TRANSITIONING THE CODA METHODOLOGY TO FULL 2-D FOR *P* AND *S* CODAS

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ABSTRACT

Over the past decade, we have developed and implemented an empirically-based regional shear wave coda methodology that provides unprecedented amplitude stability for events at local and regional distances. In regions of interest, small-scale 1-D coda calibrations have proven sufficient and result in very low variance estimates. For the broader, increasingly complex regions, it is unfeasible to perform a patch-work of small-scale 1-D calibrations due to lack of stations and events. As a first attempt at the problem, we have embarked upon 2-D path (Q) corrections. However, this has proven insufficient and it is clear that 2-D variations in the *other* coda calibration parameters are significant and their inclusion in the coda method is necessary to significantly reduce variance in broad-area coda calibrations. Specifically, lateral variations in coda shape (envelope decay), peak velocity, including coda type, and site-transfer corrections must be accounted for. Our objective is to improve the regional methodology for both *P*-coda and *S*-coda by upgrading models and transitioning to full 2-D. For example, the parameterization of the synthetic coda envelope shapes has been based on a simplistic single-scattering formulation for a homogeneous full-space. We plan to test formulations that better predict the effects of multiple scattering as well as develop 2-D empirical models. Increasingly, monitoring needs require both local and broad-area regional to far-regional calibration, usually in complex regions where we observe frequency-dependent phase blockage. For example, regions of the Middle East and Central Asia, including the Iranian plateau, present strong 2-D variations in attenuation and phase blockage effects, and we must adjust to the dominant coda type on the fly. The recent North Korean nuclear test illustrates that even a seemingly simple geological region requires 2-D corrections for L_g-coda. The highest valuable deliverable from this project will be a general 2-D coda methodology that significantly reduces amplitude variance in complex tectonic regions for both *P*-coda and *S*-coda.

OBJECTIVES

The regional shear-wave coda methodology has evolved over time; originally inspired by Aki's (1969) local single-scattering model, the method has undergone some recent modification, but is mostly used under the assumption of 1-D, radial symmetry centered on each station. The methodology has had great success at local and near-regional distances for simple regions, based on crustal *S* and L_g coda types, and at longer distances for small source regions such as test sites and aftershock zones, using codas associated with *P*, S_n or L_g, depending on the dominant coda type for each individual path. Despite recent successes with small-scale 1-D coda calibrations, there are a number of reasons to make significant enhancements to the coda methodology to encompass laterally complex regions. This project is timely because 1-D coda techniques have been implemented in a number of small regions of interest, however there is a need to extend to the broader regions, which have larger lateral complexity. Regions that have been calibrated under the 1-D assumption (Mayeda et al., 2003) have either been small and/or uniformly complicated (e.g., Yellow Sea/Korean Peninsula (YSKP), Bhuj aftershock zone, India, Persian Gulf, eastern Mediterranean, Italian Alps, California Coast ranges) or broad regions that are more or less uniform (e.g., European Arctic, Anatolian plateau, South African craton).

In each of the above-mentioned cases, we recognize that performance was limited mostly by oversimplified parameterization and that better results could have been obtained. For example in the YSKP region, calibration to the east of the peninsula requires completely different velocity, coda shape, and attenuation corrections because the path is dominated by oceanic S_n propagation, whereas the YSKP is comprised of L_g continental propagation. In fact, the recent North Korean tests illustrate this point as we found partial blockage for paths towards the south because of short (but significant) propagation through the oceanic crust that reduced broadband amplitudes by nearly a factor of two-to-three on the L_g coda (SRP presentation by K. Mayeda, March 2007). This effect was critical for yield estimation work and will be equally critical in other areas of low crustal *Q* and L_g blockage, such as the Iranian plateau. For example, the Anatolian plateau is geophysically complicated, but for lower frequencies, between 0.05 and ~1 Hz, the whole region can be treated as if it were homogeneous (e.g., Eken et al., 2004). However for the higher frequencies, 2-D corrections are required for path corrections, envelope shapes (due to varying S_n and L_g levels, and subsequent coda, and peak envelope velocity.

It has been suggested by the authors that the coda is insensitive to the source radiation pattern, while others suggest the inclusion of this term in any coda formulation. The following example would argue for the former, namely that the coda is insensitive to the source radiation pattern. We illustrate the stability of the coda using the recent 2008 Wells, Nevada sequence. Figure 1 shows amplitude ratios between the mainshock and an aftershock at 3.5-Hz for direct Lg and coda as recorded by US Array stations at roughly 200 km distance. For the coda source ratios, we see almost no variation in sharp contrast with direct Lg.

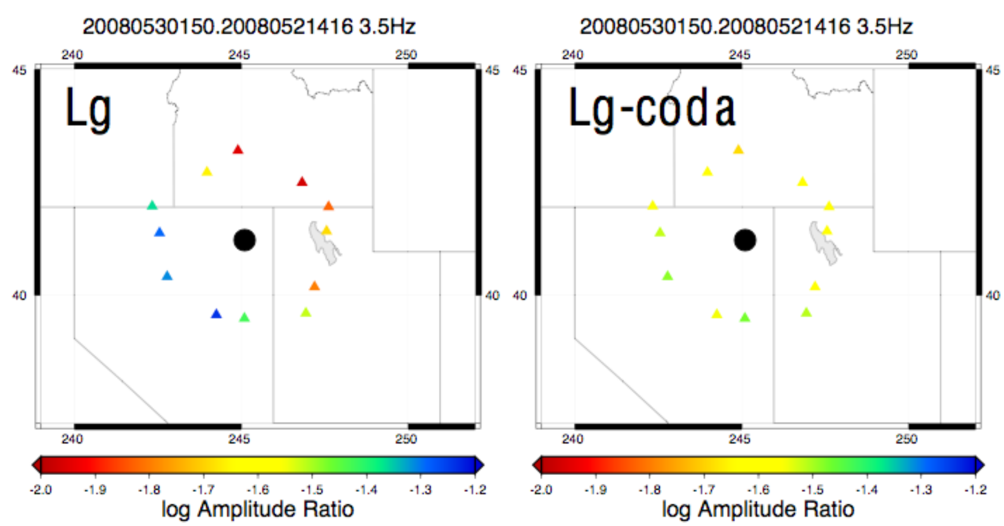

Figure 1. Coda amplitude ratios between the Wells, Nevada mainshock and an aftershock at 3.5-Hz are shown for 12 U.S. Array stations at roughly 200 km distance. The point of this figure is to show the large variation for direct Lg on the left due to differences in source radiation, versus the minimal variation in source ratio for the Lg-coda on the right.

More recently, Mayeda et al. (2005) compared 1-D versus 2-D path corrections on coda and direct S/L_g waves using moderate-sized earthquakes with long codas in the California Coast Ranges. The improvement found for 2-D path corrections for coda was roughly 30%. This was an average measure; the improvement was expected to be greater for the most anomalous regions, such as the high attenuation, seismically active area surrounding the Geysers, allowing more accurate recovery of source spectra for those regions. This situation is similar to the Korean peninsula, where we expect to see only modest improvement between 1-D and 2-D approaches on average, but dramatic improvement for critical paths through anomalous regions such as oceanic crust. Furthermore, the early coda showed significant variation from station-to-station in the California study. When event size decreases, we must rely on shorter length coda and therefore it is critical to know the early envelope shape. For example, we find that the early coda decay for event-station pairs that are confined to the Sierra batholith have lower decay rate than those that sample the Great Valley (Figure 2). However, in their 2005 study, Mayeda et al. assumed the ***same*** envelope shape and velocity for ***every*** station (1-D assumption), independent of azimuth or location. Therefore, the inclusion of ***both*** 2-D path ***and*** 2-D envelope shape, velocity, and site-transfer would have reduced the variance well below the previous 30%, which only included 2-D path corrections. We note however, that the purpose of that study was only to test the effects of 2-D path corrections, with everything else, such as velocity, envelope shape and transfer function being held to 1-D radially symmetric.

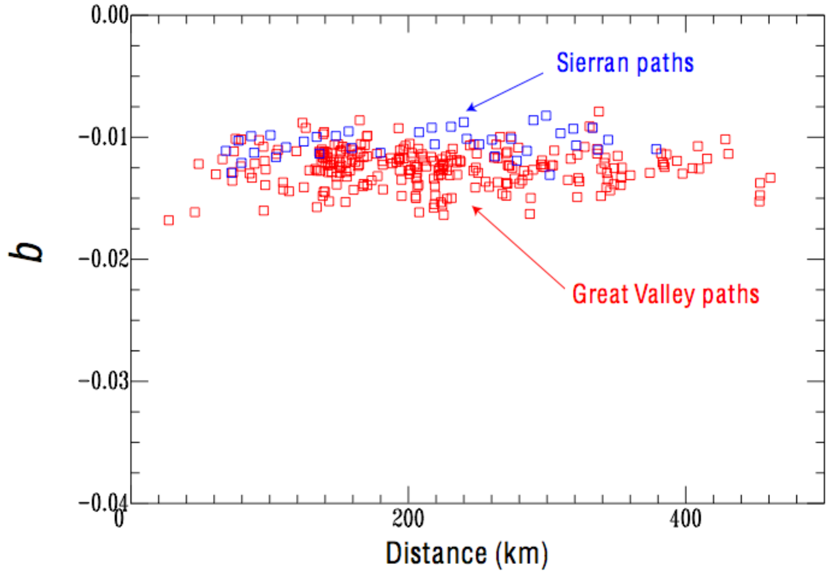

Figure 2. Coda shape parameter, *b*, taken for stations situated in the Sierra Nevada (CMB, ORV, KCC) for 1.5-2.0 Hz for events in northern California Coast Ranges. Event-station pairs that are confined to the Sierra Nevada batholith (blue) exhibit lower coda decay than event-station pairs that traverse the Great Valley (red). This clearly shows 2-D variations in coda envelope shape. See Equation 1.

Since the Mayeda et al. (2005) study assumed the same envelope shape function for all 16 broadband stations, the errors would certainly increase as the event size decreases (e.g., Figure 5) if regional variations in coda shape remain unaccounted for.

In addition, path lengths were on average, relatively short for the California Coast Range study. For the case of central Asia, the same 2-D path correction methodology results in much larger improvement, but again, this is for larger events with ample coda.

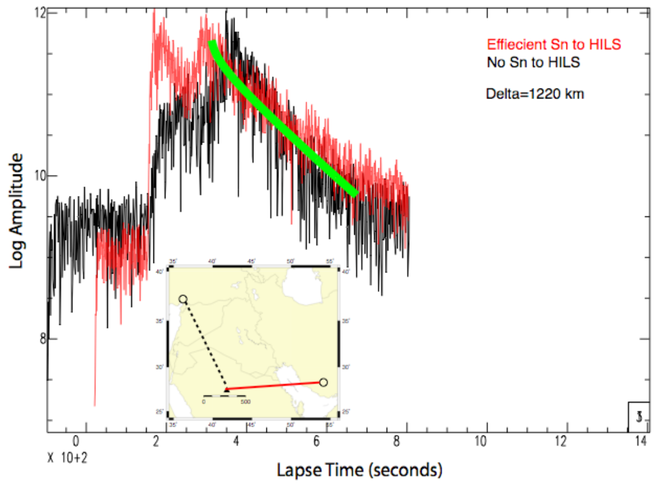

Figure 3. Middle East example of 2-3 Hz envelopes for two events recorded at station HILS on the Saudi Peninsula. The event from south-central Anatolian plateau has L_g coda whereas the event from southern Iranian plateau has S_n coda. A simple 1-D calibration for this region would introduce significant error because velocity, shape, and path effects are different.

With regard to Asia and the Middle East, we are also faced with mixing of phase types in addition to strong lateral changes in attenuation. We need to improve the coda method so that it is general enough to handle any region, including those that have lateral changes in phase type and/or blockage. This will require enhancing all aspects of coda calibration to full 2-D. Figure 3 illustrates such a case where we have two events recorded by station HILS located on the Saudi peninsula. For one event there is clear L_g and associated coda, whereas the path from the southern Iranian plateau has only S_n and its coda. This will require spatial and/or azimuthally varying parameters to account for this since a 1-D approach will introduce error. Even small error is intolerable as we are going to extra effort to calibrate coda in order to take advantage of the higher accuracy and precision relative to direct wave methods.

The motivation for making a change to the methodology is quite simple. First, regions of monitoring interest are generally tectonically complex and in fact, most appear to require 2-D corrections for velocity, path, and envelope function. Figure 4 shows a result of coda wave Q for central Asia (Q from amplitude decrease with distance, rather than temporal decay of coda) and illustrates the strong lateral changes that need to be accounted for. The partial blockage for paths from the Korean test can be seen in the Q map, although the smoothness enforced on this large-scale result decreases it's effectiveness for such short paths. We will test the application of similar, 2-D tomographic techniques on other coda parameters (i.e., peak velocity, envelope shape, and transfer function).

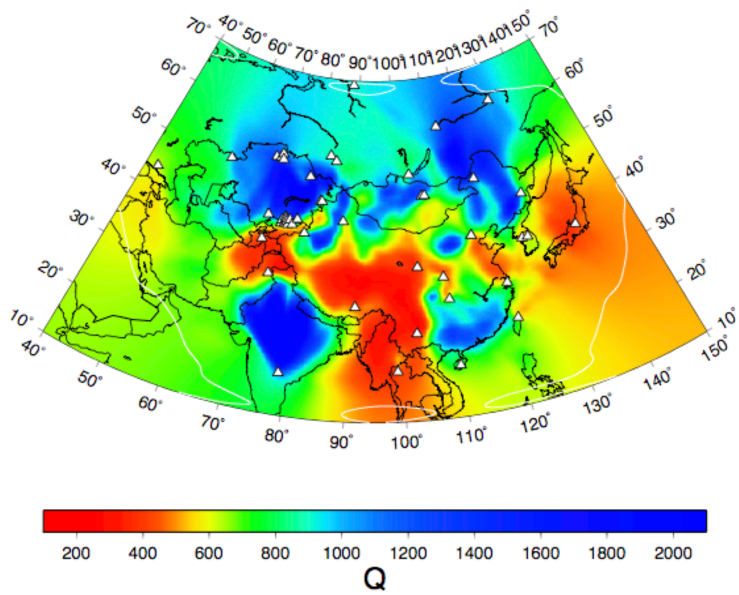

Figure 4. Coda wave apparent *Q* for central Asia for the 0.7-1.0 Hz band. This 2-D inversion was performed over a very broad region and emphasizes the need for 2-D path corrections. Stations are represented by triangles and a liberal model error (1/*Q*) indicating raypath coverage is represented by the white contour. *Q* becomes poorly resolved as the coverage contour is approached.

Second, regional seismic assets are usually sparse or on the periphery of the region-of-interest and amplitude stability as well as sufficient signal-to-noise ratio is always an issue, especially for smaller yield events. Because of this, more emphasis must be placed on the early coda, which historically has been avoided. The often used rule-of-thumb of measuring the coda after '*twice the S-wave travel-time*', is just that, a rule of thumb with empirical rather than theoretical basis. However, as Figure 5 shows, the early coda still provides more stable estimates than the direct wave and should be used to lower our measurement threshold.

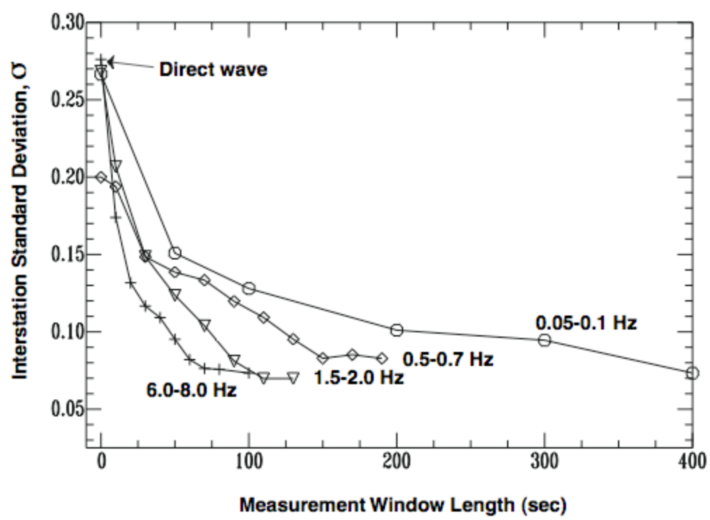

Figure 5. Interstation standard deviation, σ, is shown for a range of frequencies as a function of coda measurement window length using Gulf of Aqaba earthquakes. For longer periods, the critical window length, where reduction in scatter is minimal, becomes larger, ranging from about 80 seconds at 6.0–8.0 Hz to about 400 seconds for 0.05–0.1 Hz (from Mayeda et al., 2003). We will apply the same approach to local data in a variety of different tectonic settings to derive 'averaged' curves. We note that twice the *S*-wave travel time for this dataset is at ~150 seconds.

RESEARCH ACCOMPLISHED

As this award was funded in the spring of 2010, the authors have not started working on this project due to prior programmatic commitments. We instead, list out the proposal objectives that we plan to work on later in the Fall. The proposal objectives are straightforward and can be broken down into two parts. First, we will transition the 1-D coda methodology to a full 2-D capability including both P-coda and S-coda, with the ability to account for frequency-dependent phase blockage, as well as 2-D variations in peak envelope velocity and site-transfer corrections. Second, we will improve upon the way we make amplitude measurements and tie to an absolute scale. This will include improved synthetic envelope functions and fitting, which to date has been overly simplified using a model derived for a homogeneous full-space (i.e., the single-scattering model). For example, Figure 6 shows synthetic envelope fits using Equation 1 to observed data from the eastern Anatolian plateau. Note that the actual data has extra curvature starting at around ~120 seconds from the origin time which is not predicted in the model. The curvature could result from multiple scattering, or from increasing importance of mantle (S_n) coda with lapse time.

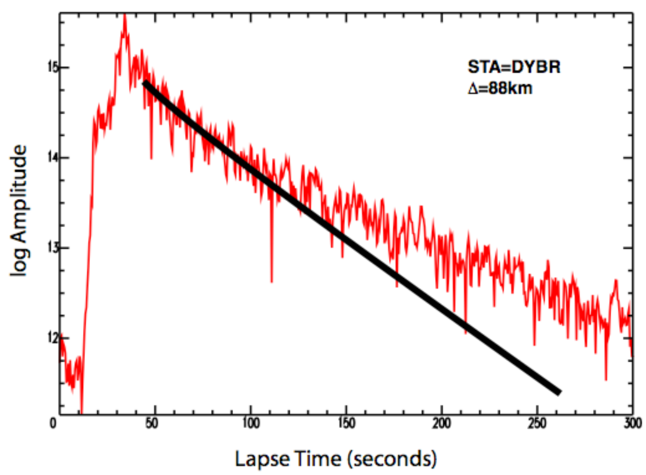

Figure 6. Example narrowband envelope from the eastern Anatolian plateau (red) illustrating that the calibrated synthetic coda envelope (black) does a poor job at longer lapse times (> ~120 seconds). The synthetic was based on an average using many events in the region, but we clearly see that for this station-event path, the model does not perform well and suggests we need 2-D envelope functions.

Unfortunately, the current envelope formulation does not account for the increased curvature. We will experiment with other formulations, such as the addition of another exponential term in Equation 1 as well as using multiple scattering formulations from the literature (e.g., see Sato and Fehler, 1998). For example, adding an additional exponential term that starts later in the coda at time t_c with a different decay rate, c, could be used.

$$A_c(f, t, r) \approx H(t-t_s)\cdot(t-t_s)^{-\gamma(r)}\exp\left[-b(r)\cdot(t-t_s)\right]+\exp\left[-c(r)\cdot(t-t_c)\right] \qquad (1)$$

In addition, for calibration earthquakes we will tie our distance-corrected amplitudes to theoretical source spectra under different source-scaling assumptions derived from *a priori* assumptions or independent source scaling studies.

CONCLUSIONS AND RECOMMENDATIONS

The applications and benefits are several-fold. First, we believe that the proposed changes to the coda methodology will provide significant improvement for complex, broad area calibrations, NOT simply an incremental improvement. This is timely since the community is embarking on calibrating complex broad regions, in contrast to the past coda applications, which were smaller in scale and complexity. We have tested the effects of only applying 2-D path corrections to a number of regions (central Asia, western North America, and recently the Middle East) and we find that the other coda calibration parameters have very large, lateral variations (e.g., coda envelope shape, peak velocity and site-transfer). Since a patch-work of small-scale 1-D coda calibrations is unfeasible in most regions of monitoring interest, our proposal for full 2-D coda parameterization should significantly reduce amplitude variance for discrimination, magnitude and yield estimation. We will develop a generalized 2-D coda methodology that accounts for lateral variations in path effects, peak envelope velocity, envelope shape, and site-transfer corrections. The coda models for both *P*-codas and *S*-coda from both small and broad regions will be seamlessly tied to each other and most importantly, constructed in an identical manner that is internally consistent. In addition to the above-mentioned 2-D improvements, new synthetic envelope functions for amplitude fitting will lower amplitude variance, especially for events where signal-to-noise ratio is low.

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