# PREDICTING CRUSTAL PHASE PROPAGATION FROM OTHER GEOPHYSICAL PARAMETERS

G. Eli Baker and Mariana Eneva, Maxwell Technologies, Systems Division

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**ABSTRACT**

Crustally guided shear and compressional waves, which generally arrive within well-defined group velocity windows, can be important indicators of the ratio of shear to compressional energy at an event source, permitting discrimination between explosions and earthquakes. Differences in the propagation efficiencies of each phase reduce their effectiveness. The objective of this work is to develop a means of accurately predicting Lg and Pg propagation effects in a manner that can be reliably extrapolated to uncalibrated regions. The basis of this effort is the division of the crust into different types, each of which has consistent effects on each phase, but not necessarily the same effects as any other crustal type. The division is based on a variety of geophysical parameters and on observed propagation efficiency.

The initial work used data from the dense southern California seismic network (SCSN), which allowed us to observe changes in phase amplitudes over very short distances. We first review the techniques developed on this data set and results obtained. In a second phase of the work, we use the large global data set of Lg and Pg amplitude measurements reported in the reviewed event bulletin (REB) of the Preliminary International Data Center (PIDC).

To analyze the SCSN data, we employed statistical analysis techniques not commonly applied to geophysical data sets, particularly categorical statistics techniques. These include cluster analyses to separate crustal types and analysis of variance to test hypotheses regarding whether differences in propagation between crustal types are significant. We also constructed models to test the extent to which propagation of each phase is predictable by various statistics of topography, gravity, and velocity structure. Surprisingly, no clear correlations were observed between propagation efficiency and velocity structure, using a detailed 3-D velocity model of southern California. That may however be due to low resolution in the shallowest and deepest crustal layers, which could be the most important for waveguide efficiency. We were able to analyze Lg and Pg propagation separately, as SCSN site amplifications are known and sufficient data exist that we were able to construct a table of known calibration problems. This enables insights into differences between shear and compressional wave propagation in the crust that are not achievable using ratios of phase amplitudes.

To apply these techniques globally, we are using measurements of Lg and Pg amplitudes from the PIDC. Because this is a major new network, much effort is being spent assessing data quality, and it may not yet prove feasible to separately analyze Lg and Pg amplitudes. Even so, the broad extent of coverage and the network's purpose of CTBT monitoring make this the most relevant and useful data set to analyze. We also have collected and merged global data sets of other geophysical parameters that are likely to vary between different lithologies. These include topography, geoid estimates, sediment thickness, crustal magnetization, and crustal thickness estimates where available. We outline the separation of large regions into distinct crustal types, and explore the relationship between propagation efficiency and the crustal types. Specifically, we describe the inverse approach we are developing to assess the effect of each crustal type and the transition between crustal types, based on the length of each path segment in each crustal type for all possible paths in a large region.

**Key Words:** Lg, Pg, regional propagation

## OBJECTIVE

The primary objective of this research program is to improve the accuracy of discrimination of nuclear explosions from earthquakes by developing a transportable path correction algorithm for the Lg/Pg discriminant.

## RESEARCH ACCOMPLISHED

### Introduction

The transportability of path corrections is difficult to assess or ensure. Good path corrections with well-defined confidence levels can be made in well-calibrated areas based on observed phase amplitudes (e.g. Phillips, 1999). The problem we address is how to provide accurate path corrections in areas with little data. The basis for such corrections is the identification of similar crustal structures that have similar effects on regional propagation. The crustal types are characterized by statistics of geophysical parameters that may vary with lithology. These may include topography, gravity, crustal thickness, sediment thickness, magnetization, age, or heat flow. This approach began with the work of Zhang et al (1994), who demonstrated a correlation between statistics of topography and P- and S-wave amplitude ratios at regional distances. The appearance of significant correlations bolstered the hope that corrections based on such correlations could be used to make path corrections. The difficulty encountered in numerous studies has been that corrections determined for a particular data set do not appear to be useful for data collected in adjacent regions (e.g. Rodgers et al, 1999).

This paper has three distinct sections. In the first, we review the research we have performed on southern California seismic network (SCSN) data, specifically focusing on the novel application of categorical statistical techniques to assess relationships between parameters and propagation, and transportability of the resulting propagation corrections. We address whether differences in the nature of Lg from explosions and earthquakes might inhibit the transportability of path corrections, and use an Israeli data set to further examine that question. Finally, we discuss the use of global IMS data to develop path corrections that will be most useful for the IMS network.

### Section 1: Categorical Analyses and Short Propagation Paths

***Review of SCSN Data Analysis Techniques and Results:***
The data used in this section were described in Baker (1998) and are reviewed only briefly here. The closely spaced short-period vertical seismometers of the SCSN provide 618 recordings with at least one of Lg or Pg having signal-to-noise ratio (S/N) greater than 2, from 10 Nevada Test Site (NTS) nuclear explosions, and 583 such recordings from 5 regional earthquakes. These are used to construct short path segments between stations along the propagation directions. Changes in phase amplitudes along those paths are compared with statistics of topography, crustal thickness, and the isostatic gravity residual along those paths segments.

Previous studies compared regional phase amplitude ratios to statistics of parameters for entire source-receiver paths, which are generally quite long. By analyzing propagation effects along short paths between SCSN stations, we avoid several problems associated with long paths. For example, differences between source S-to-P ratios become irrelevant. Also, parameter values measured along long paths can lose meaning: half of a long path could be through high mountains and half through sedimentary basin, so mean elevation along the path is not representative of any portion of the path. Structure along very short paths is more likely to be homogeneous. Further, by using estimates of site amplifications we are able to examine just changes in Lg, or Pg, without relying on the ratio. We mostly focus on analyses of Lg/Pg ratios here.

Previous studies also relied on linear fits between parameters and amplitude ratios to make corrections. Propagation effects are commonly modeled using $c=ax+b$, where $c$ is an observation, typically a P-to-S-wave amplitude ratio, x is some statistic estimated along the propagation path, such as mean elevation or topographic roughness, and $a$ and $b$ are constants. This empirical approach often has no theoretical basis, but does have the virtue of simplicity and may be justified where it provides reliable prediction. Initial analyses of the transmission efficiency (TE) of Lg and Pg however, indicate that important relationships between TE and the parameters would be missed if we only used general linear models. Instead we employ categorical models and analysis of variance (ANOVA).

We define transmission efficiency as $\log_{10}(A_d/A_u)$, where $A_u$ and $A_d$ are the amplitudes at the *upstream* and *downstream* stations respectively, that is, at the first and second station along a given raypath. Before discussing path corrections, we consider the relationships they are based on and specifically note why not all statistically significant relationships are necessarily useful. A plot of individual Lg TE observations versus median elevation demonstrates that point (figure 1, left). Only when the data are binned is a relationship apparent (figure 1, right). The high variance relative to the trend limits the variance reduction achievable using corrections based on the trend. This example also illustrates the importance of constructing testable hypotheses, since we clearly may be deceived by the manner in which the data are viewed. That is, figure 1 (left) indicates no relationship while 1 (right) does. Further, how we construct the hypotheses merits critical examination, since we are able to state and test more than one hypothesis.

We can simply hypothesize that the least squares fitting line to the data has some meaning. A t-test indicates that such a fit is significant, that is, the slope of the line found is not likely to have occurred if the data were random. This is counter to what one might assume looking at the raw data (figure 1, left). We note however that no hint of a trend is visible in a plot of Lg amplitude loss with distance, although in that case it is reasonable to assume that amplitude decreases with distance. The t-test does also indicate that the slope of Lg amplitude loss versus distance is significant. For any of the relationships considered however, we can make different hypotheses. We could assume that distinctly different types of crust, in regards to their effect on Lg propagation, are distinguished by their median elevation. For example, we can divide the crustal paths into low, medium, and high elevation groups. An examination of path locations provides a means of qualitative classification that separates the paths into geographically, and possibly tectonically, distinct groups (not shown for space considerations). We then use ANOVA to test the null hypothesis that the mean TEs of the groups are the same. ANOVA rejects that hypothesis, with probability 0.002. That we can form such different hypotheses and even find that very different types of relationships hypothesized are statistically significant, emphasizes the importance of not just applying statistical tests, but also assessing how appropriate the hypotheses may be. In this case an inspection of the distribution of paths to see whether the groups of paths are tectonically distinct, helps to make that assessment. Visual inspection of path locations for different groups also lets us avoid a dangerous circularity in the application of ANOVA. That is, we must not choose levels at which to separate the paths into different groups based on which levels provide the greatest separation, as we do not *know* yet whether such a relationship exists.

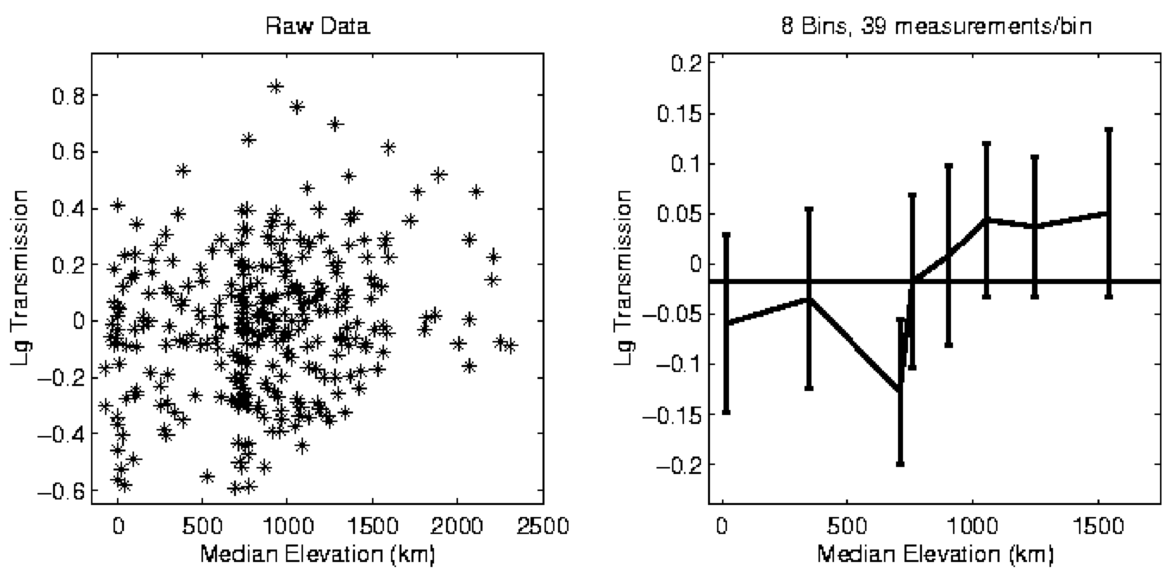


**Figure 1:** Lg TE vs median elevation along short path segments between SCSN stations.

***Variance Reduction and Transportability:***

We have systematically tested all possible single and two parameter categorical models, as well as models of crustal types based on cluster analyses of the various combinations of geophysical parameters, to predict Lg, Pg, and Lg/Pg ratio TEs. While we have found many statistically significant relationships, particularly for Lg and the Lg/Pg TEs, we do not include an exhaustive listing, but focus on how useful such models predict the TE of new data. We first consider the application of corrections to new data in the same well-calibrated region. To assess that, the SCSN Lg/Pg data are divided randomly into 2 subsets of the data, and a model is derived from one of the data subsets. The propagation correction for a particular group is simply the median value of the change in log(Lg/Pg) along all the paths in that group. The corrections provide modest variance reduction for both the data set from which they were derived and to a lesser extent, for second data set, indicating some robustness to the method. All measurements have been normalized to 20 km distance, and variance reduction reported is in addition to any achieved by the distance correction. The separation of the data into two subsets and subsequent application of corrections is repeated 100 times to ensure a robust estimate of the improvement we might typically expect. The results for single parameters are shown in Table 1 for the 1-2 Hz and 2-4 Hz data. The corrections perform better at the higher frequency, with the crustal thickness* estimate and topographic roughness providing the greatest variance reduction. The use of two or more parameters only improves the variance reduction by another 1% to 2% at best.

**Table 1:** Variance reduction achieved by path corrections based on single geophysical parameters.

| | | Crustal Thickness* | Topographic Roughness | Steepest Gradient | Isostatic Residual | Isostatic Roughness |
|---|---|---|---|---|---|---|
| 1-2 Hz | set 1 | 11% | 6% | 7% | 5% | 8% |
| | set 2 | 5% | 3 % | 4% | 3% | 3% |
| 2-4 Hz | set 1 | 13% | 15% | 8% | 5% | 4% |
| | set 2 | 10% | 10% | 2% | 2% | 1% |

An important result is that despite complete spatial overlap of the between-station paths of the nuclear explosion and earthquake data, corrections based on the earthquake data provide no variance reduction for the nuclear explosion data. For example, corrections based on the crustal thickness estimate for the 2-4 Hz data, which overall had the best results, reduce the variance by 13% when applied to the earthquake data, but *increase* the variance of the nuclear explosion data by 2%. Similarly, corrections based on topographic roughness achieve a 10% variance reduction for the entire earthquake data set, but cause a 2% variance increase for the nuclear explosion data. We explore this problem in detail in the next section. We assume for now that differences in the Lg/Pg ratio are due to Lg, as that has the greatest variance, but we still must repeat this analysis for Lg alone, rather than the ratio.

Baker (1998) showed that there are statistically significant differences in TE between different types of crust as distinguished by cluster analysis using the parameters of Table 1. We put this information to use in attacking the most difficult, but the most useful to solve problem in path corrections, that of real transportability. That is, the ability to predict propagation effects within reasonable confidence intervals in a region without prior seismicity. As demonstrated above, corrections based on levels of single or multiple parameters are useful in reducing variance of a "new" data set in the same general area.

To test extrapolation of corrections to uncalibrated crust, we apply path corrections based on changes in Lg/Pg amplitude ratios over short paths between stations to the changes that occur over paths between stations at opposite ends of the network (figure 2). The long paths connecting distant stations in the network (distance at least 150 km, and ray paths within 5 degrees of the azimuth between stations) traverse large areas not covered by the short paths (distances from 10 to 60 km). Corrections determined for the short paths may not be applicable to some sections of the crust sampled only by segments of the long paths, because that crust may be of a different type. For example, median elevation paths in the calibrated region may be in foothills, with rough topography, while some of the median elevation paths in the uncalibrated area could be flat, stable, and shield-like. We use the 2-4 Hz passband and test both the crustal thickness estimate and the topographic roughness, as they provided the greatest variance reduction for "new" data in a calibrated region (Table 1). The corrections are not based on median elevation of the entire path, but instead are determined and applied to each 20-km segment of the long paths, based on each segment's median elevation. As before, we divide the short paths into groups based on parameter values and use the median change in the Lg/Pg TE for each group as a correction term for

* Crustal thickness was found to be the single best predictor of TE (Baker, 1998), but is not known over the entire study region. Stepwise regression indicates that the sum of the minimum and maximum elevations along a path provides the best linear combination of the other parameters for predicting crustal thickness; thus this sum provides a crustal thickness estimate used over the entire region.

that group. The corrections reduce the variance of the short paths, as before, but they increase the variance when applied to the long paths. The elevation corrections do not appear to transport out of the area for which they were developed.

Presumably, some of the crust sampled only by the long paths is like that sampled by the short paths, and some is not. If so, cluster analysis should enable better distinction of which portions are similar, as it permits great flexibility in incorporating multiple parameters. We perform a cluster analysis using the minimum, maximum, and median values of topography, gravity, and crustal thickness where available, on all 20-km segments of the long paths together with the short paths. When we separate the crust into six distinct types, only four types have significant numbers of paths in both the short- and long-path groups. We use the median value of the change in Lg/Pg TE for the short paths in each cluster group as a propagation correction term. We hypothesize that these corrections will be appropriate for segments of the long paths in the same cluster group, even if they are in areas not sampled by the short paths, because the cluster analysis will have appropriately clustered similar types of crust. Segments of the long paths that are not in any cluster group with short paths will not have a correction term available. Fifty-four out of the 1292 20-km segments of long paths do not have corrections.

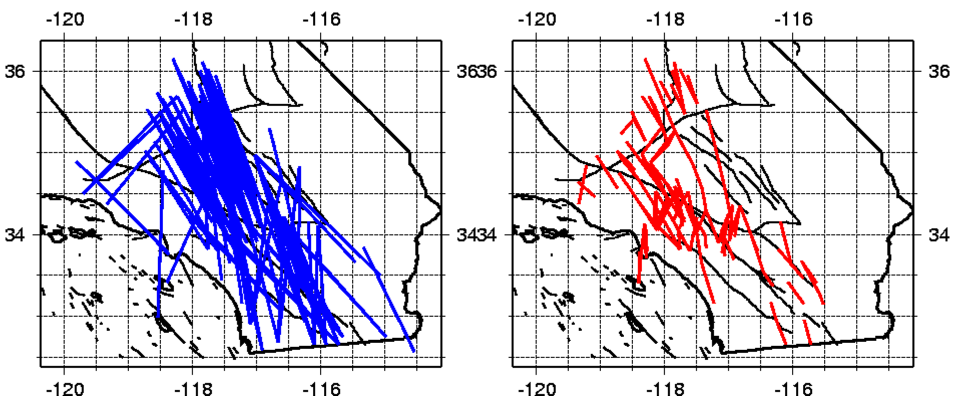


**Figure 2:** Long (left) and short (right) paths between SCSN stations. The long paths cover much terrain not sampled by the short paths, which have been used to define corrections.

The first attempt to apply these corrections caused a 28% increase in variance, much worse even than occurred with the single parameter based models. However, we also measure the change in the squared Scaled Median Absolute Deviation (SMAD), which provides an estimate of the spread of values which is less sensitive to outliers and so more appropriate in the presence of non-Gaussian errors (SMAD is equivalent to the standard deviation for Gaussian distributed data). The same path corrections that increased the variance when applied to the long paths, caused a 20% decrease in $SMAD^2$. The corrections decrease the residuals of most of the data, but very significantly increase the residuals of a small number of points, producing large outliers. Thus, the corrections are in the correct direction for most data. If we want to reduce the residuals of most of the data (i.e. reduce $SMAD^2$), we can use the corrections as they are. To avoid the creation of occasional large outliers while still reducing the residuals somewhat for most of the data, we tried applying scaled down corrections. Path corrections with the magnitude reduced by half cause a 5% increase in variance for the long paths and a 47% decrease in $SMAD^2$. Corrections reduced in magnitude by 3/4 cause no change in the variance, but still reduce $SMAD^2$ by 39%. Reducing the magnitude of the corrections based on single geophysical parameters does not appear to have a similar dramatic effect. This is a recent realization and its robustness, implications, and application must be much more thoroughly explored. Further work will include examination of which data have increased versus reduced residuals.

## Section 2: Do Earthquake and Explosion Lg differ (and if so, how?)

### *Depth/Source Type Dependence of Lg Travel Times in Southern California:*

As discussed above, the TE's of earthquake and nuclear explosion Lg appear not to be sensitive to the same parameters, at least not in the same way. To investigate if and how Lg from explosions and earthquakes differ, we first examine the timing of arrivals. We measure the midpoint of the area under the curve of absolute amplitudes within the Lg windows (3.6-3.0 km/s group velocity). The Lg window length varies from 11 to 29 seconds over the range of distances observed, so the amplitude midpoints are plotted relative to the window length. The midpoint of nuclear explosion Lg amplitude arrives much later in the Lg window than it does from earthquakes (figure 3, left). The data from one shallow earthquake (2 km depth) at NTS are not shown in figure 3. For that event, the arrival times of energy within the Lg window cluster with those of the explosions. The positions of the first and third quartiles of Lg amplitude indicate no difference in the distribution of energy between explosion and earthquake Lg. The packets simply appear to be delayed in explosion records.

The differences observed in figure 3 may enable depth discrimination and so merit further study, along with our inquiry into differences between wavetypes that make up explosion and earthquake Lg. While no simple solution appears to explain the phenomena, consideration of three possible explanations provides insight into the character of crustal shear waves. First, there may be a difference in wavetype generated by sources at different depths. Shallow sources could excite modes that travel in the upper crust at lower velocity, while deep events could excite modes that propagate deeper in the crust at higher velocity. Another possibility is that the S-waves are generated by scattering from Rg (e.g. Myers, 1999). This is one of the most popular explanations for the generation of shear waves by explosions. In that case, Lg would be delayed by $x(1/V_{Rg}-1/V_S)$, where x is the distance at which Rg scatters to S, and $V_{Rg}$ and $V_S$ are the Rg and S-wave velocities. Differences in velocity structures around the different source regions could provide a third possible explanation, since the explosions and shallow earthquake are at NTS, and the other earthquakes are in other areas. The same analysis for Pg (figure 3, right) as was done for Lg shows no difference between source types. Thus, the differences between source regions would have to be in S-wave velocity structure only, making that explanation somewhat less probable.

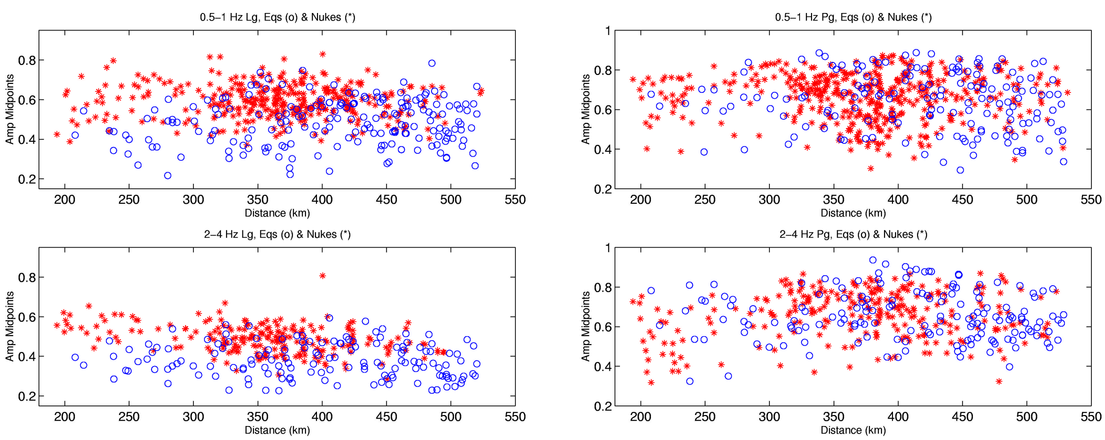


**Figure 3:** Source-receiver distance versus position within the Lg window of the amplitude midpoint (left column). At 0.5-1 Hz (top) the mean amplitude midpoint within the Lg window for earthquakes (circles) is at 0.48, where total Lg window lengths are normalized to 1.0. The same measure for explosions (asterisks) is 0.59. At 2-4 Hz, the mean amplitude midpoint is at 0.38 and for explosions is 0.49. No difference is apparent in the distribution of amplitudes within the Pg windows between explosions and earthquakes (right column).

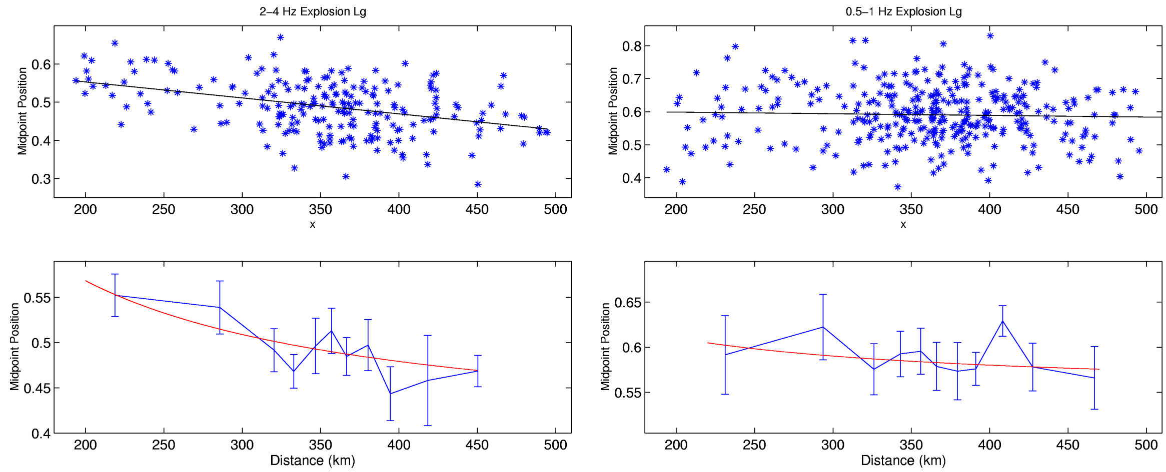


**Figure 4:** Midpoint position within the Lg window from 2-4 Hz explosion data (left). The upper left plot shows the least squares fitting line to the data. The lower left plot shows the median value in 20 data point bins with 2 SMAD confidence intervals. Lg energy arrives later in the Lg window at the distances less than 300 km, and the position within the Lg window stabilizes at greater distance. The curve is the predicted arrival of Lg energy if the explosion Lg were generated by scattering from Rg at 10 km from the source. The right column shows the same plots for 0.5-1 Hz measurements.

The effect of range is relevant to the second explanation. Energy arrives relatively later within the predicted Lg window at lesser distances. This is the effect of an approximately constant time offset, as the Lg window lengthens with range. In figure 4, we replot the high frequency explosion Lg results with a least squares straight line fit to the data (top plot). The lower plot shows the median position of the amplitude midpoint within the Lg window for successive bins of 20 data points each. That indicates that the arrival time of energy within the Lg window is later at lesser distances, but there is no apparent slope at distances greater than 300 km. A constant time offset of explosion Lg is consistent with explosion Lg being generated by Rg-to-Lg scattering at the surface. The curve superimposed on the lower left plot (figure 4) shows this effect. It assumes a 2-4 Hz Rg velocity of 2.1 km/s, Lg velocity of 3.6 km/s, and scattering at 10 km from the source. The observation of a constant time offset is also consistent with the hypothesis that earthquake and explosion Lg are composed of different modes, as long as the modal structure differences are lost through scattering at less than 200 km. Otherwise, the time offset would increase with distance.

The greater delay in Lg at lesser range is not observed in the 0.5 to 1 Hz explosion data (figure 4). This could be explained by higher Rg velocity at 0.5-1 Hz. If Rg velocity at 0.5-1 Hz were 2.9 km/sec (Revenaugh, 1995), the predicted delay would be much less, as indicated by the curve in the lower plot. We are admittedly employing more parameters (Lg and Rg velocities and the scattering distance) than we have observations. Nonetheless, within a wide range of values for these parameters, the basic observations can be explained.

***A Second Data Set:***

To try to distinguish better between explanations for the Lg delay for shallow events, we examine an additional data set. Nineteen quarry blasts and twenty-eight earthquakes in the Galilee provided 630 recordings on the local Israeli network (Grant et al, 1999). These data allow us to extend the observations closer to the source, to higher frequencies, and verify them in a different region. As in the SCSN data set, explosion Lg is delayed relative to earthquake Lg. Because these explosions and earthquakes are both distributed across the Galilee, we can rule out as unlikely the possibility that velocity structure differences between source regions cause the delays.

There are only 20 quarry blast and 45 earthquake records from distances greater than 200 km. Most data were recorded closer in, and we concentrate on Sg and Pg arrivals recorded at less than 72 km distance so that mantle phases do not complicate the interpretation. The basic observation that explosion shear waves, in Sg now, are delayed relative to earthquake shear waves, is again duplicated here. There again is no difference in Pg timing for the two source types (figure 5). These observations are consistent at all frequencies up to 22 Hz, which precludes Rg to shear wave scattering contributing to the phase and causing the delay. These observations of Sg delays are relevant to the Lg delays, since Sg will become Lg with distance. Models that only explain delays of shallow event shear waves in the crust at one range of distances, but not the other, will be less credible. The simplest explanation of the Sg observations is that the predicted times, based on the IASPEI91 model, are too fast at shallow depths. We note however that Lg, and regional distance Pg in southern California, are defined by group velocity windows, so those delays can not be explained by errors in the velocity model based predicted times.

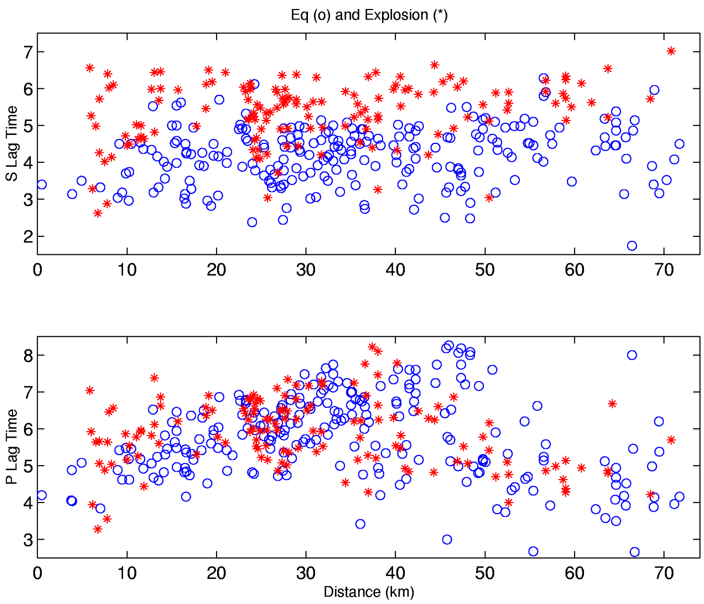


**Figure 5:** Earthquake (circles) and explosion (asterisks) lag times for Sg (top) and Pg (bottom). Lag time is defined here as the midpoint of amplitude under the curve of absolute amplitudes within the predicted phase windows. The explosion Sg is approximately 2 seconds later than the earthquake Sg, while no difference is observed between the time of Pg arrivals for the two source types.

The Galilee earthquakes had depths from 0 to 23 km, and we use those data to examine the effect of depth on the delay of Sg. Earthquake Pg and Sg travel time residuals based on analysts' picks are comparable for deep events (figure 6). Sg, but not Pg residuals increase however from approximately 12 km depth up to the surface (where they are delayed the same amount as the quarry blast Sg phases). This decrease in Sg travel time residuals with depth is also observed in automatically picked maximum peak times and in the energy midpoint times within theoretical Pg and Sg windows and is observed for all frequencies up to 22 Hz. The increased lag time of all measures of Sg energy down to 12 km depth and at all frequencies is inconsistent with Rg scattering having contributed to the Sg energy and delayed it. Further, there was no observable variation in the Sg/Pg amplitude ratio with depth and frequency such as would be predicted if Rg-to-S scattering contributed significant shear wave energy for the shallow events. Modal structure is not a consideration for these local phases.

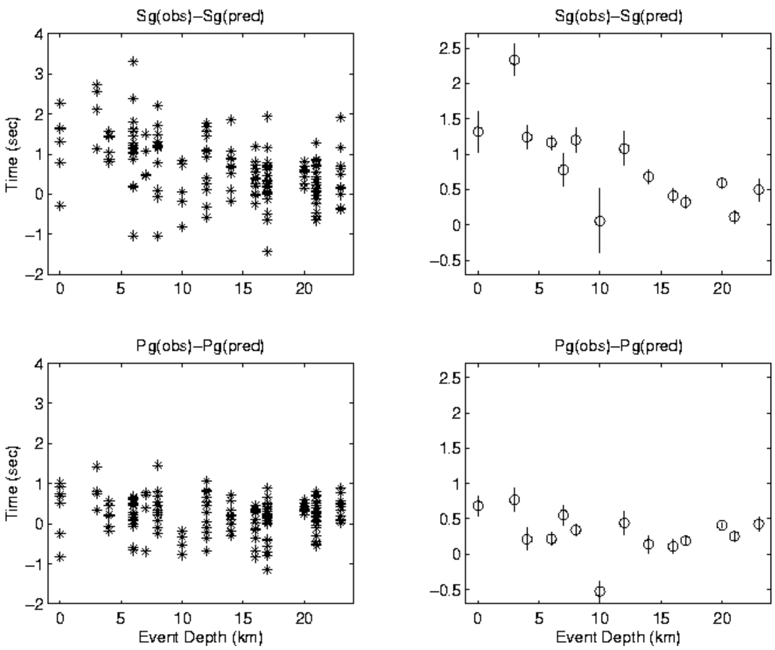


**Figure 6:** Observed minus predicted times for Sg (top) and Pg (bottom) versus earthquake depth. All the data are shown in the left column. The median and 1 SMAD confidence intervals are shown in the right column.

The rate of amplitude decay after the initial peak indicates that more energy is in the latter part of both the Sg and Pg windows of shallower events, possibly due to more scattering in the shallow layers and at the surface. We see no clear difference between the patterns for the two phases, and so can not conclude that the explosion shear wave energy for these events is due to or preferentially augmented by scattering at some distance from the source.

In summary, the question of whether there is a difference in the wavetypes making up earthquake and explosion Lg remains unresolved, but we have uncovered the potentially useful observation that Lg energy arrives later for explosions than for earthquakes. This is the most significant result of this section. The search for the mechanism is enlightening in that the initial obvious explanations are not altogether consistent with detailed analysis of all the data. The delay and that it is constant with distance are consistent with Rg scattering contributing to the explosion Lg and with differences in modal excitation, if the mode structure does not persist beyond 200 km from the source. Those observations are duplicated in the Galilee data set, but measurements made on near-source Sg from the Galilee data (which could not be observed in the SCSN data) are inconsistent with Rg scattering contributing to the S-wave energy and with the modal explanation. An incorrect S-wave velocity model could explain the Galilee observations, but this is unsatisfying, as it calls on two different explanations for the very similar observations made from both data sets. That is, the crustal S-wave phases from explosions, but not from earthquakes, are delayed relative to their respective P-wave phases. Given that we observe delays in crustal S-waves measured very near the source, it is most reasonable to assume that delays measured at greater distance are simply carried over from that initial delay. A single model that explains both sets of observations would be more credible. Because the arrival time of energy within the Lg window may prove to be a useful depth discriminant, development of such a model will be the focus of further efforts.

***Global Application:***

We have developed some promising techniques for determining path corrections and transporting them to new, uncalibrated regions. Because the goal is to improve CTBT monitoring using stations of the IMS, we next will apply these techniques, modified as necessary, to IMS data. This may also be one of the most useful data sets for such research, as it provides an extremely large set of global observations. We also will extend the analysis to the mantle phases, Pn and Sn. Because however the IMS network is large, new, and still being implemented, quality control is a concern. We describe below tests we perform to filter out errors in reported phase amplitudes.

We are concerned with both instrument calibration problems and phase identification errors. Evidence of probable calibration problems will prevent us from separately analyzing Lg and Pg, as we did in southern California. We examined 3 Hz IDC data reported between July 1996 and January 1998, when 20,159 regional phase signal and noise peak measurements were recorded. We consider two types of timing problems, chronological inconsistencies (arrival times out of order) and time-window discrepancies (arrivals falling outside theoretical time windows).

We checked for chronological inconsistencies of two types, noise measurements made after signal measurements of the same type (e.g. the Pn noise measurement being made after the Pn signal measurement), and signal arrival times listed out of the proper sequence (Pn, Pg, Sn, Lg, except for small distances where Pg may arrive earlier than Pn). Proper chronological order is violated less than 0.2% of the time, except for Sn. We will not use those data. The Sn arrival times have more problems, with 4% of the Sn measurements made later than the Lg measurements. Sn and Lg traverse very different structures, so for the creation of path corrections, we must ensure that we do not use measurements of misidentified phases.

The percentage of Pg and Lg noise and signal measurements that are made outside of the predicted time windows are shown in Table 1. Phases not being measured for some events causes some rows to sum to less than 100%. We are assessing which identifiable errors render the data unusable.

The worst problem among the four types of arrivals is seen with Sn. 8.7% of the Sn measurements are made within the predicted Lg signal window. Further, close to half of the noise measurements and 20% of the signal measurements were made outside their predicted time windows, mostly late. Some, but not all of these inconsistencies may be due to errors in the depth assumed for the event. These problems combined indicate that the use of at least a tenth of the listed Sn arrivals may be questionable.

We also looked for variations with time of pre-Pn noise, which serves as an indicator of possible problems with the instrument calibration. The median value of pre-Pn amplitude reported for station MJAR, for consecutive 20 point bins is shown in figure 1. Some time intervals appear to have unusually high pre-Pn noise, and the station appears to have been shut down after one of those time periods. This is likely typical, as this is the first station we examined. The reasonable possibility that these are not natural variations in background noise levels, but rather changes in instrument gain, suggest that we use only phase amplitude ratios.

**Table 1.** Percentages of arrival times within, before and after the predicted time windows.

| Phase | in predicted window | before predicted window | after predicted window |
|---|---|---|---|
| | | | |
| Pg noise | 91.0 | 3.0 | 6.1 |
| Pg signal | 97.3 | 1.0 | 1.7 |
| | | | |
| Lg noise | 94.4 | 2.0 | 3.5 |
| Lg signal | 99.2 | <1 | <1 |

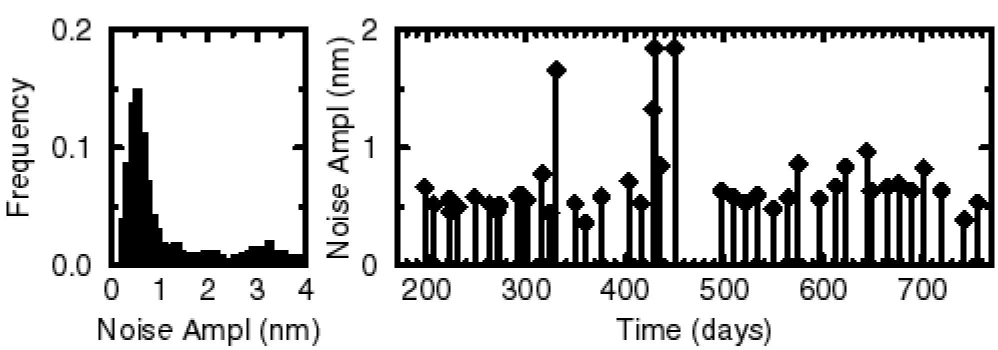


**Figure 7.** Pre-Pn noise measurements at station MJAR during the period June 1996 – January 1998. Time is counted from the beginning of 1996. The histogram of noise distribution shows a small second peak at 3 mm, rather than a smooth distribution of values (left). On the right are median values of pre-Pn noise amplitude for non-overlapping groups of 20 events each.

## CONCLUSIONS AND RECOMMENDATIONS

Analysis of correlations between topography, gravity, and crustal thickness and Lg, Pg, and Lg/Pg ratio propagation in southern California has led to the development of path corrections that are transportable, in that they reduce the distribution of discriminant values for earthquake records for uncalibrated areas. In particular, the identification of distinct crustal types using cluster analysis appears to have the most promise for this task. Earthquake record-based path corrections do not, however, reduce the spread of values for Lg/Pg ratios from nuclear explosions, leading us to examine the differences between Lg phases generated by the two source types.

Southern Californian and Israeli earthquake and explosion data sets were analyzed to assess whether explosion and earthquake Lg differ and so are subject to different propagation effects. Observations made in addressing the question suggest a possible depth discriminant based on the relative Lg-to-Pg travel time residuals. Specifically, energy within the Lg group velocity window and around the predicted arrival times for Sg arrives later for shallower events. The physical basis for this is not clear. Late Lg is consistent with either Rg-to-Lg scattering or excitation of different modes by different depth events. That shear-wave energy measured close to the source for the Galilee data is delayed for shallower events complicates the picture. Because the close in Sg energy presumably contributes to Lg at greater distance, any explanation for Lg delays should be consistent with the Sg measurements. This makes both Rg-to-Lg scattering and excitation of different modes due to event depth less likely reasons for the delay of shallow event Lg. That these initially plausible, and perhaps most obvious explanations are inconsistent with close in shear wave observations is an important result that bears on the generation of S-waves by explosions. The delay of shear wave energy from shallow events should be studied further, as it may prove to be useful in discriminating event depth. The question of whether the wavetypes that make up Lg vary with depth should also be studied further as it is important to the application of path corrections.

The next step in this project will be to apply the techniques developed for the SCSN data to the global data of the IMS. We have shown that careful checking of reported travel times permits identification of some problematic data. The path correction techniques developed for the SCSN data will be modified to deal with long paths. We will also modify the techniques to include censored data, since lack of a signal where one is expected indicates blockage somewhere along the path. We will use a maximum likelihood approach to incorporate such data. We will again use cluster analysis to distinguish crustal types, and use an inverse approach to estimate the effect of each type and transitions between types, based on their contribution to the total path.

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