Lg Site Amplification Calibration for Isolation of Lg Propagation Effects

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Abstract

We observe geographically clustered variations in Lg/Pg amplitude ratios of regional earthquakes and NTS events, using southern California seismic network (SCSN) recordings. These variations can occur abruptly over length scales on the order of ten kilometers and are the cause of significant errors in discrimination of regional earthquakes from nuclear explosions. Observations from events at different distances and azimuths suggest that variations are not due to distance effects, very near receiver or source effects, or source radiation, and so we conclude that the variations are largely due to the effects of propagation along the different source-receiver paths.

Our goal is determine which measurable path parameters, if any, (e.g. topographic roughness, waveguide thickness, waveguide thickness variation, attenuation) correlate with variations in the crustal phases. To avoid ambiguity over which phase varies, Lg or Pg, we will estimate the Lg site amplification at each station using the *diffuse* (near receiver scattered) component of teleseismic coda. Near receiver scattered coda and Lg can both be described in terms of surface waves, and measurements using a temporary array indicate that for the same passbands, Lg and diffuse teleseismic coda have similar phase velocities. The array measurements also indicate that the incoming directions of arrival of energy in diffuse coda are fairly evenly distributed. By beamforming, using all SCSN records for a given event, we make an estimate of the *coherent* (near source scattered) component of teleseismic coda, which we remove from each individual coda record. We find, in agreement with previous researchers, that the deep teleseismic coda is almost entirely composed of near receiver scattered energy while 10% to 60% of the shallow teleseismic coda may be composed of near source scattered energy. The removal of the coherent coda appears to be very effective and so lets us use shallow earthquakes as well as deep ones, for better azimuthal coverage of teleseismic events.

Objective:

The objective of this research is to better understand the propagation of regional phases important to discrimination. Specifically, we want to test whether spatial variations in regional Lg to Pg amplitude ratios exist and are strong enough to effect discrimination. Then, to separate Lg amplitude variations from Pg amplitude variations, in order to reduce ambiguity in any interpretation, we want to estimate Lg site amplifications at the recording stations using the diffuse component of teleseismic coda. Finally, we want to test whether the Lg or Lg/Pg anplitude variations may be be predicted by topography, gravity, or other easily measurable geophysical parameters.

Preliminary Research Results:

The Lg phase is very important in regional discrimination.The Lg/Pg amplitude ratio is the best performing regional discriminant, and spectral ratios of Lg are more effective discriminants than those of Pn or Pg (Taylor et. al., 1989). Lg is also important in estimating earthquake magnitude or yield of explosions, but frequency-dependent attenuation causes significant variation in scaling slopes between different paths (Xie and Lay, 1995). There is, however, significant error associated with the Lg/Pg amplitude ratio discriminant (figure 1).

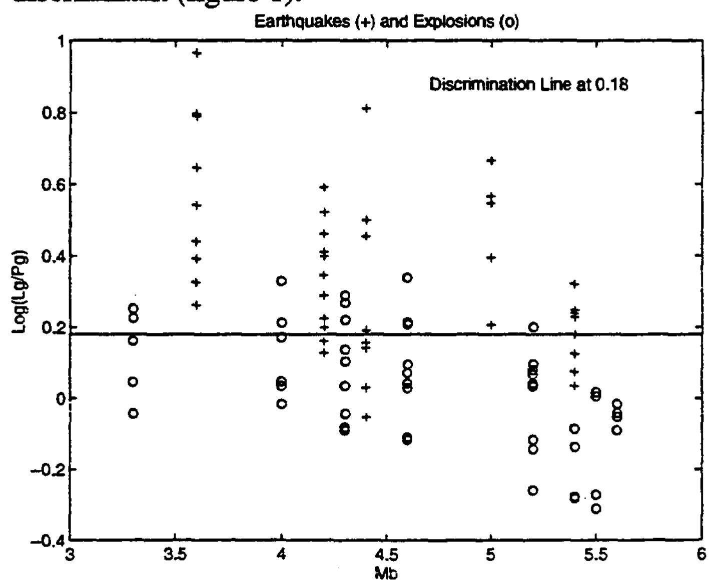

Figure 1: The discriminant Ln(lg/Pg) vs. magnitude for NTS explosions (plusses) and regional earthquakes (circles), divided by a discrimination line at 0.18 (very similar to that found by Taylor et. al., (1989), for the western U.S.). Note that many events of both types would be misclassified at some stations.

To improve discrimination, we would like to know whether the events misclassified in figure 1 have anything in common. Previous research (e.g. Baumgardt, 1985; Zhang et. al., 1994) has shown correlations of Lg amplitude variation with features along the propagation path. Thus it is reasonable to expect some systematic geographic variation in the amplitude ratios. Indeed, this is observed in southern California (see figure 2). That source radiation or near source scattering is not the primary cause of the variation is indicated in figures 2 and 3. We also see no correlation between nodes in the P radiation pattern (either predicted by known mechanisms or observed in first arrival polarizations) and maxima in Lg/Pg ratios, suggesting that the source radiation pattern does not dominate the observed geographical distribution. Figure 4 indicates that variations in the Lg/Pg amplitude ratio are neither due to a simple distance effect nor are they due to near station scattering or site effects. Similar observations for regional earthquakes at different distances and azimuths remain consistent with these findings. By elimination of other possibilities, we conclude that geographic variations in Lg/Pg amplitude ratios are due to effects along the path of propagation.

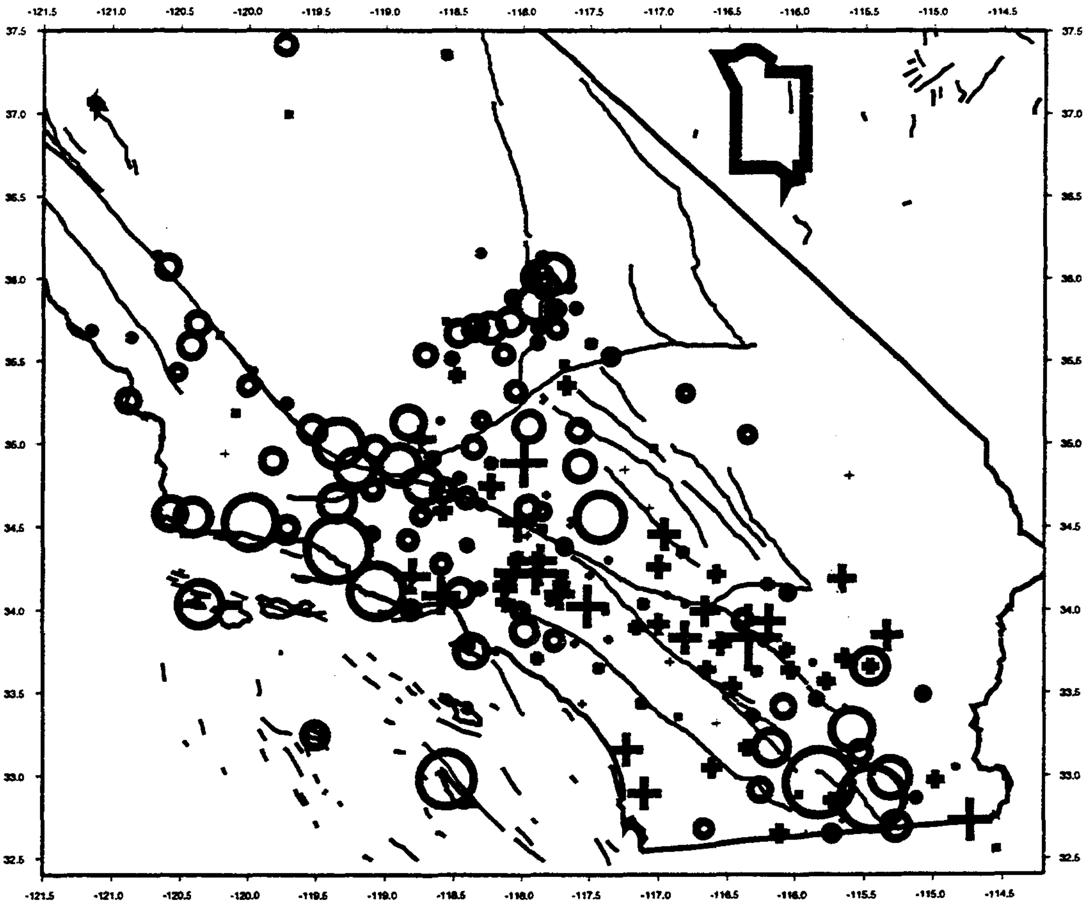

Figure 2: The symbol at each southern California seismic network station represents the typical Lg/Pg amplitude ratio at that site relative to the rest of the network, determined by averaging normalized Log(Lg/Pg) amplitude ratios for 10 NTS explosions. The symbols are as in figure 1, and are scaled by distance from the discrimination line. As these are normalized, a plus at some station does not necessarily mean that the event would necessarily have been misclassified as an earthquake, only that it appears more "earthquake-like" at that station than at other locations. The important point of this plot is the consistent very distinct geographic clustering of like symbols over many explosions with source locations separated by as much as 50 km. This suggests that near source scattering does not cause the geographic variation.

Lg amplitude variations (usually relative to the amplitude of one of a variety of other phases) have been related to other geophysical parameters that can be independently measured or estimated (e.g.Mitchell et. al. 1995, Zhang et. al, 1994, Zhang and Lay, 1994). This has laid the groundwork for the calculation of path corrections for regional discriminants. The broadband data available for those studies was limited, however, to between 7 and 10 stations spread over several thousand kilometers. The southern California seismic network (SCSN), with several hundred stations spread over a few hundred kilometers has station spacing on the order of 10 to 15 km. Such fine spatial sampling in such a heavily studied region should permit more precise correlation of Lg amplitude variations with path structure.

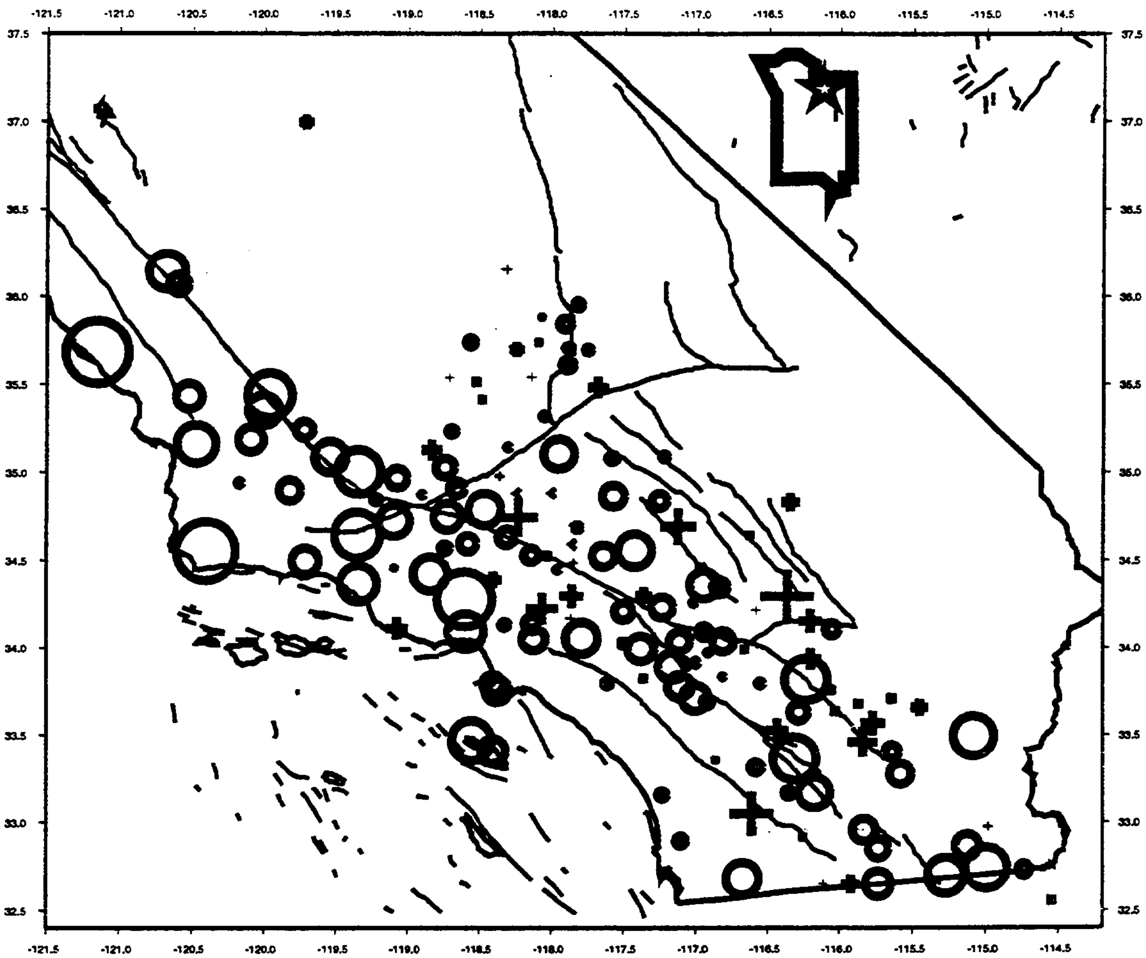

Figure 3: Classification as an earthquake or explosion, by station, of a shallow earthquake within NTS (star symbol indicates earthquake location). Note that the pattern of symbols is similar to that in figure 2, with more plusses in the central part of the network. This suggests that the source radiation pattern plays only a minor role, and provides further evidence that near source scattering may not be important.

The geographic variation of amplitude ratios could be due to either Lg or Pg amplitude variations, or both. To prevent this ambiguity from clouding any interpretation, we would like to calibrate the amplification of each site so we can obtain estimates of amplitude variations for single phases. Note that when we use amplitude ratios, we implicitly assume that site amplifications are the same for both phases used, a possible source of error if differences exist and are mapped into path corrections. Barker et.al. (1980), however, found that for recordings of events with very similar paths to adjacent stations on very different geological structures, the Lg to Pg amplitude ratios were the same. They also distinguished no azimuthal effect.

We propose to use the near receiver scattered component of teleseismic coda as an azimuthally evenly distributed source of Lg-like energy. The nature of both Lg and near-station scattered coda in the frequencies of interest merits further discussion. We must also ask how effectively we can isolate the near-station component of teleseismic coda.

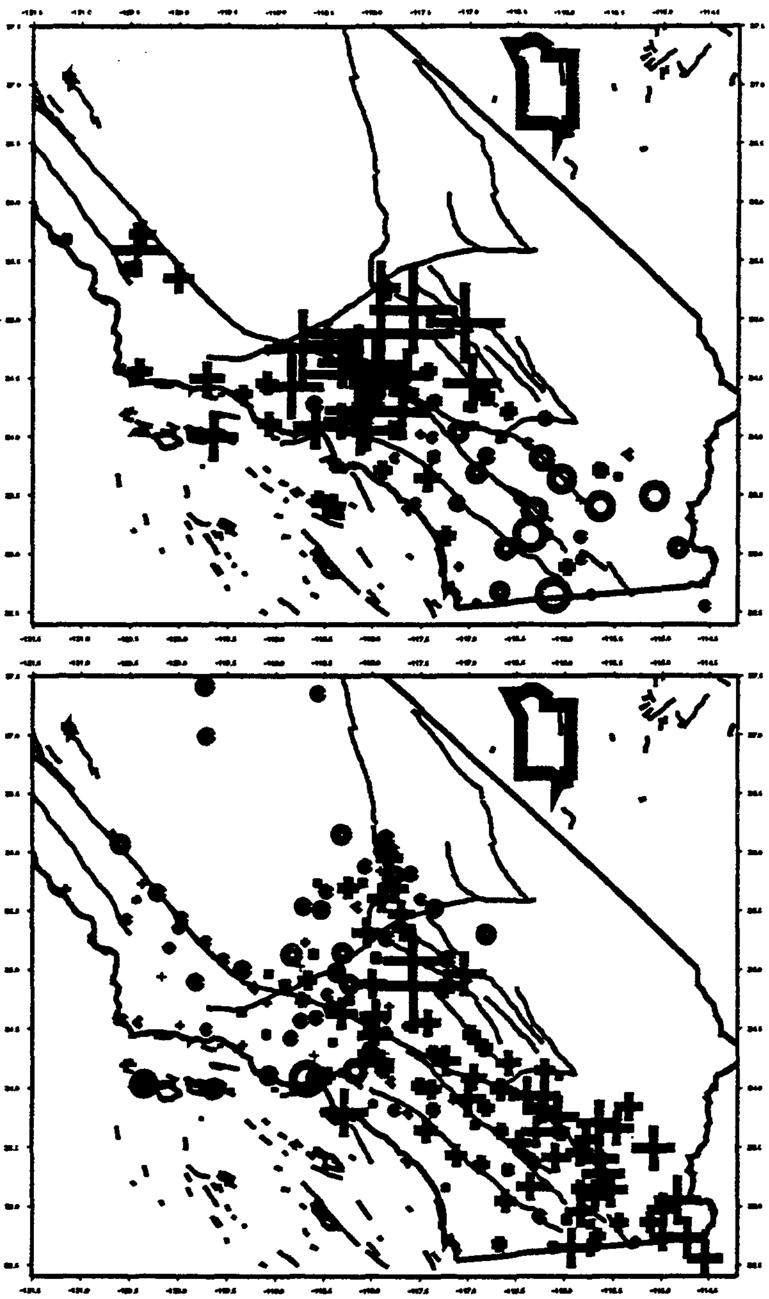

Figure 4: Symbols are as in all previous figures. Above are the classifications for an earthquake in the southern Sierra Nevada. Below are classifications for an earthquake near Cape Mendocino. In the first case, the most distant stations are misclassified as explosions, while in the second case, it is the nearest stations that would misclassify the event. This suggests that the pattern of misclassification is not a near station effect or a distance effect.

Lg is commonly thought to consist of higher mode surface waves (e.g. Båth, 1954). These phases do not remain coherent over even short distances (e.g.. Baumgardt, 1985) due to their sensitivity to variations in crustal structure and so should be especially short lived in a tectonically young region as southern California, with its rapid spatial variations in crustal thickness and velocities (e.g. Magistrale, 1992). Nonetheless, Cara et. al (1981) found that peaks in phase and group velocity measured in southern California for 2 to 5 second period data were consistent with higher mode Rayleigh waves predicted from appropriate velocity models. More recently, Wagner (1995) used 3 component array analysis to identify specific high frequency Rayleigh and Love waves (1.8 and 2.5 Hz. peak frequencies respectively) in the most prominent part of a nuclear explosion Lg wavetrain.

Teleseismic coda is generally understood to consist of the sum of near-source and near-receiver scattered energy (e.g. Langston, 1989). Energy scattered near the source, into P, travels along nearly the same path as the initial P wave, and is referred to as the *coherent* part of the coda (Dainty, 1990). The *diffuse* component of coda, that is, energy scattered near the receiver from the incoming P wave, travels with much lower phase velocity, 3.3-3.4 km/sec near NORESS. Dainty (1990) notes that this is "*typical of shear waves propagating sufficiently close to horizontal to be trapped in the crustal waveguide (Lg) or surface waves*", and suggests that those are the major components of diffuse coda. The teleseismic coda of deep focus earthquakes has been shown to consist largely of diffuse coda (e.g. Dainty, 1990), and so may provide the multi-azimuthal source of energy appropriate for Lg site calibration.

Individual very near receiver scatterers have been identified, usually by stacking large data sets in some way to enhance an image. As noted by Revenaugh (1995b), identification of individual scatterers associated with topography has been limited to those with vertical scale lengths on the order of half the seismic wavelength. Revenaugh (1995a,b) uses the southern California seismic network (SCSN) to investigate the contribution of P to P, P to S, and P to Rg scattering to teleseismic coda and finds significant scattering over large areas. Using migration, he obtains the sharpest image of Rg scattering efficiency at a group velocity of 2.9 km/sec. This is not proof that most of the energy travels at that group velocity, but only that the most coherent energy does. Revenaugh (1995a,b) finds both topographic and upper mantle scatterers, although nearly twice as many events are required to produce an image of an upper mantle scatterer. For site calibration, we will use much later coda windows than those used for identification of single scatterers, or even those used for scattering efficiency, in an effort to reduce any potential bias from nearby strong scatterers or strong scattering regions.

Another strong argument for the use of teleseismic coda for Lg site amplification calibration is found in an explanation for the existence of Lg in explosion seismograms. Patton and Taylor (1995), using synthetic modeling and a comparison of Lg and Pg spectral ratios with the strength of spall, argue that scattering of Rg into Lg at the surface is the main source of Lg energy at around 1 hz. If this mechanism works at the surface near a shallow source, it should also work for Rg generated at the surface by scattering from teleseismic P waves. This is consistent with the well known observation that high frequency Rayleigh waves suffer rapid attenuation in areas of sharp topography and complicated velocity structure (e.g. Kafka, 1990).

The phase velocities of Lg, measured for 2 regional earthquakes and one nuclear explosion at a temporary array at PFO, are similar to the phase velocities of the energy in the diffuse component of teleseismic coda, measured at the same array for 2 earthquakes (figure 5). Lg generally has a slightly higher peak phase velocity and somewhat more energy at higher phase velocity, possibly due to the contribution of P coda or to a higher percentage of higher mode Rayleigh waves in the Lg. We interpret the result as further evidence of the appropriateness of teleseismic coda for calibration of Lg.

The separation of the coherent and diffuse components of the teleseismic coda at the array merits some discussion. We used this technique on the SCSN network data, partly to test our assumption that the teleseismic coda of deep events consists mostly of near receiver scattered energy. The time lag between any near-source scattered energy and the initial P arrival should be nearly constant across the network. We will return to this point when we discuss the network data. For the array, of 6 km diameter, we will accept that assumption. To estimate the coherent portion of the coda, we simply align the seismograms on the first arrival and stack them. All near-source scattered energy should stack coherently and near-receiver scattered energy should be incoherent. We then remove the coherent coda from each individual record by subtracting the estimate of the coherent coda (the "beam") from the coda of each individual record. Before subtraction, the beam is scaled by its cross-correlation with the individual trace, to maximize the removal of energy. The result is an estimate of the diffuse coda at each station. In fact, a judicious choice must be made of which array elements to use in forming the beam. The array has closely spaced stations in its inner rings, for which much locally scattered energy will stack coherently. Synthetic tests have confirmed that we can avoid the inclusion of the lower phase velocity diffuse coda in the beam by using only very widely spaced stations for the beamforming, and so we use a subset of the array with a minimum interstation spacing of nearly 1 km. We verify, by inspecting the array response (Aki and Richards, 1980), that the station coverage is not so thin that sidelobes of the beam pattern overlap the slownesses of interest in our estimates.

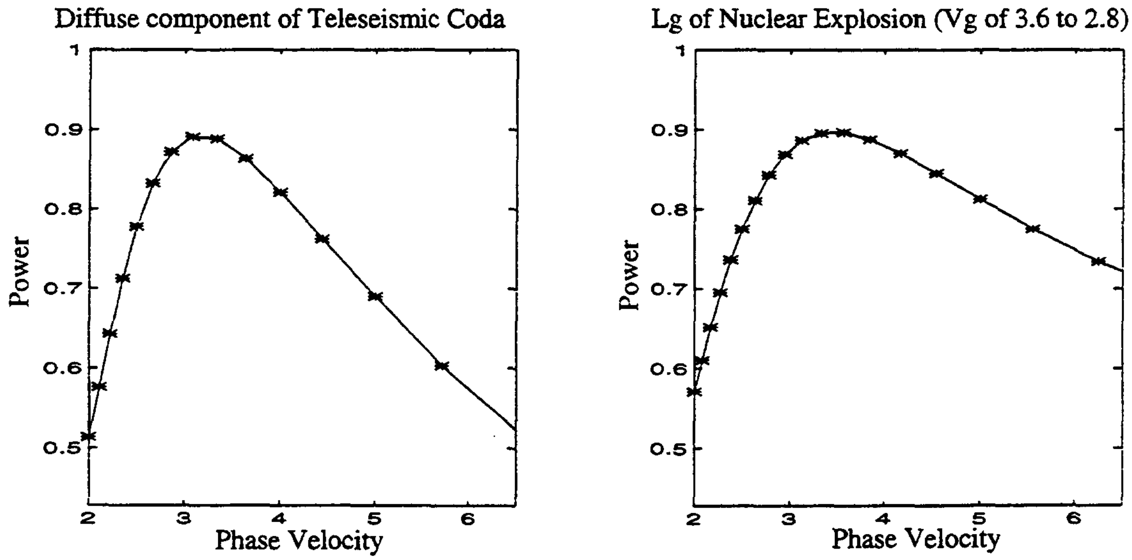

Figure 5: Power vs. phase velocity for the diffuse component of teleseismic coda (left) and Lg of an NTS explosionat 400 km distance (right).

For data collected across the SCSN, the same technique is used. For this data set, we must carefully test the assumption that all near source scattered energy will stack coherently. If scattering at several degrees distance from the source were to contribute to the coherent component of coda, the time lag between the initial P arrival and that scattered energy would not be constant over the several hundred kilometers spanned by the network and so that contribution to the *coherent* coda would not stack coherently. For example, for a source 50 degrees from the network, at 600 km depth, and a scatterer 3 degrees from the source at the same depth (to maximize the variation in ray parameter), the difference in time lag between the direct and scattered P wave for stations 0.1 degrees apart in the plane of the ray would be 0.02 seconds. For stations 1 degree apart, the difference in time lags would be 0.19 second, and so the coherence of the scattered phase would be degraded, as energy in the signal peaks at approximately one hz. For stations 3 degrees apart in the propagation direction, the difference in direct and scattered P times would be 0.6 seconds, and so when stacked, aligned on the initial P arrivals, the scattered arrivals would be nearly 180^0 out of phase and would largely cancel. As we want to use only energy traveling laterally in the crust to estimate Lg amplification, we are concerned about how much steeply incident energy may exist that is not removed by subtraction of the beam. In a situation as described above, where the change in wavenumber across the network of some scattered energy in the coherent coda is significantly different from the change in the initial arrival wavenumber across the network, the correlation coefficient between coda records should vary with station spacing. Figure 6 shows the correlation coefficients of coda windows for all SCSN station pairs plotted vs. distance for a deep earthquake. Before beam removal (top), the least-squares fit line to the points is virtually horizontal, with a slope of -5×10^{-5}. The mean value is 0.0354. Hence, while some non-zero coherence is apparent, it does not vary significantly with distance from the source. That the coherent portion of the coda is effectively removed by beam subtraction is illustrated in the lower half of the figure. There, the mean value is effectively zero. We obtained similar results for shallow earthquakes, with much larger initial values of mean coherence, but effectively zero coherence after beam removal, indicating effective separation of the coherent from the diffuse coda even for shallow earthquakes. This result has allowed us to improve our azimuthal coverage of teleseismic sources..

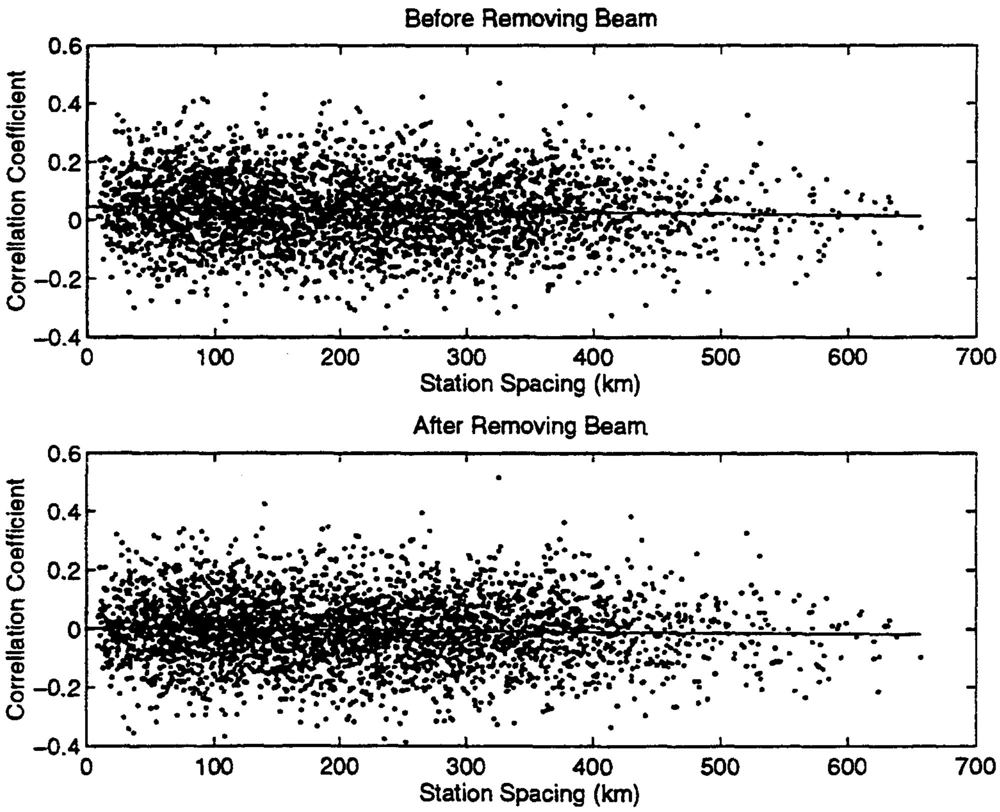

Figure 6: The correlation coefficient of the teleseismic coda records for the same time window after the initial P, at each pair of stations, for one deep event recorded at the SCSN, plotted vs. interstation spacing. (top) before beam removal and (bottom) after beam removal.

The mean ratio of energy in coherent to diffuse coda for 10 deep events was 0.05. The ratio for 9 shallow events varied from 0.12 to 1.18. It also was necessary to calculate instrument calibrations (Wald et. al., 1994), even though the magnification could have been absorbed into the site response. This is so we could take into account the times when calibrations changed. It also will permit a comparison with site amplifications determined from local S-wave coda (Su F. and K. Aki, 1995) once our site response calculations are completed.

For the actual calculation of site amplifications, we will need to take into account the censoring of the data. That is, at certain stations, records are clipped for large signals, and at others the amplitudes remain below the pre-event noise level for small signals. Ignoring those facts would lead to biases in the estimates of amplitudes over the whole network, downward for large signals and upward for small signals. Following Ringdal (1977) and Blandford (1982). we can write

$$A_{i,j} = E_j \times S_i \tag{1}$$

where, $A_{i,j}$ is the measured amplitude of event j at station i, E_j is the mean amplitude of the coda averaged over the network for the chosen window for event j, and S_i is the site amplification at station i. We take the natural log of equation 1, to get

$$a_{i,j} = e_j + s_i, \tag{2}$$

where $a_{i,j}$ is $\ln(A_{i,j})$, e_j is $\ln(E_j)$, and s_i is $\ln(S_i)$.

The likelihood function for our amplitude observations is then,

$$L(a_{1,1}, a_{1,2}, \ldots, a_{i,j}, \ldots, a_{n,m} \mid e_1, e_2, \ldots, e_m, s_1, s_2, \ldots s_1) =$$

$$\prod_{i,j\epsilon\mathcal{D}} \phi_{i,j}\left(a_{i,j}\right) \prod_{k,l\epsilon\mathcal{N}} \Phi_{k,l}\left({}_1t_{k,l}\right) \prod_{p,q\epsilon\mathcal{C}} \Phi_{p,q}\left({}_2t_{p,q}\right)$$

where ϕ and Φ are the normal and cumulative normal distribution functions, $\mathcal{D}$ is the set of measured amplitudes, $\mathcal{N}$ is the set of observations in which the signal was below the noise level, and $\mathcal{C}$ is the set of clipped records. For the latter 2 sets, ${}_1t_{k,l}$ and ${}_2t_{p,q}$ are the estimated threshold values. So we find

$$\frac{\delta}{\delta e_j} ln(L) = \sum_{i,j}\sum_{\epsilon \mathcal{D}} \frac{1}{\sigma_{i,j}^2}\left(a_{i,j} - e_j - s_i\right) + \sum_{k,l}\sum_{\epsilon\mathcal{N}} \frac{1}{\sigma_{k,l}^2} \frac{\phi_{k,l}\left({}_1t_{k,l}\right)}{\Phi_{k,l}\left({}_1t_{k,l}\right)} + \sum_{p,q}\sum_{\epsilon\mathcal{C}} \frac{1}{\sigma_{p,q}^2} \frac{\phi_{p,q}\left({}_2t_{p,q}\right)}{\Phi_{p,q}\left(t_p^{(2)}\right)} \tag{3}$$

where

$$\phi_{i,j}\left(a_{i,j}\right) = \frac{1}{\sigma_{i,j}} \phi\left(\frac{a_{i,j} - e_j - s_i}{\sigma_{i,j}}\right), \text{ and}$$

$$\Phi_{i,j}(t) = \int_{-\infty}^{t} \phi_{i,j}(x_i)\delta x_i$$

Setting the right side of equation 3 equal to 0 provides the set of equations we must solve numerically to obtain station corrections.

Recommendations and Future Plans:

We have concluded that propagation effects cause variations in Lg/Pg amplitude ratios of sufficient size to affect discrimination significantly. Once station calibrations have been computed from diffuse teleseismic coda, they will be applied to Lg of regional earthquake and explosion records for all possible azimuths (such as those shown in figures 2-4). Mitchell et. al. (1995) distinguish the effects of intrinsic from scattering attenuation in Eurasia by comparing Lg Q and Lg coda Q. A similar approach with the very dense data set in southern California may provide good results. If scattering is very important to Lg amplitude variation in southern California, it should also prove useful to compare variations in Lg amplitude with changes in path parameters in the direction of propagation.

Having a measure of absolute Lg amplitude variation will permit a comparison with Lg/Pg amplitude ratio variation, and so determination of which phase varies. Hence, in addition to furthering our basic understanding of Lg propagation, we should be able to bring our results to bear on the development of path corrections for the Lg/Pg regional discriminant.

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