# QUANTIFYING SOURCE EXCITATION AND PATH EFFECTS FOR HIGH FREQUENCY REGIONAL WAVES

Ru-Shan Wu, Xiao-Bi Xie, Zengxi Ge, and Thorne Lay

University of California, Santa Cruz

Sponsored by Air Force Research Laboratory

Contract No. DTRA01-01-C-0076

## ABSTRACT

For the purpose of monitoring nuclear testing, the range of interest for Lg-wave simulations spans a broad frequency band and long propagation distance, while factors that control the source energy partitioning depend on the detailed source model and multi-scale near source velocity structures. We use the finite-difference (FD) modeling plus slowness analysis method developed in this project to solve this problem and investigate the near source Lg-wave excitation and energy partitioning. Our approach is to separate the problem into consideration of near-source energy partitioning effects apart from long-range propagation effects. This method allows a very fine near source model to be used to investigate the near-source processes. A slowness analysis is used for tracking where energy will be partitioned into the long-range propagation regime. The high efficiency of the method is the major advantage, as it allows us to examine a broad source/model space using numerical simulations. To verify the validity of the method, we calculated a suite of full-scale two-dimensional (2D) FD simulations. The trapped energy measured in the waveguide at short distance is compared with the Lg energy obtained from the surface seismograms at long distance. The consistency of these measurements confirms the validity of our approach.

Several preliminary results have been obtained from the numerical simulation and the ensuing slowness analysis. The near source P-to-S conversion in the presence of small-scale lateral heterogeneities is tested as a mechanism for generating the near source S-wave energy from an explosive source. The numerical results reveal that the depth of the source and the depth of the scattering region have strong effects on the P-to-S conversion and the partitioning of energy into trapped and leaking signal. The excitation spectrum for the trapped energy from the S*-wave is also investigated. The modeling shows that the excitation is generally favorable for lower frequencies and shallow source depth. The frequency dependence of these excitation spectra can provide the basis for evaluating the dominant mechanisms for Lg-wave excitation. It also provides the relationship between the observations and the characteristics of the source and near source structure. The amplitude ratios between the P- and S-phases (e.g., Pn/Lg, Pg/Lg, Pn/Sn and Pg/Sn) are widely used as discriminants. We simulate the amplitude ratio between the P-wave and trapped modes for a relatively broad frequency range using velocity models with and without lateral velocity variations. For a typical explosion source and a shallow earthquake source, the results show a general feature similar to that in the observations. At the low frequency end, the earthquakes and explosions have similar ratios but at higher frequencies, the explosive source generates less S-energy.

## OBJECTIVE

With the current emphasis on global monitoring for low-yield nuclear tests, regional seismic phases such as Lg and Lg coda have become very important for magnitude and yield estimation of underground nuclear tests. (e.g., Nuttli, 1986; Xie, et al., 1996; Patton, 2001). In addition, various P/S-type amplitude ratios for high frequency regional phases (e.g., Pn/Sn, Pn/Lg, Pg/Lg, Pg/Sn) have become important for event discrimination (e.g., Taylor et al., 1989; Kim et al., 1993, 1997; Walter et al., 1995; Fisk et al., 1996; Taylor, 1996; Taylor and Hartse, 1997; Hartse et al., 1997; Fan and Lay, 1998a-c, Xie and Patton, 1999). Several possible near source energy transfer mechanisms have been proposed, including P- Lg scattering, pS-Lg conversion at the free surface, Rg-to-Lg coupling, S*-Lg conversion, spall excitation of S, tectonic release and rock-damage (e.g., Day and Mclaughlin, 1991; Gupta et al., 1992, 1997; Walter, et al., 1995; Wallace, 1991; Gutowski, et al., 1984; Vogfjord, 1997; Johnson and Sammis, 2001). There is continuing controversy about which mechanism(s) dominate the explosion source energy partitioning processes. Another unsolved puzzle is the frequency dependence observed for regional P/S discriminants. Numerous studies (e.g., Walter et al., 1995; Fisk et al., 1996; Taylor, 1996; Taylor and Hartse, 1997; Hartse et al., 1997; Fan et al., 2002) have demonstrated that regional P/S measurements (Pn/Lg, Pg/Lg, Pn/Sn, Pg/Sn) provide useful discrimination of earthquakes and explosions at frequencies above about 3 Hz, but the discrimination performance is much lower at low frequencies. There is very incomplete theoretical understanding of this strong frequency-dependent phenomenon.

Due to the complex excitation and energy partitioning processes associated with regional phases, it is difficult to separate the contribution of individual energy partitioning mechanisms from the observed data empirically. Numerical modeling approaches are thus of great importance for investigating the excitation and propagation of regional phases. Early research investigated various propagation properties of the Lg phase using 1D models and the results were very limited. A one-way wave equation based method (Wu, et al., 2000a,b) has been used to investigate the path effect of the Lg wave propagation but it is not suited for the excitation issue. Full wave numerical techniques such as finite-difference (FD) are also widely used for investigating Lg-wave excitation and propagation in complicated crustal waveguides (Xie and Lay, 1994; Jih, 1995, 1996; Bonner, et al., 2003; Stevens et al., 2003). The main disadvantages of these numerical methods that provide complete synthetic seismograms are the low computation efficiency and huge computer memory requirement, especially when applied to long distance Lg propagation.

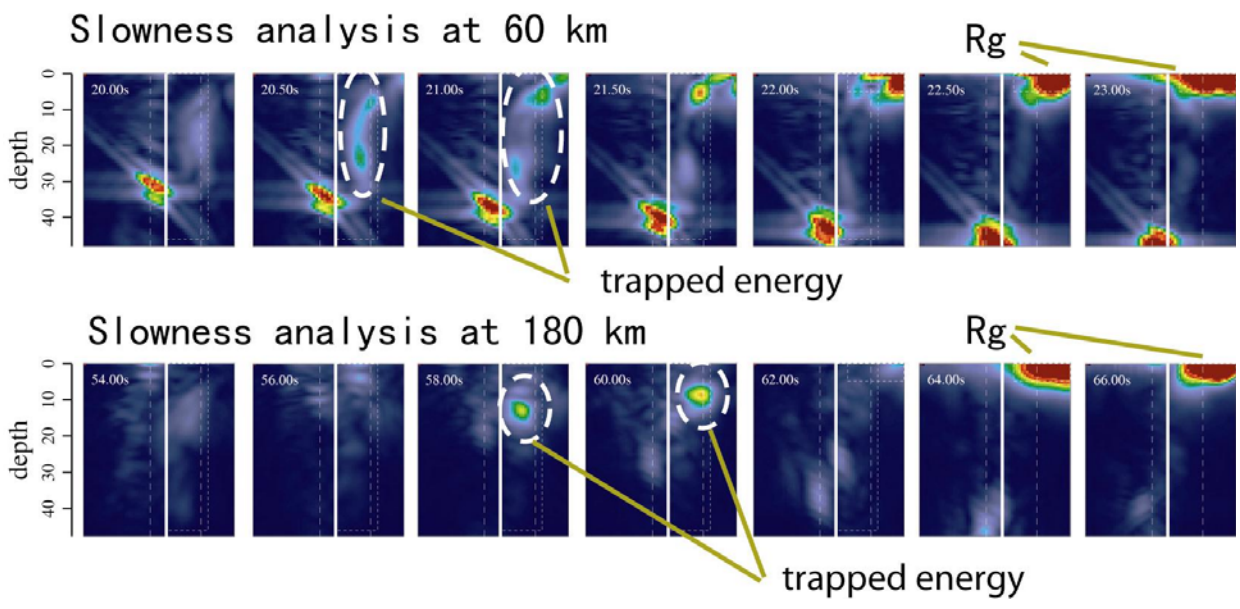


**Figure 1. Examples showing the slowness analyses at distances of 60 km (upper panel) and 180 km (lower panel). In all slowness diagrams the range of slowness is 0–0.4 s/km and the thick white vertical line is the upper mantle S wave slowness (0.22 s/km). The energy that can be trapped is indicated in the figure. The wavefields show quite different features at these distances but give consistent predictions for the trapped energy fluxes.**

Most investigators agree that appreciable energy from explosion sources is converted to S-waves in the near-source region (Myers, 2003). Following this perspective, we developed a "finite-difference modeling plus slowness analysis method" (FDSA). Using this approach, the wave propagation process can be investigated in a joint time-frequency-space-slowness domain. Very detailed near-source structures and high frequencies can be used to investigate the underlying physical process of Lg excitation and energy partitioning. The frequency dependent properties of the energy partitioning can also be investigated.

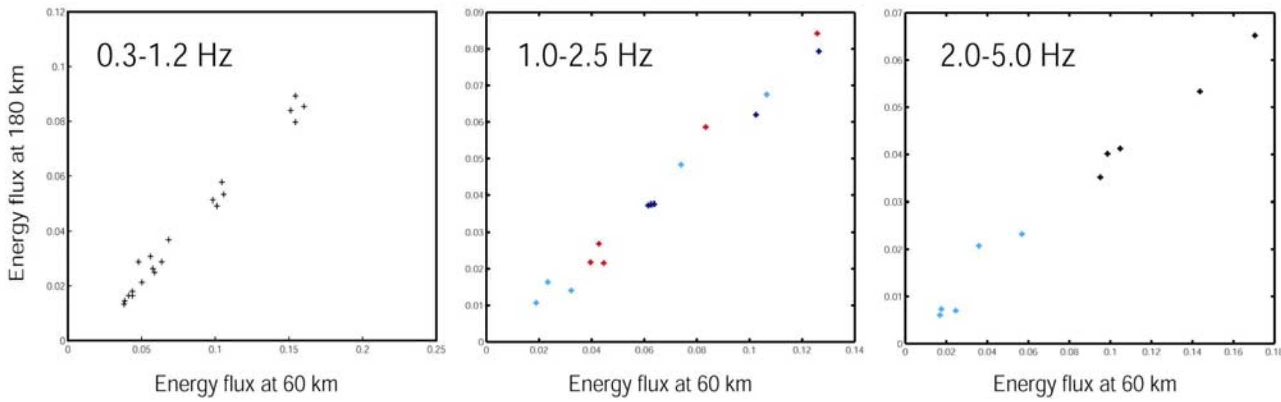


**Figure 2. Comparison between trapped waveguide energy measured at 60 km (horizontal coordinate) and 180 km (vertical coordinate) for frequency bands 0.3-1.2 Hz, 1.0-2.5 Hz and 2.0-5.0 Hz. The results are from different velocity models and source depths. Different colors represent different velocity models. The results show a general linear relationship for all frequency bands.**

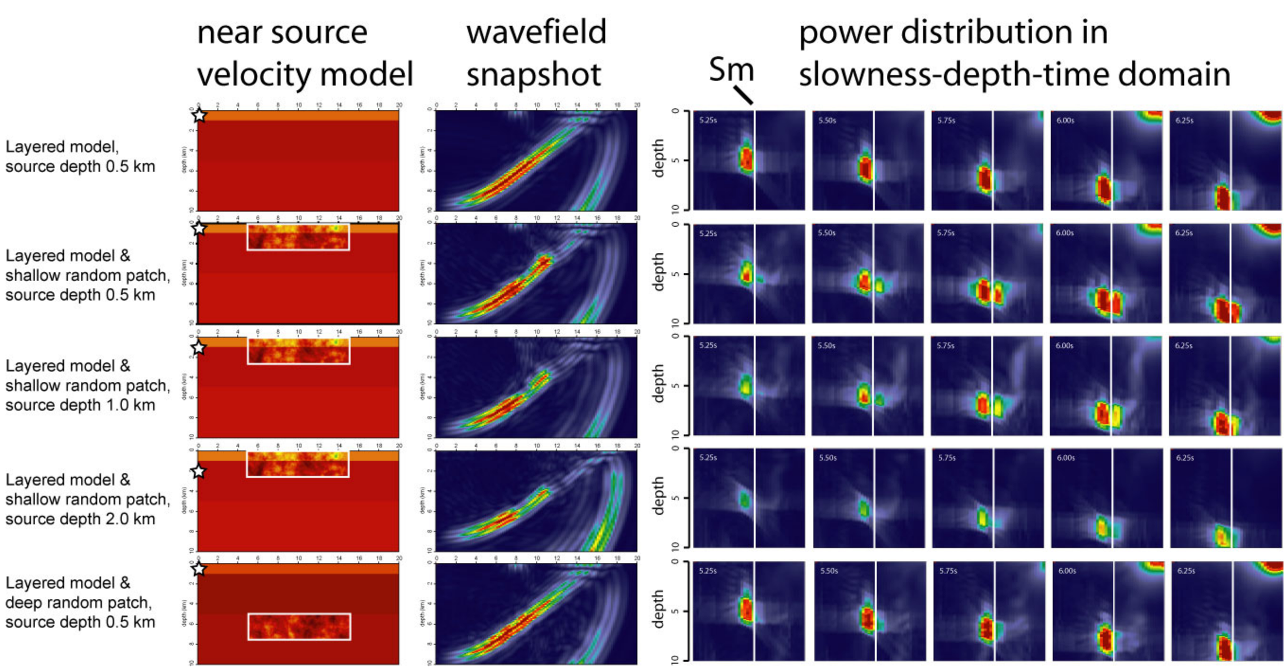


**Figure 3. Summary of the P-pS-Lg wave coupling. From left to right are velocity models, wavefield snapshots and energy distributions in the slowness-depth domain. For details see text.**

## RESEARCH ACCOMPLISHED

### Numerical test of the method

The "finite-difference modeling plus slowness analysis method" (FDSA) is described in Xie and Lay (1994) and Wu, et al., (2002, 2003). For verifying the method, the waveguide energy flux at short distance is compared to the surface Lg-wave energy (Wu, et al., 2003). To examine the energy flux measurements obtained at even shorter distances, we compared the slowness analysis measurements at 60 km with measurements at 180 km distance. For all numerical examples calculated in this report, we use the EK (Eastern Kazakh) model (Priestley et al., 1988) as the background and modify it by adding different laterally varying structures. A range of sources and near source structures was used in the simulations. Figure 1 gives examples for energy with different slowness (phase velocities) at these two distances. The wave fields at these distances show quite different features in the slowness-depth domain but give consistent predictions for the wave field energy fluxes. Figure 2 compares the corresponding wave guide energy measured at 60 km and 180 km distances. Although a wide range of near-source structures and source depths are used to generate these measurements, they show very good linear relationships. This further verifies that we can use a small model to predict the energy distribution at greater distances.

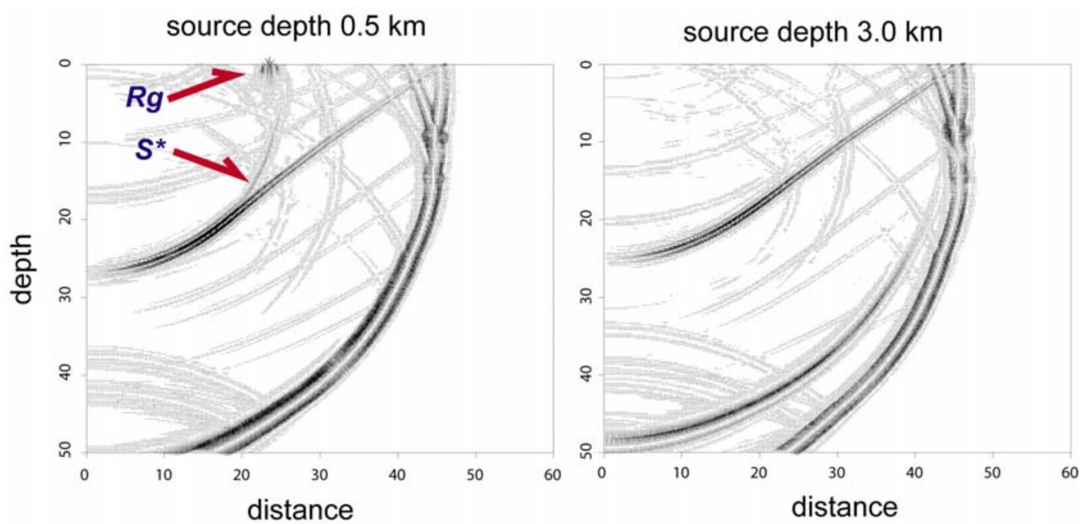


**Figure 4. Wavefield snapshots for explosion sources at different depths. The source depths for left and right panels are 0.5 km and 3.0 km, respectively. A shallower explosion is a more efficient source for S* and Rg-waves.**

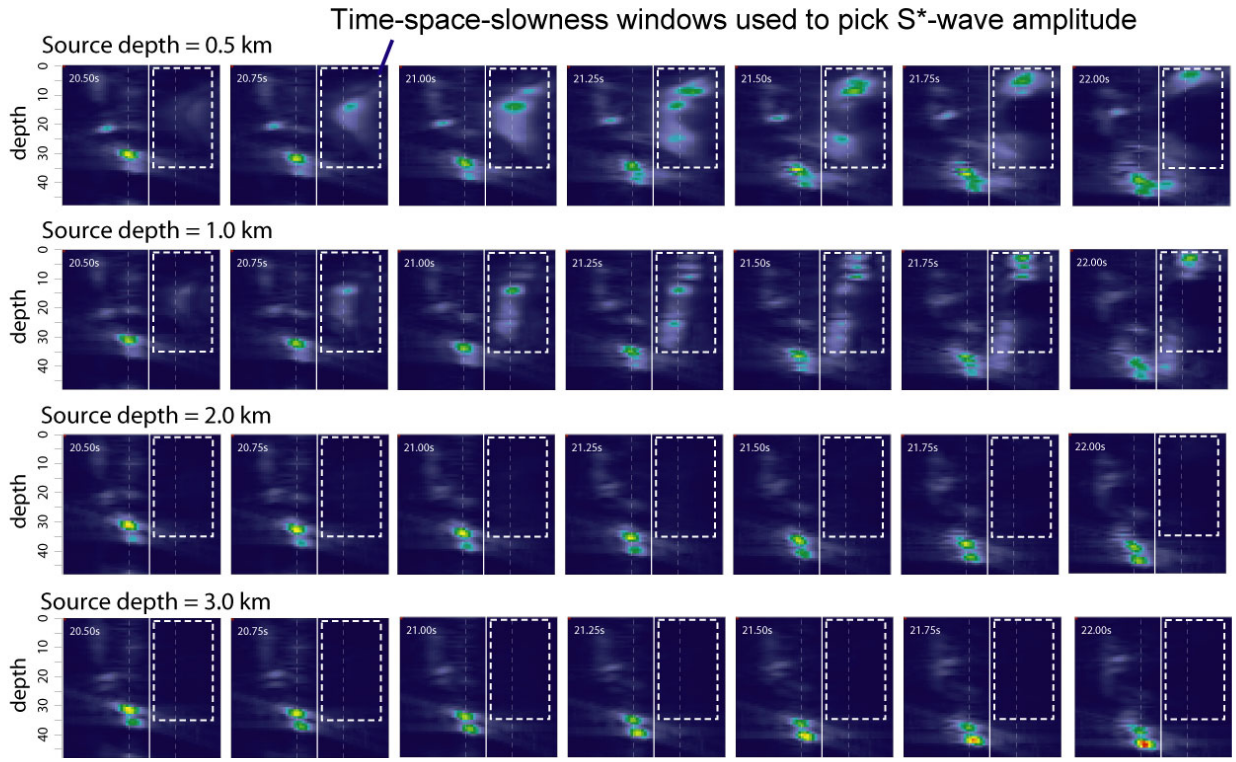


**Figure 5. Slowness analysis for investigating the S*-wave energy contributing to the Lg-wave. Different rows are for different source depths. Dash line rectangles indicate the time-space-slowness windows used to pick the S* energy.**

**Investigating P-Lg and pS-Lg conversion**

Figure 3 summarizes how the near-source lateral velocity variations affect the explosion P-to-S energy conversion. From left to right are velocity models, wave field snapshots and energy distributions in the slowness domain. Slowness analysis is used at a distance of 16 km and depth 0-10 km. We use different source/model combinations in the simulations and test their effects on the P-to-S conversion. This example shows that without the lateral velocity heterogeneity, the energy of the free-surface reflected pS wave falls to the left of the upper mantle S-wave slowness and therefore cannot form trapped energy at regional distance. With a random velocity layer added to the model, the pS-wave front becomes distorted and its slowness content crosses the upper mantle S-slowness. Assessing the energy that builds to the right of the upper mantle S-slowness allows us to predict the Lg-wave component associated with P-to-S conversion. As can be seen from the numerical simulation, the depth of the source and the depth of the scattering region have strong effects on the P-to-S conversion and the partitioning of energy into trapped and leaking signal.

**Contributions from S*-wave**

For shallow spherical explosions, depending on the situation, the S*-wave may become a significant contributor to Lg (Gutowski, et al., 1984; Xie and Lay, 1994; Vogfjord, 1997). The amplitude of S* can be large as long as the source depth is within a fraction of a wave length from an interface. This makes its excitation highly dependent on the source depth and frequency. Figure 4 shows snapshots for explosion sources at 0.5 km and 3.0 km, respectively. This clearly shows that a shallow source generates larger S*- and Rg-waves. Figure 5 gives slowness analysis at 60 km distance for explosions at different depths. The S* energy is marked using dash line rectangles located to the right of the upper mantle S-wave slowness. With the FDSA method, we can isolate and quantify the S* energy even within the complicated near source region, e.g., separate the S* from the pS-wave. Using a band pass filter, the excitation function of the S*-wave can be easily obtained. This can be used to compare with various observations such as the spectral content of Sn and Lg, and various types of P/S amplitude ratios.

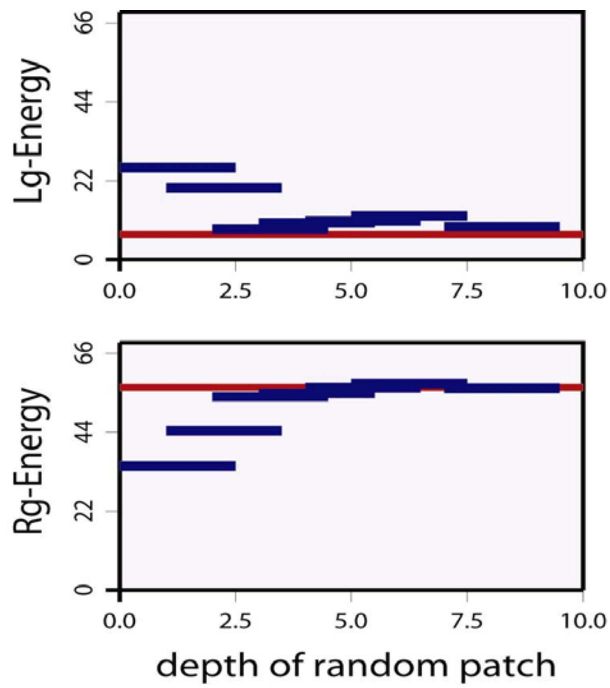


**Figure 6. Apparent relationship between the Lg- and Rg-wave energy at 180 km in the waveguide vs. the depth of near source random scattering. Frequency range is 0.3-1.2 Hz. Red lines are for the background layered model. Blue bars are for models with near source random patches at different depths.**

**<u>Possible Rg-to-Lg coupling</u>**

Rg-to-Lg coupling has long been proposed as a potential mechanism for low frequency Lg-wave excitation. However, there is disagreement as to whether this is a dominant mechanism or not. This is mainly due to the lack of knowledge about the actual mechanism of this process. Although it is generally agreed that Rg-to-Lg coupling is caused by scattering in the near-surface environment, systematic investigation of this process is still lacking. We have conducted two types of tests: a) for a shallow explosion source, we locate scattering regions at different depths; and b) for a shallow scattering region, sources are located at different depths. Figure 6 shows the waveguide energy fluxes for Lg and Rg versus the depth of near-source heterogeneities. The frequency range is 0.3-1.2 Hz. For models with shallow scattering, Rg loses energy while Lg gains energy. Figure 7 gives the apparent relationship between the source depth and the Rg and Lg energy. The three frequency bands are 0.3-1.5, 1.0-2.0 and 2.0-5.0 Hz, respectively. The sources are located at different depths and scattering is provided by adding a near source random patch at the top of the crust. A shallower source raises both Rg and Lg energy while shallow scattering increases the Lg energy but decreases the Rg energy. The apparent Rg-Lg coupling occurs in the low frequency band and Pg-Lg coupling occurs in the high frequency band. Although these preliminary results provide an apparent relationship similar to some observations, they do not yet provide robust evidence that the energy lost from Rg necessarily transferred to the Lg, since the S*-wave also has a similar excitation function. To solve this problem, further investigations which can reveal direct energy exchange between Rg and Lg at the near source region are required.

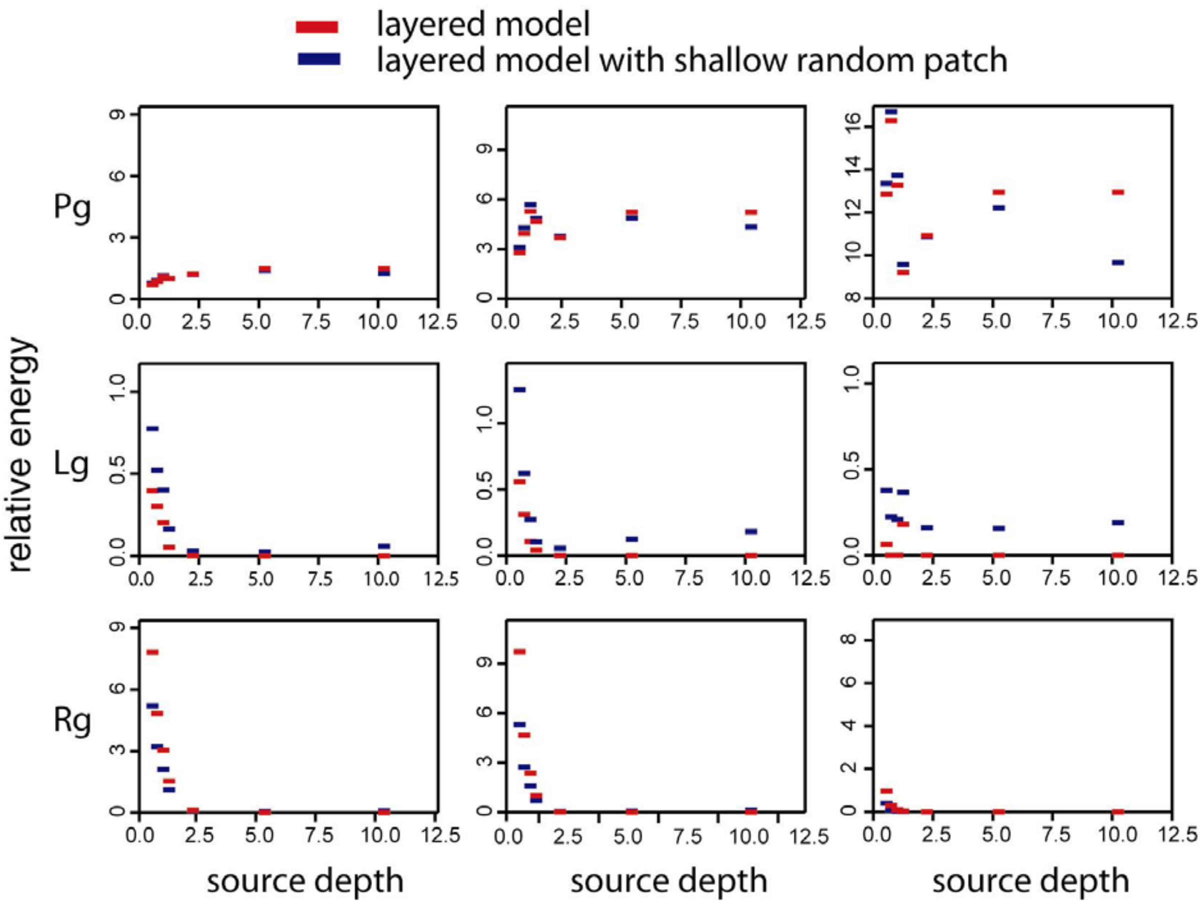


**Figure 7. Effects of shallow near source scattering on the energy partitioning of Pg-, Lg- and Rg-waves. Sources located at different depths between 0.5 and 10 km. Results for background model are shown with red bars and results for models with random patches are shown with blue bars.**

**Frequency dependent excitation spectra and P/S ratios**

We emphasize simulating the observed frequency dependent attributes of P and S partitioning. These frequency variations are rooted in the underlying physical processes and are usually controlled by different characteristic scales. For example, the excitation of Lg by S*, Rg-to-S scattering and spall are all highly source-depth dependent. The excitation spectra of specific phases depict the frequency dependence of these processes. Frequency-dependent P/S ratios will depend on the excitation functions of multiple phases. Figure 8 gives the excitation spectrum for the trapped energy from the S*-wave (without calibration using the source spectrum). The result clearly shows that the excitation is generally favorable to lower frequency and shallow source depth. Although the maximum amplitude usually appears at the low frequency end, the spectrum of a 1 km deep source has a maximum at around 3 Hz. This may result from that the particular velocity model used, which has an interface at 1 km depth. The frequency dependence of these excitation spectra can provide a basis for evaluating the dominant mechanisms for Lg-wave excitation, or for down-weighting particular mechanisms as being less significant. It can also provide a relationship between the observations and the characteristics of the source and near source structure.

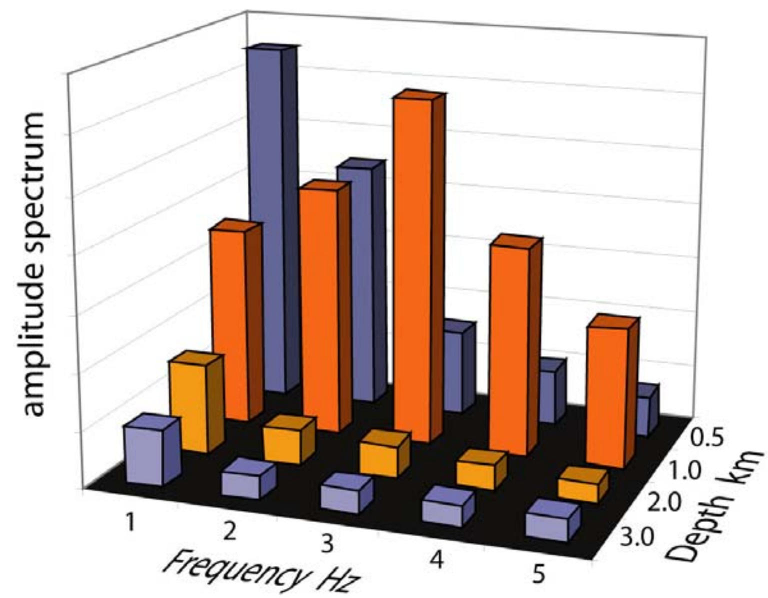


**Figure 8. S*-to-Lg excitation spectra for sources at different depths. Note that the power is mostly concentrated at lower frequencies and for shallower sources.**

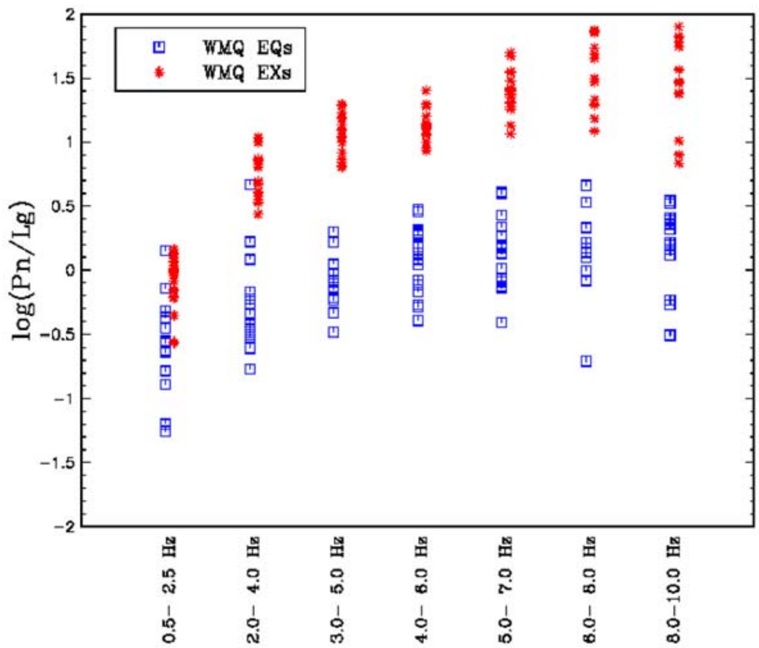


**Figure 9. Log Pn/Lg amplitude ratios in frequency bands from 0.5 to 10.0 Hz for 20 Balapan nuclear explosions (asterisks) and 24 earthquakes (squares) recorded by WMQ (Fisk, 2003). The two populations exhibit poor separation below about 2 to 3 Hz and good separation at higher frequencies. SNRs for three of the nuclear explosions are marginal at frequencies above ~8 Hz.**

Figure 9 shows observed Log (Pn/Lg) amplitude ratios in the frequency band between 0.5 and 10.0 Hz for explosions and earthquakes (Fisk, 2003). The two populations exhibit poor separation below about 2 to 3 Hz and good separation at higher frequencies. Figure 10 gives a simple simulation of the Log(P/Lg) amplitude ratio in the frequency band 0.2 to 5.2 Hz. Two types of sources are used, an isotropic explosive source at 0.5 km depth representing a typical "explosion", and a 45-degree dip-slip dislocation source at 3.0 km depth representing a typical "shallow earthquake". Two velocity models are used in the calculation, EK and EK plus a shallow near source random layer (depth 0-2.5 km, distance 5-25 km). The slowness analysis is conducted at a distance of 60 km. For the explosive source in the EK model, the Lg energy mainly comes from the S* phase. For the EK plus random layer model, it is expected that S*, P-to-Lg and Rg-to-Lg couplings will jointly contribute to the Lg energy. Compared with the explosive source, the somewhat deeper dislocation source is less affected by the shallow random layer. The general features of the simulation are similar to the observations (Figure 9): at the low frequency end, the earthquakes and explosions have similar P/Lg ratios but at higher frequencies, the explosive source generates less S energy.

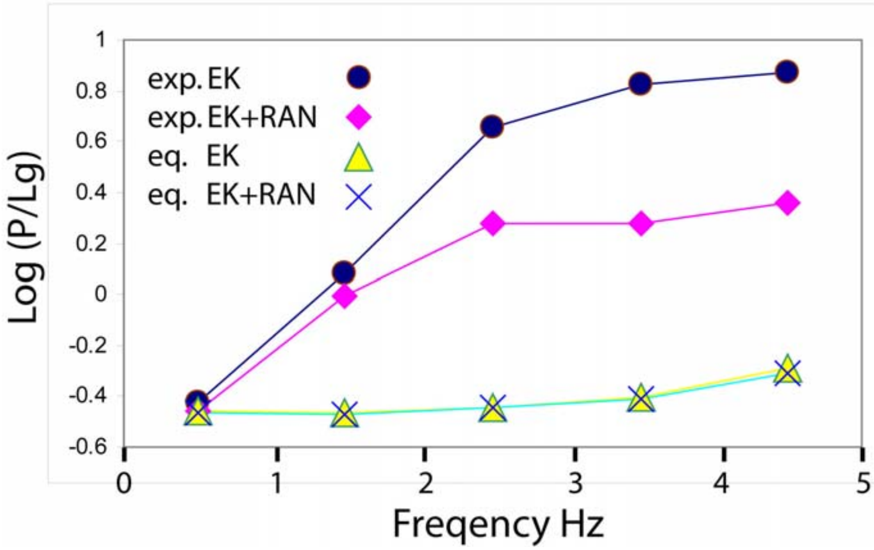


**Figure 10. Simulated Log (P/Lg) amplitude ratios in frequency domain. The circle, diamond, triangle and cross represent explosion source in the EK model, explosion source in the EK model with shallow random patch, dislocation source in the EK model and dislocation source in the EK model with shallow random patch. The explosion source is located at depth 0.5 km and the dislocation source is located at depth 3.0 km.**

## CONCLUSIONS AND RECOMMENDATIONS

The "finite-difference modeling plus slowness analysis method" is used to investigate the excitation and near source energy partitioning for crustal guided waves. The method has two major advantages. First, it allows us to study the wavefield property in multiple domains including space, time, slowness and frequency, which gives a better opportunity to isolate different mechanisms within the complicated near source region. Second, the method can be applied at close range, well before Lg is actually formed. This makes the method very efficient. It allows us to use very fine near source velocity models, calculate a broader frequency band and test a large quantity of source/model combinations. Using this method, several excitation and partition mechanisms, e.g., P-Lg, pS-Lg, Rg-Lg and S*-Lg, are separately investigated. The results are preliminary.

Since the FDSA is an efficient method, we suggest using this method to systematically assess the relationship between the near-source velocity structure, source parameters and the resulting Lg energy. The relative importance of different excitation mechanisms can be evaluated. The statistical features of the velocity structure, RMS value and correlation length, along with the depth of the scattering region and the source depth will control the frequency-dependent transfer functions. It is expected that with more complexities being added to the model (CLVD, different overburden structures and scattering models, source depth changes, different source time functions, etc.), these frequency dependent features will be complicated, but can be systematically mapped out. This is an essential undertaking for placing regional phase energy partitioning on a sound physical basis. The numerical modeling will set up a link between the physical model and observable frequency dependent features, which can provide guidelines for improving the empirical discrimination relations. Feedback from the observations will guide the simulations towards the correct physical models as well.

Although most Lg observations are taken from the vertical component of seismograms, the tangential component often has as much energy as the vertical component. Some researchers reported that in the near field strong motion records, clear SH energy comparable to that from SV component can be observed and they must be generated in the source region. Any Lg-wave excitation theory must provide an explanation for these observations. Since 2D geometry decouples the P-SV problem and the SH problem, it does not provide any information on the coupling between the source and SH component. We propose to extend the FDSA method from 2D to 3D case to address this problem.

## ACKNOWLEDGEMENTS

This research is supported by the Air Force Research Laboratory under the Contract No. DTRA01-01-C-0076. Facility support from the W.M. Keck Foundation is also acknowledged.

## REFERENCES

Bonner, J.B., H.J. Patton, A.C. Rosca, H. Hooper, J. Orrey, M. Leidig and I. Gupta, (2003), Aspects of Rg and Lg generation from the Shagan depth of burial explosions, *Proceedings of the 25th Seismic Research Review, Muclear Explosion Monitoring: Building the Knowledge Base*, LA-UR-03-6029, Vol. I, pp. 384-394.

Day, S.M. and K.L. McLaughlin, 1990, Seismic source representations for spall, *Bull. Seism. Soc. Am.*, 81, 191-201.

Fan, G.W. and T. Lay, 1998a, Statistical analysis of irregular waveguide influences on regional seismic discriminants in China, *Bull. Seismol. Soc. Am.*, 88, 74-88.

Fan, G.W. and T. Lay, 1998b, Regionalized versus single-station wave-guide effects on seismic discriminants in western China, *Bull. Seismol. Soc. Am.*, 88, 1260-1274.

Fan, G.W. and T. Lay, 1998c, Statistical analysis of irregular waveguide influences on regional seismic discriminants in China: additional results for Pn/Sn, Pn/Lg and Pg/Sn, *Bull. Seismol. Soc. Am.*, 88, 1504-1510.

Fisk, M. D., H. L. Gray and G. D. McCartor 1996, Regional discrimination without transporting thresholds, *Bull. Seism. Soc. Am.*, 86, 1545-1558.

Gupta, I.N., W. Chan, and R. Wagner, 1992, A comparison of regional phases from underground nuclear explosions at East Kazakh and Nevada Test Sites, Bull. Seism. Soc, Am., 82, 352-382.

Gupta, I. N., T. Zhang, and R. A. Wagner 1997, Low-frequency Lg from NTS and Kazakh nuclear explosions: observations and interpretations, *Bull. Seism. Soc. Am.*, 87, 1115-1125.

Gutowski, P.R., Hron, F., Wagner, D.E. and Treitel, S., 1984, S*, Bull. Seism. Soc. Am. 74, 61-78.

Hartse, H.E., S.R., Taylor, W.S., Phillips, and G.E., Randall, 1997, A preliminary study of regional seismic discrimination in central Asia with emphasis on western China, *Bull. Seism. Soc. Am.*, 87, 551-568.

Jih, R.S., 1995, Numerical investigation of relative contribution of Rg scattering and incomplete dissipation to Lg excitation, *Proceedings of the 17th Seismic Research Symposium on Monitoring a CTBT, PL-TR-95-2108*.

Jih, R.S., 1996, Waveguide Effects of large-scale structural variation, anelastic attenuation, and random heterogeneity on SV Lg propagation: a finite-difference modeling study, 182-194, *Proceedings of the 18th Annual Seismic Research Smposium on Monitoring a CTBT, 4-6 September 1996*.

Johnson, L.R., and C.G. Sammis, 2001, Effects of rock damage on seismic waves generated by explosions, *Pageoph*, 158, 1869-1908.

Kim, W. Y., V. Aharonian, A. L. Lerner-Lam and P. G. Richards 1997. Discrimination of earthquakes and explosions in southern Russia using regional high-frequency three-component data from IRIS/JSP Caucasus Network, *Bull. Seism. Soc. Am.*, 87, 569-588.

Kim, W. Y., D. W. Simpson and P. G. Richards 1993. Discrimination of earthquakes and explosions in the eastern United States using regional high-frequency data, *Geophys. Res. Lett*., 20, 1507-1510.

Myers, S.C., J. Wagoner, S. Larsen, A. Rodgers, K. Mayeda, K. Smith, and W. Walter, 2003, Simulation of regional explosion S-phases (SIRES) project, *Proceedings of the 25th Seismic Research Review, Muclear Explosion Monitoring: Building the Knowledge Base*, LA-UR-03-6029, Vol. I, pp. 117-124.

Nuttli, O.W., 1986, Yield estimates of Nevada Test Site explosions obtained from Lg waves, *J. Geophys. Res*., 91, 2137-2151.

Priestley, K. F., G. Zandt, and G. E. Randall, 1988, Crustal structure in Eastern Kazakh, USSR from teleseismic receiver functions, *Geophys. Res. Lett*., 15, 613-616.

Patton, H.J., 2001, Regional magnitude scaling, transportability, and Ms:mb discrimination at small magnitudes, *Pageoph*, 158, 1951—2015.

Stevens, J.L., G.E. Baker, H. Xu, T.J. Bennett, N. Rimer, S.M. Day, 2003, The physical basis of Lg generation by explosion sources, *Proceedings of the 25th Seismic Research Review, Muclear Explosion Monitoring: Building the Knowledge Base*, LA-UR-03-6029, Vol. I, pp. 456-465.

Taylor, S.R., 1996, Analysis of high frequency Pn/Lg ratios from NTS explosions and western U.S. earthquakes, *Bull. Seism. Soc. Am*., 86, 1042-1053.

Taylor, S. R., M. D. Denny, E. S. Vergino, and R. E. Glaser 1989, Regional discrimination between NTS explosions and western U.S. earthquakes, *Bull. Seism. Soc. Am*., 79, 1142-1176.

Taylor, S. R., and H. E. Hartse (1997). An evaluation of generalized likelihood ratio outlier detection to identification of seismic events in western China, *Bull. Seism. Soc. Am*., 87, 824-831.

Vogfjord, K.S., 1997, Effects of explosion depth and earth structure on the excitation of Lg waves: S* revisited, *Bull. Seism. Soc. Am*., 87, 1100-1114.

Wallace, T.C., 1991, Body wave observations of tectonic release, in: S.R. Taylor, H.J. Patton and P.G. Richards (editors), *Explosion Source Phenomenology*, pp 161-170, American Geophysical Union.

Walter, W.R., K.M., Mayeda, and H. Patton, 1995, Phase and spectral ratio discrimination between NTS earthquakes and explosions. Part I: Empirical observations, Bull. Seism. Soc. Am., 85, 1050-1067.

Wu, R.S., S. Jin and X.B. Xie, 2000a, Seismic wave propagation and scattering in heterogeneous crustal waveguides using screen propagators: I SH waves, *Bull. Seism. Soc. Am*., 90, 401-413.

Wu, R.S., S. Jin and X.B. Xie, 2000b, Energy partition and attenuation of Lg waves by numerical simulations using screen propagators, *Phys. Earth and Planet. Inter*., 120, 227-243.

Wu, R.S., X.B. Xie, X. Wu and T. Lay, 2003, Quantifying source excitation and path effects for high frequency regional waves, *Proceedings of the 25th Seismic Research Review, Muclear Explosion Monitoring: Building the Knowledge Base*, LA-UR-03-6029, Vol. I, pp. 173-181.

Xie, J.K., Cong, L.L., and Mitchell, B.J., 1996, Spectral characteristics of the excitation and propagation of Lg from underground nuclear explosions in central Asia, *J. Geophys. Res*., 101, 5813-5822.

Xie, J.K. and Patton, H.J., 1999, Regional phase excitation and propagation in the Lop Nor region of central Asia and implications for P/Lg discriminations, *J. Geophys. Res*., 104, 941-954.

Xie, X.B. and Lay, T., 1994, The excitation of Lg waves by explosions: A finite-difference investigation, *Bull. Seism. Soc. Am*., 84, 324-342.