Lenk and I. Sanlı (1997). Global positioning system measurement at present-day crustal movements in the Arabia-Africa-Eurasia plate collision zone, *J. Geophys. Res.*, 94, 9983-9999.

Sengör, A.M.C. (1979). Northern Anatolian fault: Its age offset and tectonic significance, *J. Geol. Soc. London*, 136, 269-282.

Street, R. L., R. Herrmann and O. Nuttli (1975). Spectral characteristics of the Lg wave generated by central United States earthquakes, *Geophys. J. R. Astron. Soc.*, 41, 51-63.

Taymaz, T., J. Jackson and D. McKenzie (1991). Active tectonics of the north and central Aegean Sea, *Geophy. J. Int.*, 106, 433-490.