PATH CORRECTIONS FOR REGIONAL PHASE DISCRIMINANTS

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ABSTRACT

In order to utilize regional seismic phases for reliable source identification, it is essential to account for wave propagation effects that may obscure the subtle differences in source radiation for distinct source types. Recent work has established three main approaches to the problem of characterizing and correcting regional phases for propagation effects: empirical methods based on parametric dependence on path properties such as pathlength or crustal waveguide parameters, empirical interpolation methods such as cap-averaging and Kriging for station-dependent source region correction surfaces, and waveform modeling methods based on complete waveform synthesis for one-, two-, or three-dimensional crustal models. Empirically based methods remain the most viable general approach, as model based methods are still greatly limited by our wave propagation techniques and by lack of independent constraints on three-dimensional waveguide structure. Kriging and waveguide parameter regressions for frequency dependent regional phase amplitude ratio measurements for International Seismic Monitoring Stations, NIL and ZAL were conducted in the first year of this study. The data have a large amount of scatter, much of which is attributed to wave propagation effects; however, propagation corrections are limited by our understanding of source induced scatter and by effects of partial or total blockage of regional phases. We have addressed the issue of source induced scatter by analysis of a well-controlled data set of regional recordings of shallow earthquakes with reasonably well-determined focal mechanisms. By using events in very close proximity with varying depth and/or focal mechanisms recorded on common paths, we have isolated source-related contributions to variance in regional seismic discriminant measurements involving P/S-type ratios (e.g., Pn/Lg, Pg/Lg, Pn/Sg, and Pg/Sg) for earthquakes in southern California and southern Nevada. Broadband waveforms for earthquakes near the Nevada Test Site (NTS) and in southern California recorded at stations of the Livermore NTS Network (LNN), the Caltech TERRAscope Network, and the Berkeley Digital Seismic Network (BDSN) are used to obtain the seismic discriminant measurements. Pn/Lg and Pg/Lg spectral amplitude ratios for various frequency bands between 0.5 and 10 Hz from vertical velocity waveforms are computed for 17 tightly located clusters of earthquakes. For each cluster, we examine the correlations between observed Pn/Lg and Pg/Lg ratios and estimated source depths or previously determined source mechanisms. Focal mechanism predictions do not match the observations well, likely due to refraction and directivity effects that overwhelm the point-source radiation pattern. However, the data do show significant scatter that is clearly not attributable to varying path structure. Source depth effects show weak trends, with events shallower than 3 kilometers having enhanced Pg/Lg and Pn/Lg ratios that contribute to the overall scatter. Depth dependence is of great concern, as it undermines the empirical approaches to path correction. Variance estimates for logarithmic amplitude ratios normalized by mean amplitude ratios vary from 0.01 to 0.05 for different phase pairs, and there is strong dependence on propagation distance. These variance parameters appear to be suitable for use in spatial interpolations of observed P/S type ratios for a specific unidentified event path. With respect to blockage effects, we have undertaken a specific study of blockage associated with Lg phases traversing the northern margin of Tibet. Using observations at WMQ, we explore the spatial variation of Lg transmission across the Plateau, manifested in large corner frequency shifts and disappearance of the Lg signal. The corner frequency shift shows systematic evolution with transit length in the Plateau, indicating that there is progressive, not discrete, blockage of the wavefield, and this is likely due to the anomalous crustal properties of Northern Tibet. Correction using

Kriging or parametric regression does not appear to be sufficiently accurate for safe incorporation of the discriminants into event identification procedures.

Key Words: seismic discriminants, regional seismic phases, amplitude corrections, regional wave propagation

OBJECTIVE

One of the major challenges confronting seismic monitoring of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) is discriminating the seismic signals of small underground explosions from those produced by other sources. There is tremendous regional variability in short-period signals from all sources, and the characteristics that define the source type may be subtle, easily overwhelmed by propagation complexities in the heterogeneous crust. Reliable regional seismic discriminants must have sufficiently small scatter in the background earthquake population that rare single-shot explosion events will produce diagnostic outlying measurements. That component of the scatter caused by propagation effects can be reduced by path corrections of varying sophistication. We are seeking to develop and test various approaches to reduce the scatter in regional discriminant populations, using numerous observations in Eurasia (China, Russia, and Southeast Asia, in particular) and the Middle East collected under this and a previous PL/DOE-funded effort. Multi-variate regressions of various path attributes (to assess which parametric path characterizations are significant), spatial representations of the path influences such as kriging (to enable interpolation to a unique path for a suspect event), and tests of significance of the corrections (ability to tighten up scatter in discriminant measures to a useful extent) are all being considered in our effort to develop a unified strategy for discriminant calibration that will transport into the operational regime and lead to high confidence discrimination. Basic understanding of the causes and statistical nature of source-related scatter in discriminant measurements is also being pursued, for the purpose of establishing intrinsic thresholds for propagation corrections.

RESEARCH ACCOMPLISHED

The second year of our research project has involved work on two critical problems that have emerged in the course of seeking a robust propagation correction procedure. These are the problems of source-mechanism and source-depth related scatter and phase blockage. We have conducted two separate investigations of these issues, as their resolution is required for developing an integrated approach to discriminant processing.

Seismic recordings at regional distances tend to be very complex due to the superposition of energy traveling on multiple paths within the crustal waveguide, compounded by source radiation pattern and source depths effects. The waveform complexities result in substantial scatter in various regional discriminant measurements that are designed to measure attributes diagnostic of the source type. This becomes a particular problem for isolated stations in tectonically complex areas with great variation in path and earthquake properties. For CTBT monitoring, identification of rare explosion signals becomes a statistical problem of recognizing measurements with explosion attributes as outliers in a population of corresponding measurements for earthquake signals. Reduction of the scatter in the reference earthquake population is essential for high confidence outlier detection (e.g., Fisk, 1994). Scatter in regional discriminant measurements associated with path propagation effects is typically suppressed by empirical means such as distance corrections, attenuation corrections, spatial averaging of event populations by methods such as cap-averaging and kriging (e.g., Schultz et al., 1998; Phillips, 1998; Hartse et al., 1998; Rodgers et al., 1999) or regression on waveguide parameters such as crustal thickness and elevation (e.g., Fan and Lay, 1998a). When such methods are applied, there is always a question of how much of the scatter can really be attributed to propagation effects, versus source effects? Corrections that reduce all of the variance would likely map source induced scatter into erroneous path corrections, potentially giving poor performance of the discriminant for the next unknown event in the region. A firm statistical basis for separating correctable path contributions from intrinsically non-correctable (other than by simple methods such as azimuthal averaging, which is seldom viable in the CTBT monitoring context) source contributions is needed. There are many examples in the literature of individual regional distance waveform anomalies attributed to source depth or focal mechanism effects, typically for nearby events recorded on the same path, but as yet there has not been a thorough statistical analysis of the variance contributed by source effects that can guide efforts in path correction.

In our efforts in quantifying source radiation pattern and source depth effects, the following strategy evolved for isolating the near source contributions and seeking to quantify them. We used three sets of events, each comprises one or more clusters of earthquakes with accurate locations within a few kilometers of one another. For the first and second sets of events, we seek clusters of small earthquakes with known focal mechanisms. The events in the first set are aftershocks of the 29 June 1992 Little Skull Mountain earthquake (Mw=5.7) near NTS and are located in a single cluster. The events in the second and third sets are earthquakes located in Southern California, which comprise three and seventeen clusters, respectively. The focal mechanisms and depths for all the events in the second set were determined by Thio and Kanamori (1995). The third set of events is the extended events set, which includes the second set of events as well as events for which focal mechanisms are not available and the magnitudes are small. The hypocentral parameters of the events in the third set are from the Southern California Earthquake Center (SCEC) catalog. Hereinafter we will refer to these event sets as the LSM-Events set, TK-Events set, and SCEC-Events set.

Because events in a given cluster are located within a few km from the center of the cluster, regional recordings several hundred kilometers away should share common propagation structure. Propagation effects can still vary in a common structure as a result of source depth effects intermingled with source radiation effects. Multipathing effects are expected to be complex and frequency dependent and cause focal-mechanism dependent wave propagation with partitioning between various paths for a given type of wave depending on source radiation pattern.

We began with analysis of the first set of events, for which radiation pattern variations among various events can be estimated using the focal mechanisms determined previously. The focal mechanisms and source depths can be used to predict synthetic P/S amplitude ratios for specific discriminants to assess how deterministic the scatter observed in the discriminants is. For events with similar source depths and focal mechanisms, the scatter observed in regional discriminant measures for these common paths can be used to define the statistical variance in earthquake measurements that we expect to have to deal with, as a function of distance and frequency. We can correlate the scatter with source depth and radiation pattern variations to further quantify the contributions from specific source properties.

The strategy is illustrated in Figure 1 for aftershocks of the Little Skull Mountain earthquake. Focal mechanisms and relative source depths are available for these events from Harmsen (1994) and Meremonte et al. (1995), and discriminant measurements are from Walter et al. (1995). We compared data with focal mechanism predictions for the Little Skull Mountain events, finding little correlation between observed and predicted P/S ratios for most stations, but some stations do indicate systematic variations with source depth. Figure 1 shows that there is moderate variability in mechanism type, which is primarily normal faulting with the exception of two strike slip events. For station MNV Pg/Lg measurements range over a factor of 4, while Pn/Lg measurements vary over a factor of 2.5; the scatter is larger for both phases for station KNB. The magnitude of the scatter does not vary much with frequency, and correlations between frequency bands are relatively high for Pn/Lg at station KNB, but low for other ratios at KNB and MNV. Predicted P/S ratios obtained by integration of the focal mechanisms over appropriate take-off angles and azimuths show weak correlations with the observed amplitude variations for MNV (Figure 1) as well as KNB (not shown here). For MNV the variation of predicted ratios for Pg/Lg is comparable to that for observed ratios, while for Pn/Lg the variation of predicted ratios is a factor of two larger than that for measurements. Little correlation with depth was found for the Pg/Lg and Pn/Lg measurements as well.

Given that the Little Skull Mountain events have substantial uncertainty in focal mechanism, we sought to find other clusters of earthquakes with known mechanisms recorded at regional distances by broadband stations. Southern California provides numerous earthquake clusters for which the focal mechanisms have been determined by broadband waveform inversions (e.g., Thio and Kanamori, 1995). Figure 2 shows locations of a total of 17 clusters of Southern California earthquakes and broadband stations used in this study. The events in the clusters occurred in 1992-1998 and were located at regional distances from the stations (100-1100 km). Some of the events have known focal mechanisms and belong to both the TK-Events and SCEC-Events sets, while others do not have known focal mechanisms and are included only in the SCEC-Events set.The clusters comprise 350 earthquakes with magnitudes ranging between 3.5 and 7.0 (there are 210, 93, 38, 15, and 3 events with magnitudes less than 4.0, 4.0-4.5, 4.5-5.0, 5.0-5.5, 5.5 and larger, respectively). Each cluster includes 40-70 earthquakes that were located within 10 km from the center of the cluster. Some of the clusters are closely located and named with similar identifications; events in A-clusters are associated with the earthquake sequence of Northridge of 17 January 1994 (Mw=6.7); B-clusters for the Joshua Tree sequence of 23 April 1992 (Mw=6.1) and Landers sequence of 28 June 1992 (Mw=7.3); C-clusters for the Big Bear sequence of 28 June, 1992 (Mw=6.2).

One of the main difficulties encountered in this analysis involves the windowing of regional phases at these relatively close distances of less than 200 km, particularly when source depths vary from 5 to 15 km. The problem is that as the source depth increases, the depth phases may move out of one group velocity window (say, for Pn) and into another (say, for Pg), thus causing contamination of the energy measures computed for the separate phases. This is difficult to account for in the prediction of amplitudes by focal mechanism integration.

In order to 'tune' the integrations to better reflect the actual contributions from phases for different source depths, we constructed regional distance synthetics for various source/receiver geometries using the range in source depths and focal mechanisms of the observations. Then we found ranges of radiation pattern integrations that provide reasonably good predictions of the observed relative amplitudes in the Pn, Pg, and Lg windows. This guided us to incorporate sPn contributions to the Pn window for shallow events and Sg contributions to the Pg window (S waves that come out from the source, convert to P, and then arrive in the Pg window). We found quite good predictability at distances of 220 to 400 km, but shorter distance windows are very problematic due to the short time windows and overlapping of depth phases.

Using our refined radiation pattern integration criteria, we further analyzed three clusters of events (clusters A1, B1, and C1); each cluster comprises events located within a 10 km radius, recorded at several TERRAscope and BDSN stations, and had diverse focal mechanisms. The correlations with focal mechanism predictions and source depth are generally found to be weak, certainly much lower than for synthetic predictions. Yet the scatter in the observations is very substantial, and it presumably does reflect either a source effect or some remarkable sensitivity to the precise travel path taken.

We further analyze characteristics of Pg/Lg and Pn/Lg measurements for events in the SCEC-set, which comprises all the events in the 17 earthquake clusters (Figures 2). This is the extended events set from the TK-set, with focal mechanisms for most events here are not known. The corresponding data are broadband waveforms recorded at eleven BDSN and seven TERRAscope stations. For each cluster we calculated Pn/Lg and Pg/Lg spectral amplitude ratios for various frequency bands between 0.5 and 10 Hz (the frequency passbands span 0.5-1, 1-2, 2-4, 4-6, 6-8, and 8-10 Hz) using vertical velocity waveforms. Then, to characterize the scatter of the observed Pn/Lg and Pg/Lg measurements for the cluster we computed the variance, mean, minimum, and maximum of the amplitude ratios for all the events in the cluster.

With the exception of Pn/Lg measurements for cluster A1 events, all the Pn/Lg and Pg/Lg measurements span in the range from -0.5 and 0.5 in the 10 base logarithm. A weak correlation between observed P/S ratios with source depth suggests some relationship between source depth and Pg/Lg and Pn/Lg measurements. The weak correlation indicates that Pg/Lg and Pn/Lg measurements are more sensitive to source radiation pattern or the precise location of each event in the cluster. Figure 3 shows the distribution parameters of Pg/Lg, for the 2-4 Hz passband for all the station-cluster pairs used in this study. Figures 3 shows that there are considerable differences between scatter of the distribution parameters; the scatter for epicentral distances of 100-300 km is much larger than that for longer distances; the distribution parameters tend to become small in absolute value at large distances. This distance dependence may be important for Kriging applications.

In this analysis for various station-cluster pairs we found little correlation between P/Lg measurements and source depth for Little Skull Mountain events and TK-set events. This presumably reflects some remarkable sensitivity to the effect of source radiation pattern (including focal-mechanism dependent wave propagation) and the precise location of each event in a cluster (including location dependent wave excitation and propagation). Because effects of source radiation pattern and wave propagation on Pn/Lg and Pg/Lg ratios vary among stations located in different azimuths and distances, the effects are expected to be reduced by stacking (averaging) the ratios for various stations. Therefore the stacking procedure allows us to examine the effects of source depth on observed Pn/Lg and Pg/Lg ratios for events in various clusters. In calculation of the station averaged ratio it is desirable to use stations that are azimuthally well distributed. However, most stations used here are distributed to the north or northwest of the event cluster, and there are usually a few stations with good SNR for small events with magnitudes less than 4. Therefore, we expect that much of the effects of source radiation pattern and wave propagation remain in the station averaged ratios calculated using our data set, in particular, for the Pn/Lg ratio; the effects are large for the depth range where only small events are included in our events set.

We examined the depth distribution of the station averaged Pg/Lg and Pn/Lg measurements for events in each cluster. The station averaged Pg/Lg or Pn/Lg ratio for each event was plotted in logarithm against the depth of the event, normalized with the average value for all the events in the cluster. For A-cluster events, which comprise the largest events set used in this study, negative logarithmic Pg/Lg ratios for events near the free surface indicate large Lg excitations relative to Pg in comparison to events with other depths; the logarithmic Pg/Lg and Pn/Lg are positive and have relative maxima at depths less than 3 km and minima at depths between 3 and 5 km; below 5 km the overall trend of Pg/Lg and Pn/Lg is increasing with depth. Large Lg excitations for shallow events are also found for C- and D-cluster events, but not for B-cluster events. Since the events in A-, C-, and D-clusters occurred in basin-like structures in contrast with B-cluster events, the large Lg excitations may be caused by surface geology and/or topography associated with the basin structures for clusters A, C, and D. An overall trend of increasing Pg/Lg and Pn/Lg for depths below 5 km is also found for events in clusters B, D, and

F, which suggests that deep events excite stronger Pg and Pn waves and weaker Lg waves than shallow events. The Pg/Lg and Pn/Lg minima at depths between 3 and 5 km are also found for B-cluster events, which may correspond to large Lg excitations in comparison with events at other depths. The minima may indicate discontinuities of material properties, a situation similar to the free surface, which are favorable for Lg excitations.

One of the main observations of this analysis is that there is little correlation between observed and predicted P/S ratios for most stations for the Little Skull Mountain events and Southern California events, for which focal mechanisms were determined previously. This is caused primarily by our inability to predicted P/S ratios for realistic structures between source and station, although we found quite good correlation between computed P/S ratios using waveforms computed from the reflectivity methods and point-source radiation pattern integrations. Another source of the weak correlation is the limitation of point-source radiation pattern integrations. Although this analysis has not been encouraging with respect to isolating deterministic focal mechanism contributions to the scatter in discriminant measures for Little Skull Mountain and California earthquakes, further examination of the source mechanisms effects on regional signals in diverse regions of the world is necessary. There may be possible explanations for the weak correlation between observed and predicted focal-mechanism-dependent scatters, with the limitation of point-source radiation pattern integrations being a likely source of inaccuracy. Even small events can have directivity effects and complex weighting of the specific arrivals at a given range that are difficult to account for. It is also possible that the source mechanisms for many of the small events are very poor, and this likely to be true for the source depths (even in a densely-instrumented region such as California).

The second part of our effort this year has been to improve our understanding of continental Lg blockage. Lg is sensitive to the laterally heterogeneous velocity structure and changes in crustal discontinuities and crustal thickness. Usually, Lg can be described as a superposition of many higher modes or trapped postcritical S reverberations. Blockage of Lg was first observed for travel paths involving segments of oceanic crust (Press and Ewing, 1952). Lg blockage also was noted in continental areas with large changes in crustal thickness, such as the mountain belts in central Asia (Ruzaikin et al., 1977). It is believed that scattering of Lg energy from fractures within the crust may be a major cause of strong Lg attenuation in tectonically active regions. It is also possible that the lack of continuous waveguide in areas with significant variations of crustal thickness may result in strong attenuation of Lg.

For most parts of the Asian continent, Lg is observed, however, Lg blockage is reported for paths crossing the Tibetan Plateau (Ni and Barazangi, 1983; McNamara et al., 1996; Rapine et al., 1997). Qualitative analysis of Lg propagation efficiency relative to P-wave coda reveals that Lg signals are attenuated within central Tibet and along its southern boundary (Ni and Barazangi, 1983; Rapine et al., 1997). Using data recorded at 11 broadband stations around Tibet, it is found that Lg is generated inside the Plateau, and can propagate to distances of at least 600 km; however, for the paths crossing the Himalayan and Kunlun mountains Lg is either blocked or strongly attenuated (McNamara et al., 1996).

In this study, we used regional waveforms recorded at a broadband station WMQ to investigate energy partitioning of Lg, as defined by a group velocity of 3.6 to 3.0 km sec^{-1}. We analyze 81 earthquakes with magnitudes of $4.4 \leq m_b \leq 6.4$, that occurred between 1987 and 1998 in the Tibetan Plateau and around its margins (Figure 4). The recorded seismograms show great variability in broadband waveform complexity on different paths. For events prior to the middle of 1997, we use source parameters given by the International Seismological Centre (ISC) bulletin, for later events we use source parameters provided by the USGS Preliminary Determination of Epicenters (PDE) catalog. Only events with focal depths less than 45 km are condsidered in this study. All events used have signal-to-noise ratios greater than 2 based on the measurements for Pn signals and pre-Pn noise. Because all events are recorded at a single station, the site effects and instrument response are not concerns in evaluation of attenuation of Lg energy.

To quantifying Lg attenuation and blockage effects, we first visually examine all vertical seismograms to see how Lg is manifested. We measure the corner frequency (f_c) of the amplitude spectra for each event, and use corner frequency as a parameter to demonstrate the degree of relative attenuation of Lg energy. For the events located near the northern margin of the Tibetan Plateau, Lg has large amplitude and a corner frequency of 1 – 2 Hz. The Lg energy decays slowly at frequencies higher than 2 Hz and more rapidly after 5 Hz. Figure 5a shows velocity spectrum for an event that is located close to the northern margin of the plateau. The signal-to-noise ratio is high at frequencies up to 10 Hz. A comparison with amplitude spectra for events outside the Plateau at similar distances and approximately equal seismic moment indicates that Lg is very normal for events near the northern margin. This is consistent with the observation that Lg from events northeast of the Plateau can be recorded at seismic stations near the northern edge of the Plateau for about 200 km (McNamara et al., 1996). It is also supported by a numerical simulation of Lg wave propagation, which shows that a Moho step does not cause Lg blockage (Gibson and Campillo, 1994).

In contrast, for the events that are located near the Himalayan mountains, Lg wave is very weak or entirely absent. Corresponding corner frequencies for amplitude spectra are observed to be lower, usually ranging between 0.2 ~ 0.4 Hz. Since observable Lg is generated by the source within the Plateau (McNamara et al., 1996), the lack of Lg energy and low corner frequencies indicates a strong attenuation of Lg energy at frequencies between 0.3 ~ 0.5 and up to 1 Hz along the paths crossing through the Plateau (see Figure 5b). In general, a good signal-to-noise ratio is expected at frequencies below 3 ~ 5 Hz. On a profile crossing the Tibetan Plateau, the corner frequency of the amplitude spectra decreases systematically with distance. Figure 6a shows the corner frequency of the amplitude spectra as a function of the path length. There is a shift in linear trend as the back azimuth changes. We performed linear regression analysis to investigate which physical factor is the most important contributor to Lg extinction. Although low Q beneath the plateau is certainly a very important candidate (Ruzaikin et al., 1977), we only consider topographic features and waveguide structure in our analysis due to the limited availability of information. Regression analysis shows that corner frequency of Lg amplitude spectra has a strong negative correlation with the topography measures of the Tibetan Plateau (as high as 0.92 ~ 0.94), such as mean elevation along the paths (see Figure 6b) or the travel distance over the plateau above a certain elevation. At the same time, there is little evidence for a relationship between the corner frequency and the event magnitude or type of the faulting. The absence of Lg energy can be attributed to the effects of partial path within the Plateau. While this is a progressive path effect, the effect is so overwhelming that correction is difficult and inaccurate.

CONCLUSIONS AND RECOMMENDATIONS

We have explored two fundamental problems that challenge efforts to develop an integrated strategy to discriminant processing. We have empirically characterized the frequency dependence and distance dependence of variance in regional discriminant measures for events in California. The intrinsic scatter is substantial, and represents the combined effects of focal mechanism and source depth. These results can be applied for improved kriging procedures and for better understanding the limitations of path correction procedures. Central Asia, an area of great interest for CTBT monitoring, has long been recognized as a region with regional phase blockage, for either Sn or Lg arrivals. We have systematically explored the phenomenon of blockage associated with the Tibet Plateau, for the purpose of assessing whether blockage is progressive, discrete or correctable.

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