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Transitioning the Coda Methodology to Full 2-D for P and S Codas

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ABSTRACT

Over the past decade, the PI's in conjunction with AFTAC 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 yield 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 Iran, 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 tests illustrate that even a seemingly simple region requires 2-D corrections for L_g -coda.

INTRODUCTION:

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, radially symmetric Earth centered on each station. The methodology has had great success at local and near-regional distances for simple regions, for crustal *S* transitioning to 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 in 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 the use of the 1-D coda has 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 India, Kuwait, eastern Mediterranean, northern Italy, Northern California) or broad regions that are more or less uniform (*e.g.*, European Arctic, Turkey, South Africa). 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 Iran. For example, Turkey is geophysically complicated, but for lower frequencies, between 0.05 and ~ 1 Hz, the whole country 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.

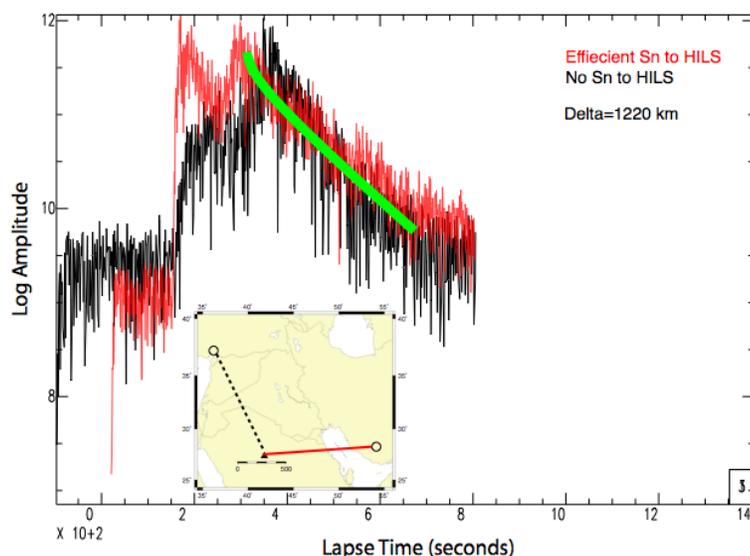


Figure 1: Middle East example of 2.0-3.0-Hz envelopes for two events recorded at station HILS in Saudi Arabia. The event from south-central Turkey has L_g coda whereas the event from southern Iran has S_n coda. A simple 1-D calibration for this region would introduce significant error because velocity, 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 1 illustrates such a case where we have two events recorded by station HILS located in Saudi Arabia. For one event there is clear L_g and associated coda, whereas the path from southern Iran 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.

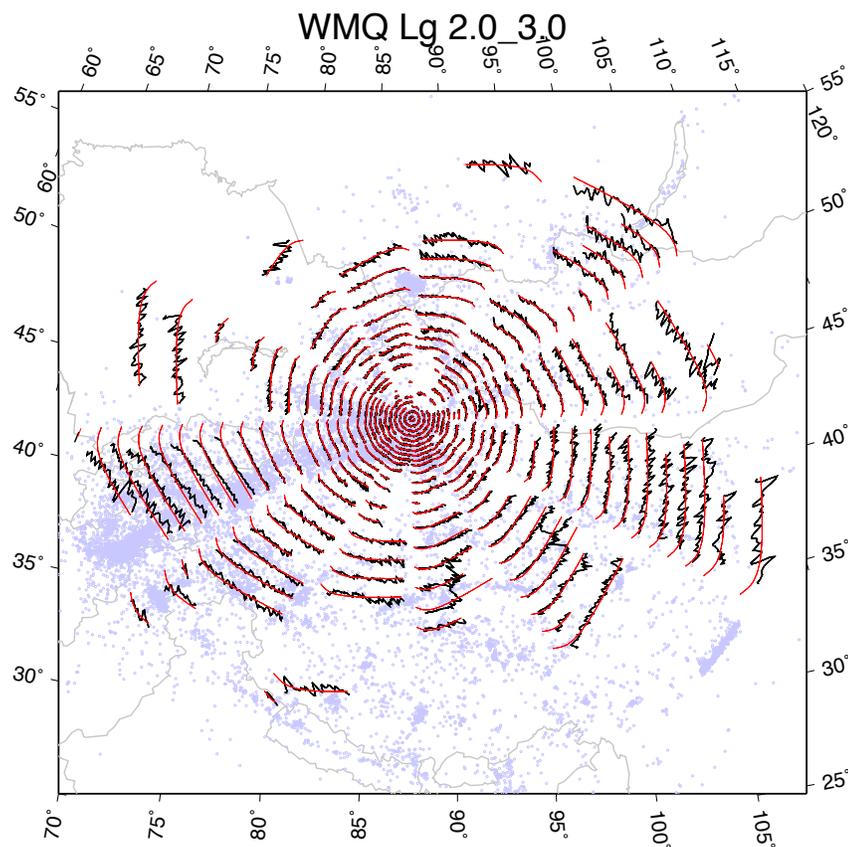


Figure 2: Radially and distant dependent envelopes are shown for station WMQ. Black envelopes are the result of stacking in bins and the red lines are synthetic fits. This region is particularly complicated and highlights the need for 2-D coda calibration.

In addition to azimuthal variation shown in Figure 1, in Figure 2 above we show 2.0-3.0-Hz coda stacks for station WMQ as a function of both distance and azimuth. Stacking was performed for events in azimuth-distance bins, and results are plotted at each bin center. Coda stacks are plotted in polar format with time increasing tangentially in the CCW direction, and amplitude increasing radially inward. Axes not shown. Fits for a distance dependent coda shape model for broad area Asia are plotted in red. Event distribution is shown in the background. Note the smooth stacks in areas of high event density. 2-D variations can be seen in the model fits. Tien

Shan coda are shallower than the model predicts, thus experience lower attenuation, possibly due to influence of the Tarim basin and Kazakh platform. Codas from the southeast are steeper than the model, reflecting higher attenuation along those azimuths.

The motivation for making a change to the methodology is quite simple. First, regions of monitoring interest are rarely tectonically simple and in fact, most appear to require 2-D corrections for velocity, path, and envelope function. Figure 3 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 its effectiveness for such short paths.

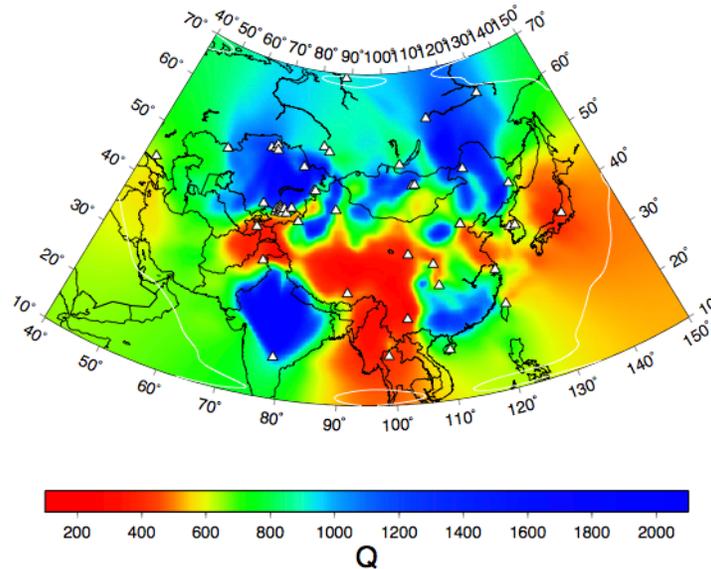


Figure 3: Coda wave apparent Q for central Asia for the 0.7-1.0 Hz band. This 2-D inversion was performed over a very broad region and emphasizes the need for 2-D path corrections. Stations are represented by triangles and a liberal model error ($1/Q$) indicating raypath coverage is represented by the white contour. Q becomes poorly resolved as the coverage contour is approached. Note: Coda wave apparent Q is not to be confused with coda Q as defined by *Aki* (1969).

CONCLUSIONS AND FUTURE WORK:

The project 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, including 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).

Aside from some preliminary project planning which has taken place during this current year, we summarize our project tasks. Our plan is to improve the coda methodology by

upgrading models and transitioning to full 2-D for both P -coda and S -codas. For example, the parameterization of the synthetic envelopes has been based on a simplistic single-scattering formulation for a homogeneous full-space. We plan on testing multiple scattering formulations as well as developing other empirical models. In addition, *ad-hoc* 1-D path corrections were developed, mostly because the regions of study were relatively small and/or had P_n -codas, S_n -codas or L_g -codas, but not a mixture. Increasingly however, monitoring needs require both local and broad-area regional to far-regional calibration, usually in complex regions where we observe frequency-dependent phase blockage.

We are leveraging existing data holdings at both institutions and also use new results that stem from local background coda models, earthquake source scaling studies, and more sophisticated scattering models in the literature.

The following lists our planned tasks for this project.

- 1) Evaluate error improvement when we account for 2-D variations in coda type for both P and S -codas. This will involve developing and testing methods that account for multiple coda types in 2-D sense.
- 2) Evaluate error improvement when we change from 1-D to 2-D for peak envelope velocity. This will initially involve a 1-D background model of peak velocity, then using 2-D corrections that are obtained either through a 2-D tomography or station-centric lookup table. We will evaluate both approaches and make recommendations based on error.
- 3) Evaluate error improvement when we change from 1-D to 2-D for envelope shape. Again, we will have a 1-D background model, then test tomography and station-centric lookup methods for exponential decay (b) and spreading terms that describe coda shape. This is similar to what we plan to do for peak envelope velocity in (2).
- 4) Evaluate advanced 1-D models for envelope shape that account for multiple scattering or shifts to mantle coda with increased lapse time. There are a number of theoretical formulations in the literature that model scattering mean-free path changing as a function of depth as well as multiple scattering models in 1-D varying velocity structure.
- 5) Blend 2-D calibrations for P and S -coda from central and east Asia networks with Middle East calibrations. Our goal is to have a seamless calibration that is consistent with Knowledge Base deliveries from one year to the next and allows for re-calibration when new stations and waveform data become available.
- 6) Evaluate error improvement transitioning from 1-D to 2-D coda transfer function corrections (*i.e.*, empirical Green's function). We will test tomography methods that invert for source-region specific transfer functions. For example, the P -to-coda and S -to-coda transfer functions may be region-specific due to crustal structural variations (*e.g.*, impedance contrast and scattering efficiency differences from one source region to the next).

- 7) Evaluate error improvement using theoretical source models as calibration events versus empirical Green's function approach outlined in *Mayeda et al.*, (2003).

REFERENCES:

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

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**, 11, L11609.

Mayeda, K., A. Hofstetter, J.L. O'Boyle, and W.R. Walter (2003). Stable and transportable regional magnitudes based on coda-derived moment-rate spectra, *BSSA*, **93**, 224-239.

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