

**ROBUST MAGNITUDE AND PATH CORRECTIONS FOR REGIONAL SEISMIC PHASES IN EURASIA
BY CONSTRAINED INVERSION AND ENHANCED KRIGING TECHNIQUES**

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ABSTRACT

Many studies have demonstrated the need to apply distance (geometrical spreading and attenuation Q) corrections to regional seismic phases for their reliable use in discrimination procedures. Additional studies have also demonstrated that significant improvements to regional discrimination performance (e.g., using Pn/Sn and Pn/Lg) are obtained by applying station/path-specific (kriged) corrections to regional phase amplitudes or ratios. While substantial advances have been made to develop and apply such capabilities, two key issues have limited their reliability. The first is related to the fact that standard models and procedures used to invert simultaneously for geometrical spreading, frequency-dependent Q , site, and source corner frequency parameters for regional seismic phases include many trade-offs and instabilities over the parameter space. The second is related to concerns that regional phase amplitudes from earthquakes with anomalous mechanisms could significantly bias kriged correction grids and, thereby, bias discrimination results. Both of these issues and their potential impact on discrimination errors are legitimate. Under this new effort, we plan to implement, apply, and evaluate two techniques that will significantly enhance Q models and the robustness and reliability of magnitude and path corrections for regional seismic phases. The first is a constrained inversion approach to improve parameter estimates of geometrical spreading and Q models for Pn, Pg, Sn and Lg in Eurasia, by eliminating trade-offs with source corner frequencies. This will be accomplished by fitting model source parameters to relative spectra for pairs of nearby earthquakes to constrain the source corner frequencies before estimating Q models. The second is to implement, apply, and evaluate an extension to Bayesian kriging, that properly treats localized calibration events which may have anomalous, correlated amplitudes, to provide robust path corrections and appropriate uncertainties for regional phase amplitudes. We will evaluate the corrections and uncertainties using applications to multiple data sets. We plan to deliver these techniques, parametrizations of stress drop, corner frequency scaling, geometrical spreading and Q models, and kriged amplitude correction and uncertainty grids for stations in Eurasia, for potential incorporation into the Department of Energy National Nuclear Security Administration (DOE/NNSA) Knowledge Base (KB). We expect that this will significantly enhance nuclear explosion monitoring capabilities in Eurasia.

OBJECTIVES

We are just starting a two-year project to develop and test two methods to improve magnitude and path corrections for regional seismic phase amplitudes. Objectives of the first method, a constrained inversion approach, are to improve estimates of geometrical spreading and Q models for Pn, Pg, Sn, Lg in Eurasia, by eliminating trade-offs with source corner frequencies, and to improve source parametrizations in Eurasia, in terms of grids of stress drop and corner frequency scaling. The objective of the second method, an extension to Bayesian kriging, is to provide robust path corrections and uncertainties for regional phase amplitudes, that properly treats localized calibration events that may have anomalous, correlated amplitudes. This project has three main tasks: (Task 1) Assemble multiple data sets of regional seismic recordings of earthquakes throughout broad areas of Eurasia. Apply waveform cross-correlation techniques to determine nearby pairs/clusters of events. Assemble spectral amplitude measurements of Pn, Pg, Sn, Lg for the events. (Task 2) Implement a technique to estimate corner frequencies and scaling parameters for Pn, Pg, Sn, Lg, by fitting relative Brune model spectra to data for pairs of nearby earthquakes of different moments. Compute grids of stress drop and earthquake corner-frequency scaling with moment for Eurasia. Use spectral amplitude data for regional phases and constrained source parametrizations to perform a robust inversion for geometrical spreading and Q model parameters. Test and evaluate resulting magnitude and distance corrections on events in Eurasia, using cross-validation methods. (Task 3) Investigate clusters of earthquakes at the Nevada Test Site (NTS) and regions in Eurasia, and assess the potential for events with anomalous, correlated mechanisms to bias kriged amplitude correction grids beyond existing uncertainty estimates. Develop a technique to quantify the correlation of regional phase amplitudes within clusters. Extend a Bayesian kriging method to incorporate these correlation measures in the computation of amplitude correction and uncertainty grids. Test and evaluate the methods on events in Eurasia, using cross-validation techniques. We plan to deliver the techniques, parametrizations of stress drop, corner frequency scaling, geometrical spreading and Q models, and kriged amplitude correction and uncertainty grids for stations in Eurasia.

Background and Motivation

Many studies have demonstrated the need to apply distance corrections to regional seismic phases for reliable use in discrimination procedures (e.g., Fisk et al., 1996, 2001; Taylor and Hartse, 1998; Taylor et al., 2002). Additional studies have further demonstrated substantial improvements to regional discrimination performance by applying path-specific corrections to regional phase amplitudes or their ratios (e.g., Pn/Sn and Pn/Lg). While considerable advances have been made to compute and apply such corrections, e.g., MDAC [Magnitude and Distance Amplitude Corrections] (Taylor et al., 2002) and various forms of kriging or Bayesian calibration (e.g., Schultz et al., 1998; Bottone et al., 2002), two key issues have limited their reliability. The first is related to the fact that the models and procedures used to invert simultaneously for geometrical spreading, attenuation Q , site, and source corner-frequency parameters for regional seismic phases include many trade-offs and instabilities over the parameter space (Taylor and Hartse, 1998). The second is related to concerns that regional phase amplitudes from earthquakes with anomalous mechanisms could significantly bias kriged amplitude correction grids and, thereby, bias regional discrimination results. Both of these issues can lead to significant discrimination errors. They also have tractable solutions.

First, it is well known that there are substantial trade-offs between Q parameters and source corner frequencies that are very difficult to constrain by standard techniques and available data (e.g., Taylor and Hartse, 1998). Following Taylor et al. (2002), the amplitude spectrum for a given phase and station, for event i , may be expressed as

$$A_i(f) = S_i(f, f_c) G(r_i, r_0) \exp\left(-\frac{\pi f}{Q(f)v} r_i\right) P(f), \quad (1)$$

where f is the frequency, $S_i(f, f_c)$ is the source spectrum with corner frequency f_c , r_i is the epicentral distance, $Q^{-1}(f)$ is the frequency-dependent attenuation, v is the group velocity, $P(f)$ is a unitless station term, and $G(r, r_0)$ is the frequency-independent geometrical spreading term, assumed to be inversely proportional to distance to a power η , beyond some reference distance r_0 . Frequency dependence of Q is modeled by a power-law relation of the form

$$Q(f) = Q_0 f^\eta. \quad (2)$$

The logarithm of Equation (1) is used in a grid-search inversion procedure to simultaneously estimate the parameters related to source corner frequency, geometrical spreading, and frequency-dependent Q . Trade-offs between these parameter estimates can have disastrous effects of improperly correcting regional phase amplitudes for distance and magnitude. Figure 1 illustrates the serious nature of this problem for two earthquakes on 27 and 30 January 1999 near the Lop Nor Test Site (LNTS). It shows relative spectra of Pn, Sn, and Lg for the smaller event (Mw 4.38) relative to the larger event (Mw 5.69). The ratios were computed for each phase at 18 stations and then network averaged. Note that both events have similar epicenters and depths of about 20 km, based on well-constrained depth-phase solutions. Thus, path and station effects should cancel out in the relative spectra. Also shown are theoretical predictions, based on a Brune (1970) model for P and S waves, using corner frequency scaling relations for Pn and Lg estimated by Xie and Patton (1999), (XP99, dashed curves) and results by Fisk et al. (2005) by fitting the empirical relative spectra (dotted curves). It is clear that the dashed curves do not match the empirical relative spectra. Also, for a given moment, the XP99 Pn and Lg corner frequencies differ by a factor of about 4.7, quite different than many published results of between 1.73 and 1.0 (e.g., Madariaga, 1976; Choy and Boatwright, 1995; Walter and Taylor, 2002). The disagreement of the XP99 corner frequency relations with many past studies, and the empirical spectral ratios shown here, is presumably due to invalid attenuation corrections for Pn, Lg, or both. Applying these source corrections (dashed curves), based on the XP99 corner frequency relations, would lead to P/S ratios for these earthquakes that are grossly inaccurate, and would likely lead to invalid discrimination results.

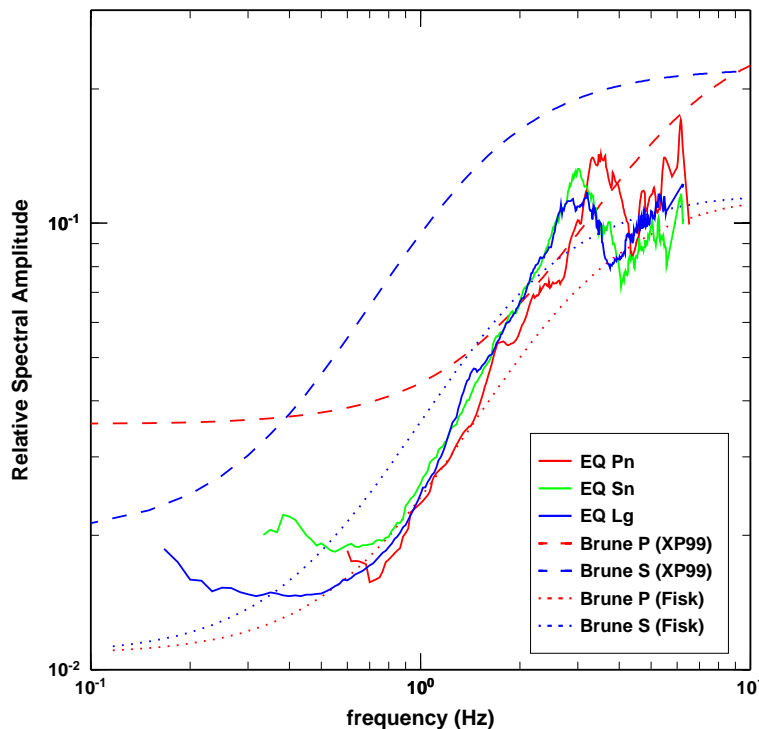


Figure 1. Network-averaged relative spectra of Pn, Sn, and Lg for two earthquakes (Mw 4.38 and 5.69) near LNTS. The empirical ratios were computed by dividing the spectra, for a given phase type, of the smaller event by those of the larger event. Also shown are theoretical predictions for P and S waves, based on a Brune (1970) model, using the corner frequency scaling relations published by XP99 and estimated by Fisk et al. (2005).

In addition, many of the MDAC2 parameters, initially estimated for geometrical spreading and Q at stations in Asia, do not seem physically reasonable, based on prior experience in China. They appear to be the result of trade-offs and insufficient constraints in the grid search for these parameter estimates. For example, many of the Pn geometrical spreading coefficients η are estimated to be 2.0 (a restricted upper bound), as compared to more typical estimates of 1.3 for this region of China (e.g., Xie and Patton, 1999; Taylor et al., 2002). Similarly, MDAC2 estimates of Pn Q_0 for regional stations surrounding LNTS are between 560 and 900, in striking contrast to the average Pn Q_0 values of 354

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over all paths, estimated by Xie and Patton (1999). At present, it is difficult to assess which, if any, of these Q and geometrical spreading parameters are appropriate, but it is clear that there are substantial differences in the reported estimates. To compensate for these problems, MDAC further utilizes a “non-physical” bilinear regression fit to obtain frequency-dependent amplitude corrections as functions of magnitude and distance (Taylor et al., 2002), which seems to provide reasonable corrections, but does not lend much confidence that they are physically appropriate.

While Figure 1 illustrates a serious problem, it also shows a straightforward solution. Since geometrical spreading, Q , and site effects are factored out of relative spectra of a given phase for nearby pairs of events with similar mechanisms, the corner frequencies of a Brune model may be fit to the relative spectra, as was done by Fisk et al. (2005) for LNTS earthquakes (cf. Figure 1). Thus, by first eliminating path and station effects, the source parametrization can be constrained reasonably well. Then the inversion for geometrical spreading, Q , and site parameters will be more robust by eliminating the trade-off with corner frequency. The feasibility of this approach depends on sufficient pairs of nearby events to constrain the source parameters over a broad enough spatial extent. Fortunately, Schaff and Richards (2004) showed that about 4200 events in and near China, listed in the Annual Bulletin of Chinese Earthquakes (ABCE) over a 15 year period, have at least one other event with Lg waveform (0.5-5.0 Hz) cross-correlations greater than 0.5. This indicates that there are indeed many pairs of replicated events throughout much of China and surrounding regions that can be exploited for our approach. We expect to find many other such events for other regions throughout Eurasia. Below we describe our plans to collect and process such data and our constrained inversion procedure.

Second, despite compelling demonstrations that kriging of path-specific amplitude corrections can significantly improve regional P/S discrimination performance (e.g., Phillips et al., 1998; Phillips, 1999; Rodgers et al., 1999; Fisk et al., 2001; Bottone et al., 2002; Fan et al., 2002; Taylor et al., 2002), there are concerns regarding the robustness of the amplitude corrections to aberrant calibration data. To first illustrate the substantial benefit obtained by using kriged corrections for Pn/Sn and Pn/Lg, Figure 2 shows the locations of explosions and presumed earthquakes that we used in a global discrimination study, as well as the locations of 52 International Monitoring System (IMS) stations and 4 non-IMS stations with regional recordings of these events. Bottone et al. (2002) and Fisk et al. (2001) described these data sets, the distance corrections for Pn/Sn and Pn/Lg, station-specific kriged correction and uncertainty grids for the amplitude ratios, a discrimination hypothesis test, application of the correction and discrimination techniques to these global data sets, and in-depth analyses of the results for each nuclear test site. They found that an additional 28% of the earthquakes (78% versus 50%) are classified properly by using the Bayesian calibration (kriging) method than just using distance corrections, without misclassifying any of the explosions in either case. However, there are valid concerns that earthquakes with anomalous mechanisms, depths, or paths could significantly bias kriged amplitude correction grids. This is certainly possible, especially for kriging algorithms that fit each data point (e.g., Schultz et al., 1998). The Bayesian kriging method, developed by Bottone et al. (2002), estimates the local mean, weighted by the global average and nearby calibration data relative to the calibration grid point. This approach is far less sensitive to data with anomalously high or low values. Nevertheless, a cluster of events with anomalous amplitudes (such as an aftershock sequence with atypical focal mechanism) could impact the correction surface near those data.

These concerns regarding the correction grids, while justified, must be viewed in the context of the associated uncertainty (variance) grids, which are intended to represent the variability from localized source mechanisms (i.e., residual variance) and from the amount of calibration data in proximity to the correction grid point (i.e., calibration variance). We generally estimate these variances in a conservative manner by using global sets of earthquakes in variogram analysis, which also estimates the correlation length. By properly using conservative estimates of these variances in a discrimination procedure, the overall uncertainty accounts for the fact that earthquakes from a global population can have anomalous amplitudes, that could result in aberrant corrections. This treatment of the uncertainty protects from making erroneous event classifications in poorly calibrated areas (effectively lowering the confidence level due to greater calibration uncertainty). Thus, isolated or limited data points with anomalous amplitudes may impact the correction grid some, but the uncertainties should, and generally do, account for this potential behavior.

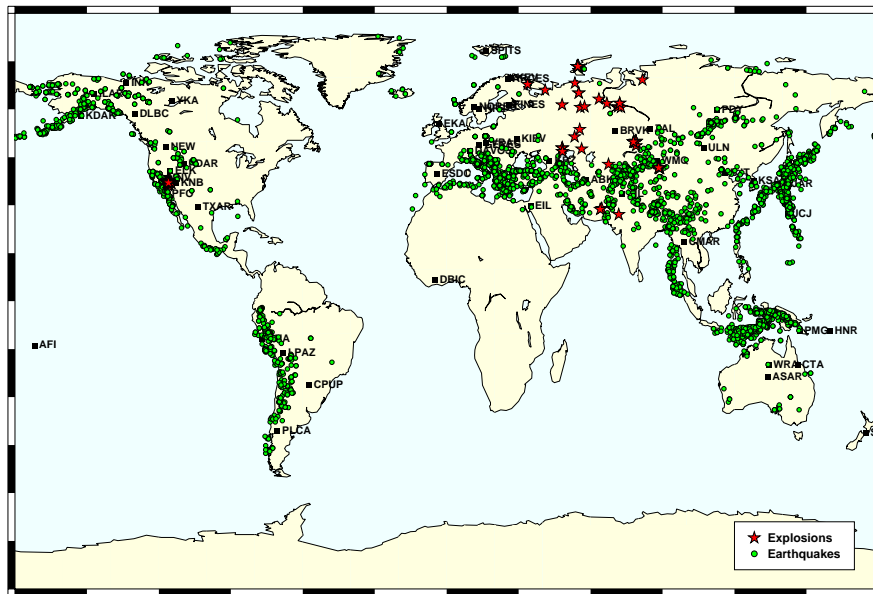


Figure 2. Locations of 161 explosions (stars) and 4173 REB events (circles) above mb 3.5. Locations of 52 IMS and 4 non-IMS stations with regional recordings of these events are also shown.

However, a real problem can arise if there is a localized cluster of many events with atypical amplitudes. In this case, most kriging algorithms reduce the calibration variance without any assessment of how representative or atypical the data might be. Only the correlations, which depend just on relative distances of reference data to the calibration point, are presently used. In such cases, the calibration variance could be reduced to a level where the overall variance does not adequately reflect the potential bias in the correction grid. Indeed, the real problem is that most kriging methods treat clustered calibration data as independent samples, with no assessment of whether they have correlated source mechanisms. If this type of correlation was explicitly treated, then the calibration variance would be reduced more slowly as a function of the number of calibration data. As an extreme case, if all of the waveforms for a cluster of events were perfectly correlated, then the calibration variance should treat this cluster as a single data point, and the uncertainties, based on a global earthquake population, would still conservatively reflect potential anomalies.

As an example of this problem, several aftershock sequences with distinct mechanisms have occurred at the NTS (e.g., Walter et al., 1995). During 1992, about 35 earthquakes in the Little Skull Mountain (LSM) sequence, with depths of 6-12 km, were recorded with good signal-to-noise ratio (SNR) by MNV and KNB. In 1993 and 1994, unusually shallow (1-3 km) earthquakes occurred in Rock Valley (RV), about 10-20 km from the LSM sequence. About 10 of these events have good SNR at MNV and KNB. Walter et al. (1995) showed that Pn/Lg(6-8 Hz) values for the RV events are systematically higher than those for the LSM events (Figure 3), especially at KNB. Figure 4 shows that near NTS the kriged Pn/Lg correction grid for MNV is higher than the global average (green) and the variance grid has its lowest values, where many calibration events are available. Fisk et al. (2001) showed that application of Bayesian kriging (path corrections and uncertainties) to Pn/Lg (6-8 Hz) did not misclassify any NTS explosions and most nearby earthquakes were classified properly, except for the RV earthquakes that were classified as *undetermined*. Thus, although the correction grid for MNV is higher than the global average, the uncertainties are adequate to produce appropriate discrimination results. However, if all of the calibration earthquakes near NTS were like the shallow RV events, the kriged Pn/Lg correction grid would have even much higher values and the calibration variance would still be small. The potential to misclassify explosions with lower Pn/Lg values would be likely, since the RV earthquake mean falls within the explosion population (Figure 3).

This is exactly the type of problem that requires research to know if kriged amplitude correction and uncertainty grids, based on aberrant earthquake clusters, can lead to discrimination errors. It must be resolved before kriged corrections can be applied confidently to broad areas lacking explosion data, where discrimination results cannot be

directly validated. Fortunately, a tractable solution may be implemented by treating correlations of waveforms or amplitude measurements for clusters of events in a manner that properly accounts for the effective independent number of calibration data. In the example above, using only RV earthquakes to calibrate NTS, the effective amount of independent calibration data would be limited by the fact that the mechanisms for these events were similar. Thus, the calibration variance would be relatively large and the discrimination criteria would be aptly conservative.

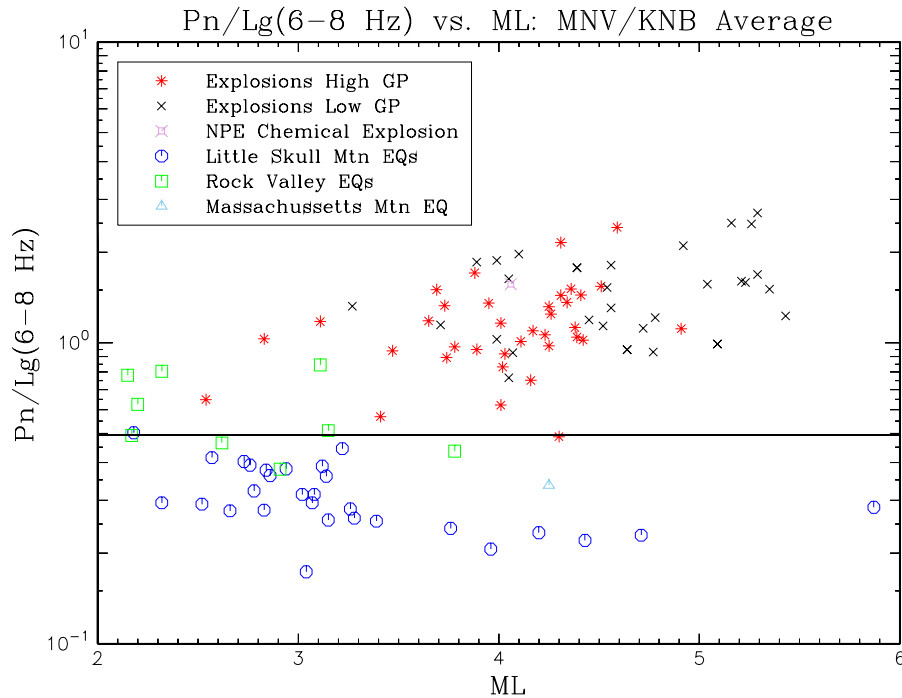


Figure 3. Averaged MNV and KNB $P_n/L_g(6-8 \text{ Hz})$ values versus ML for NTS explosions and earthquakes. The line corresponds to the lowest P_n/L_g value for the explosions. Most Rock Valley earthquakes fall above the line.

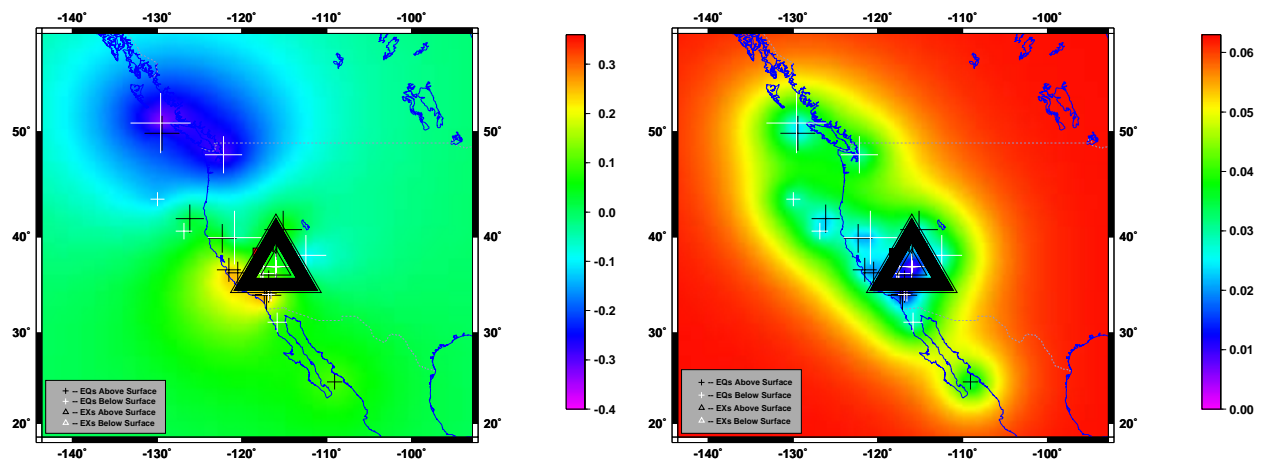


Figure 4. Correction (left) and uncertainty (right) grids for $\log[P_n/L_g(6-8 \text{ Hz})]$ at MNV. Triangles depict explosions and crosses depict earthquakes. Black (white) markers have values greater (less) than the local value of the correction grid. Marker size is proportional to the absolute difference from the correction surface.

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Below we present the data sets, an inversion technique for distance correction parameters that first constrains the source parameters, extension of our Bayesian kriging method, and plans to test and evaluate these techniques.

Data Sets

Several excellent data sets will be considered for this project, to obtain large numbers of pairs or clusters of events in Eurasia. First, we have compiled and processed regional recordings of 4173 presumed earthquakes above mb 3.5 in the Reviewed Event Bulletin (REB) (green circles in Figure 2). We will apply waveform cross-correlation software to various regional phase windows and assess events with significant correlations. Our primary focus will be on Eurasia, but we expect that some interesting event clusters will be found in other regions, that will be useful for investigating effects of anomalous path corrections. Second, regional recordings for several thousand earthquakes in Eurasia exist at LANL (Figure 5). Spectral amplitudes in several frequency bands have already been processed for these events. We plan to assess earthquakes in this large database that have significant waveform cross-correlations for regional phases and utilize these data for our constrained inversion of geometrical spreading and Q models for various regional phases, and for our kriging efforts. Third, Schaff and Richards (2004) assembled International Seismological Centre data for over 14,000 events in and near China, listed in the ABCE from 1985 to 2000. They processed Lg waveform cross-correlations to find large subsets of replicating events. We plan to utilize their results to obtain pairs/clusters of events.

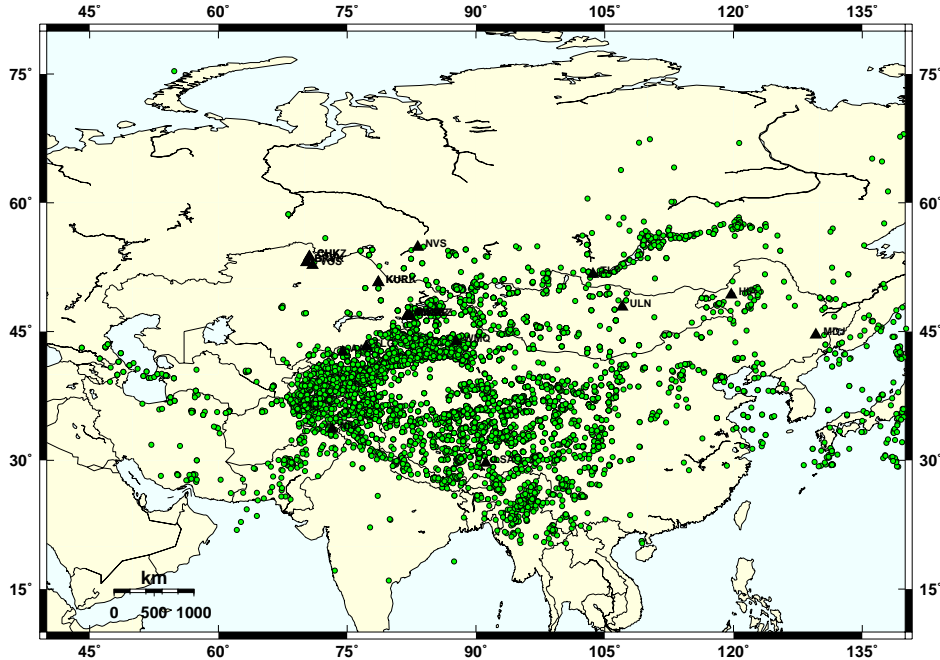


Figure 5. Locations of presumed earthquakes with regional seismic data in the LANL database.

Constrained Inversion Technique

To characterize the source spectral function in Equation (1) for earthquakes, we use a modified Brune (1970) model. For a particular phase type, ξ (P or S), the amplitude spectrum is given by

$$S(f, f_c(\xi)) = \frac{M_0 R_{0\phi}(\xi)}{4\pi \sqrt{\rho_s \rho_r} v_s(\xi)^5 v_r(\xi) [1 + (f/f_c(\xi))^2]}, \quad (3)$$

where M_0 is the seismic moment, $R_{0\phi}$ is the radiation pattern coefficient for P or S waves, ρ_s and ρ_r are the source and receiver medium densities, v_s and v_r are the source and receiver medium velocities for P or S waves, and f_c is the source corner frequency. For a Brune (1970) dislocation source, the corner frequency is given by

$$f_c(\xi) = c_\xi v_s(\xi) \left(\frac{\sigma_b}{M_0} \right)^{1/3}, \quad (4)$$

where σ_b is the stress drop and c_ξ is a constant that depends on phase type. Cong et al. (1996) and Nuttli (1983) show that corner frequency scaling as $M_0^{-1/4}$ is more appropriate than $-1/3$ scaling for earthquakes in central Asia. This departure from cube-root scaling can be viewed as a result of non-constant stress drop. Following Walter and Taylor (2002), non-constant stress drop may be treated by defining the apparent stress drop for a given moment, M_0 , as

$$\sigma_b = \sigma_b^{(0)} \left(\frac{M_0}{M_0^{(0)}} \right)^\psi, \quad (5)$$

where $\sigma_b^{(0)}$ is the stress drop at a reference moment $M_0^{(0)}$. Parameters $\sigma_b^{(0)}$, $M_0^{(0)}$, and ψ may be estimated from data. Instead of doing a grid search for all source and attenuation parameters simultaneously, we will use relative spectra to first estimate and fix the source parameters, and then invert for values of η , Q_0 , and γ . That is, for a pair of nearby earthquakes with similar radiation patterns and media, the model relative spectra for a given phase type is given by

$$\frac{A_1(f)}{A_2(f)} = \frac{S_1(f)}{S_2(f)} = \frac{M_0^{(1)} [1 + (f/f_c^{(2)})^2]}{M_0^{(2)} [1 + (f/f_c^{(1)})^2]}. \quad (6)$$

Using pairs of localized earthquakes, we will fit the parameters $\sigma_b^{(0)}$, $M_0^{(0)}$, ψ , and c_p/c_s of this model to empirical relative spectra of regional phases (e.g., as depicted by the dotted curves in Figure 1, above). We will generate grids of stress drop and corner frequency scaling parameters for regional phases in Eurasia. We will adapt the MDAC algorithm to constrain the source parameters and estimate geometrical spreading, Q , and site terms of Equation (1) for stations in Eurasia. We will compare the results among these data sets (and to published results) to assess their robustness. We will then perform a final application using the merged data sets to obtain and evaluate the final results. We will quantify the uncertainties and remaining trade-offs of the estimated source and attenuation parameters in terms of root mean square (RMS) residual misfits and residual sum of squares (RSS) values of the model and empirical relative spectra, and using Principal Components Analysis to assess the eigenvectors that quantify the most relevant contributions to the variance and trade-offs among the parameters, with and without using the source constraints.

Enhanced Bayesian Kriging Methodology

Among other geophysical applications, kriging has been used to calibrate and treat uncertainties of regional phase amplitudes or amplitude ratios (see Bottone et al., 2002; and references therein). Kriging provides optimal prediction at a new location, as a weighted linear combination of reference data, with greater weight given to data that are spatially closer to the prediction location. That is, given N reference data values, $x(\mathbf{s}_1), \dots, x(\mathbf{s}_N)$, at locations $\mathbf{s}_1, \dots, \mathbf{s}_N$, the optimal predictor for the mean at a location \mathbf{s}_0 is given by the weighted linear combination of data:

$$\hat{\mu}(\mathbf{s}_0) = \sum_{i=1}^N w_i x(\mathbf{s}_i). \quad (7)$$

In previous applications, $x(\mathbf{s}_i)$ has represented MDAC-corrected amplitudes or distance-corrected amplitude ratios. The set of all predictions, $\hat{\mu}(\mathbf{s}_0)$, over permissible locations \mathbf{s}_0 , provides a correction grid. The corresponding uncertainty surface, $\sigma^2(\mathbf{s}_0)$, also results from the calculation. This posterior variance and the weights w_i depend on the correlations, ρ_{ij} , between the data means at \mathbf{s}_i and \mathbf{s}_j , the calibration variance, σ_c^2 , and the residual variance, σ_r^2 :

$$w_i = F(\sigma_c^2, \sigma_r^2, \rho_{ij}) \quad (8)$$

$$\sigma^2(\mathbf{s}_0) = G(\sigma_c^2, \sigma_r^2, \rho_{ij}). \quad (9)$$

Explicit forms of F and G depend on the distribution of the $x(\mathbf{s}_i)$, but not on the data themselves. Assuming the $x(\mathbf{s}_i)$ have a normal distribution, the expressions for F and G have closed forms. The correlations, ρ_{ij} , between the means at \mathbf{s}_i and \mathbf{s}_j , are generally assumed to depend only on the distance $\Delta(\mathbf{s}_i, \mathbf{s}_j)$ between \mathbf{s}_i and \mathbf{s}_j , and are often taken to be the exponential function $\rho_{ij} = \exp(-\Delta(\mathbf{s}_i, \mathbf{s}_j) / \alpha)$, where α is the correlation length. Input parameters for the kriging

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algorithm are σ_c^2 , σ_r^2 , and α . In practice, they are estimated from data using variogram analysis. Further details regarding this Bayesian kriging approach, variogram analysis, and applications are presented by Bottone et al., 2002.

The issue we plan to redress, that is common to most kriging methods, is that the weights and variances in Equations (8) and (9) treat an effective correlation, based only on the distances of reference data to the calibration point, but do not depend on the intrinsic correlations among clustered events, which could be high if the events have similar mechanisms. In such cases, existing methods compute the weights too high and the variances too low near the cluster, because the data are treated as independent. The first step will be to assess the impact on discrimination performance. Several aftershock sequences are well suited for this analysis. First, we will examine the LSM and RV earthquakes at NTS. We will quantify waveform cross-correlations for events within each cluster and regress these values against the correlation of Pn/Lg values among the events. This information will be used to determine how many independent degrees of freedom actually exist for these data sets and how the weights and variances of the kriging algorithm should be modified to guard against potential discrimination errors. Second, aspects of these analyses will be applied to several known aftershock sequences in Eurasia and other clusters of events found by waveform cross-correlation methods. For example, there are three large earthquake sequences (20-80 events) in India near Bhuj, Chamoli, and Koyna, a sequence of about 70 events near Jiashi in western China, over 30 events near Tabas, Iran, and a large number of aftershocks in Kyrgyzstan during 1998. Third, to examine the effects on discrimination performance we will take one or more earthquakes with the highest P/S ratios near nuclear test sites in China, Pakistan, Kazakhstan, and India and replicate those data, based on the correlations and variances measured for the aftershock sequences elsewhere. We will quantify discrimination performance for these simulated (worst-case) earthquake calibration sets as a function of the number of replicated reference events. We will develop a fundamental improvement to kriging methods by incorporating correlations of waveforms or amplitudes that properly treats the independent degrees of freedom of localized calibration data. We will apply the enhanced kriging algorithm to broad data sets of almost 4200 global REB earthquakes and several thousand earthquakes in Eurasia. We will evaluate the correction and variance grids using cross-validation methods (eliminating entire groups of nearby events) and assess the discrimination performance near known nuclear test sites, based on these final grids.

RESEARCH ACCOMPLISHED

The start date for this contract was too late to obtain results for this paper, but we are working on the first milestone of assembling and processing the data sets.

CONCLUSIONS AND RECOMMENDATIONS

We expect that our innovative inversion technique for constraining source corner frequencies and then estimating attenuation parameters will significantly improve geometrical spreading and Q models and the robustness/reliability of magnitude and path corrections for regional seismic phases. Our approach will utilize multiple data sets, assessing and treating trade-offs between Q parameters and source corner frequency scaling, and assessing the uncertainties. This effort will also provide improved source characterization for events in Eurasia, in terms of stress drop grids and corner-frequency scaling parameters. We also expect that our research and extension to Bayesian kriging will provide robust path corrections and uncertainties for regional phase amplitudes, generalized to properly treat localized calibration events that may have anomalous, correlated amplitudes. This method will explicitly quantify the resulting variances of regional phase amplitudes in Eurasia. Both of these research areas will be directed at improving regional phase amplitude corrections and the uncertainties throughout major regions of Eurasia. These methods and the resulting amplitude correction and uncertainty terms will be directly applicable for use in existing monitoring systems. The results of this effort will be delivered to LANL for potential incorporation into the DOE/NNSA KB. We expect that this will significantly enhance U.S. nuclear explosion monitoring capabilities in Eurasia.

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