

26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

A SEISMIC EVENT DISCRIMINATION SYSTEM BASED ON IMPROVED UNDERSTANDING OF Lg FROM EXPLOSIONS – PRELIMINARY RESULTS

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ABSTRACT

Nuclear monitoring requires identification of small events observed at regional distances for which Lg is generally the largest and sometimes the only well-recorded seismic phase. Recent research, including ours, has provided significantly better understanding of the generation of Lg from explosions, but the new concepts have not yet been fully exploited for improving discrimination between low magnitude explosions and earthquakes in geologically distinct regions. Our analysis of regional data from nuclear explosions from both Nevada and Kazakh test sites and nearby earthquakes indicates several significant differences in the characteristics of the seismic phase, Lg. Spectrograms of underground nuclear explosions and earthquakes recorded at regional distances show the Lg wavetrain only from the explosions to consist of several distinct low-frequency arrivals with progressively lower frequency content and diminishing strength or amplitude. Comparisons of the spectral ratios of Lg based on ratio of spectral amplitudes within the low-frequency range of 0.5 to 2.0 Hz to those within a higher frequency range, such as 3.0 to 7.0 Hz, and of the mean spectral slopes of Lg over a fairly large range of frequencies, such as 0.5 to 7.0 Hz, show significant differences for the two types of seismic sources. Frequency-domain skewness – a measure of spectral shape – over a broad range of frequencies, such as 0.5 to 7.0 Hz, of the Lg spectra is also significantly different for the explosion and earthquake sources. These results suggest several source discrimination methods based on the use of only the Lg phase, including (a) amplitude-frequency-time analysis of spectrograms, (b) Lg spectral ratios, (c) Lg spectral slopes, and (d) skewness of Lg spectra. Remarkable similarity of discrimination results from the two geologically different regions suggests that these results should be applicable for identifying small seismic events in other regions of the world as well.

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OBJECTIVE

Lg is generally the largest seismic phase from both explosion and earthquake sources recorded at regional distances. For small events, Lg may sometimes be the only well-recorded seismic phase. It is therefore important to develop a reliable source identification method based on the use of only the Lg phase, enabling discrimination of smaller events. Gupta et al. (1992) provided observations and theoretical model suggesting that near-source scattering of explosion-generated Rg into S makes a significant contribution to the low-frequency (less than 2 Hz) Lg. Observational support for this mechanism has grown in recent years (Patton and Taylor, 1995; Gupta et al., 1997; Myers et al., 1999; Patton, 2001). Several more recent studies, such as Bonner et al. (2003), Myers et al. (2003), and Wu et al. (2003), also provide strong evidence in favor of the Rg-to-S scattering mechanism for the generation of the low frequency S and Lg. It is important to make use of these new concepts regarding the generation of Lg from explosions for exploring the possibility of significant improvements in source discrimination.

RESEARCH ACCOMPLISHED

Discrimination Based on Analysis of Spectrograms

Spectrograms of underground nuclear explosions recorded at regional distances generally show the Lg wavetrain to consist of several distinct low-frequency arrivals with progressively lower frequency content and diminishing strength or amplitude. The most probable reasons for this are: the scattering of explosion-generated Rg into S occurs at several discrete near-source locations at different distances from the source, Rg has a significantly lower propagation velocity as compared to that of Lg, and Rg suffers considerably larger attenuation with distance than Lg. On the other hand, Lg wavetrains on earthquake spectrograms do not show such characteristics.

A spectrogram may be considered as a three-dimensional matrix of numbers providing amplitude and frequency information for each point in the time series. Instead of relying on subjective visual examination, we need to evaluate the most effective discriminants by making the required measurements within the spectrograms. Accurate measurements must be made of the sought-after patterns such as discrete Lg energy arrivals with decreasing frequency content and decreasing amplitudes. For this purpose, we first normalized the Lg wavetrain from events at various recording distances so that the number of time windows used for spectrograms is the same for all events. Lg from seismic events at regional distances is known to have a fairly constant velocity of 3.5 km/sec. The term Lg coda generally refers to seismic arrivals at travel times greater than about twice the direct Lg (e.g., Hartse et al., 1995). Our selection of Lg wavetrain represents a time window starting at Lg (i.e., at velocity of about 3.5 km/sec) and ending at a travel time no greater than about twice the direct Lg time. Henceforth, we will refer to this Lg window as Lg "wavetrain", since it does not contain any usual Lg "coda."

We tried to quantify the two features (i.e., decreasing frequency content and decreasing amplitudes with time) of Lg wavetrain on spectrograms by first selecting the Lg wavetrain starting at a velocity of 3.3 km/sec (instead of 3.5 km/sec) because the scattered arrivals are expected to be somewhat delayed as compared to the direct Lg. The Lg wavetrain used for analysis was taken to be from t_1 to t_2 ($= t_2 - t_1$), where $t_1 = D/(3.3 \text{ km/sec})$ and $t_2 = D/(1.65 \text{ km/sec})$. Thus, $t_2 - t_1 = D/(3.3 \text{ km/sec})$. The moving time window, w , for spectrograms was selected to be 1/10 of the selected Lg wavetrain, i.e., $w = (t_2 - t_1)/10$ and the slice interval (time shift) was one-fourth of the moving window length. With these parameters, each spectrogram contained results from approximately 40 time windows within $t_2 - t_1$.

Several measurements on both explosion and earthquake spectrograms were made, but most of these did not look promising for source discrimination. However, the following measurement that combines both temporal features (i.e., decreasing frequency and decreasing amplitudes) for explosions provided encouraging results.

For each time slice, a mean weighted frequency, $f(\text{mean})$ is defined as

$$f(\text{mean}) = (f_1 A_1 + f_2 A_2 + f_3 A_3 + \dots) / (A_1 + A_2 + A_3 + \dots) \quad (1)$$

where A_1, A_2, A_3, \dots are amplitudes associated with frequencies of f_1, f_2, f_3, \dots . The frequency range is generally selected to be 0.3 to 2.0 Hz for which the short-period Rg is generally dominant.

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When these $f(\text{mean})$ values are plotted versus time within t_1 and t_2 , a series of peaks representing prominent low-frequency arrivals are observed. For explosions, the frequency values corresponding to these peaks may be expected to decrease more systematically than for earthquakes. A linear regression of these peak frequency values versus time should therefore indicate much smaller variance for explosions than for earthquakes. The above statement is of course based on several simplifying assumptions, including (i) a single dominant source of explosion R_g , (ii) several near-source discrete sources of scattering generate similar scattered S waves (i.e., similar scattering functions), and (iii) attenuation of R_g with distance is strong and not much dependent on epicenter-to-scatterer azimuthal direction. If these assumptions are valid, all prominent spectral peaks in the L_g wavetrain should be due to R_g -to-S arrivals and they should progressively decrease with arrival time in both frequency content and amplitude. Most of the contribution to $f(\text{mean})$ for a given value of arrival time comes from the peak frequency and amplitude associated with the distinct R_g -to-S scattered arrival.

Our objective is to examine the variance associated with linear regression between $f(\text{mean})$ versus time based on the use of only prominent large-amplitude arrivals. For this purpose, we need to (1) correct for the general decrease in wavetrain amplitude with time and (2) remove the influence of low-amplitude arrivals filling the gaps between adjacent spectral peaks. For (1), all spectral amplitudes within the 0.3-2.0 Hz frequency band and within the selected L_g wavetrain (i.e. from time t_1 to t_2) were plotted versus travel time, t . A linear regression is carried out and the mean slope, s , is determined. This slope, s is almost always negative for both explosions and earthquakes because of attenuation with distance and time. In order to include the later arriving spectral peaks with generally lower amplitudes into our analysis, an attenuation with time correction was applied to all amplitude values by increasing the amplitudes at a given travel time, t , by the positive amount $-s(t-t_1)$. In this way, the mean slope for the selected amplitude values became 0. In order to correct for (2), we retained only those amplitude points that were within the top 25% values. These amplitude and associated frequency values are used for the linear regression in equation (1) and the corresponding standard deviation is determined. A correction for amplitude differences between various seismic events because of their magnitudes is applied by using normalized standard deviation values based on division by the average value of all mean weighted frequency values within t_2-t_1 .

We carried out the above analysis on 10 Yucca Flat (Nevada Test Site, NTS) explosions and 10 nearby earthquakes recorded at the Lawrence Livermore National Laboratories (LLNL) broadband station, Mina, Nevada (MNV). As examples, spectrograms and linear regression results from the Yucca Flat explosion, Starwort (26 April 1973) and the Massachusetts Mountain earthquake (5 August 1971), both recorded at MNV, are shown in Figures 1 and 2. The L_g wavetrain on the Starwort spectrogram (Figure 1) shows several prominent peaks with progressively decreasing frequency content, combined with generally decreasing amplitudes. On the other hand, the spectral peaks on the earthquake spectrogram (Figure 2) indicate significantly different characteristics. The linear regression plots of $f(\text{mean})$ versus travel time for the L_g wavetrain for the two events (bottom plots in Figures 1 and 2) indicate significant difference in their normalized standard deviation values. The results for all 20 events are shown in Figure 3a. The mean value for the earthquake population is about 55% higher than for the explosion population. Considering that results from only one recording station are shown, it seems that the observed differences in normalized standard deviation values should be useful for source discrimination.

We performed analysis similar to that for the U.S. events for 10 Kazakh Test Site (KTS) explosions and 10 earthquakes recorded at the broadband digital station Wulumuchi, China (WMQ). However, because of the much larger epicentral distances, the L_g wavetrain used for analysis was considered to be the interval within group velocities of 3.4 and $(2/3) \times 3.4 = 2.27$ km/sec. Thus $t_2-t_1 = D/(2.27) - D/(3.4) = D/(6.8 \text{ km/sec})$. The moving time window, w , for spectrograms was selected to be $1/20$ of t_2-t_1 and the slice interval was one-half of the moving window length. With these parameters, each spectrogram contained results from approximately 40 time windows within t_2-t_1 , the same number as for the U.S. data. Similar to Figures 1 and 2, the explosion and earthquake spectrograms generally indicated significantly different characteristics and the linear regression plots of $f(\text{mean})$ versus travel time for the L_g wavetrain also showed significant difference in their normalized standard deviation values. The results for all 20 events, shown in Figure 3b, indicate the mean value for the earthquake population to be about 52% higher than that for the explosion population. These results, similar to those for the U.S. data (Figure 3a), suggest that observed differences in the normalized standard deviation values could be useful for source discrimination based on the use of only L_g . It should be noted that, unlike the U.S. events, the available earthquakes (located in Russia and China) used for comparison with KTS nuclear explosions (which are clustered together) are at significantly different locations. This means that the differences in propagation paths and source-receiver distances for the two types of events are likely to significantly

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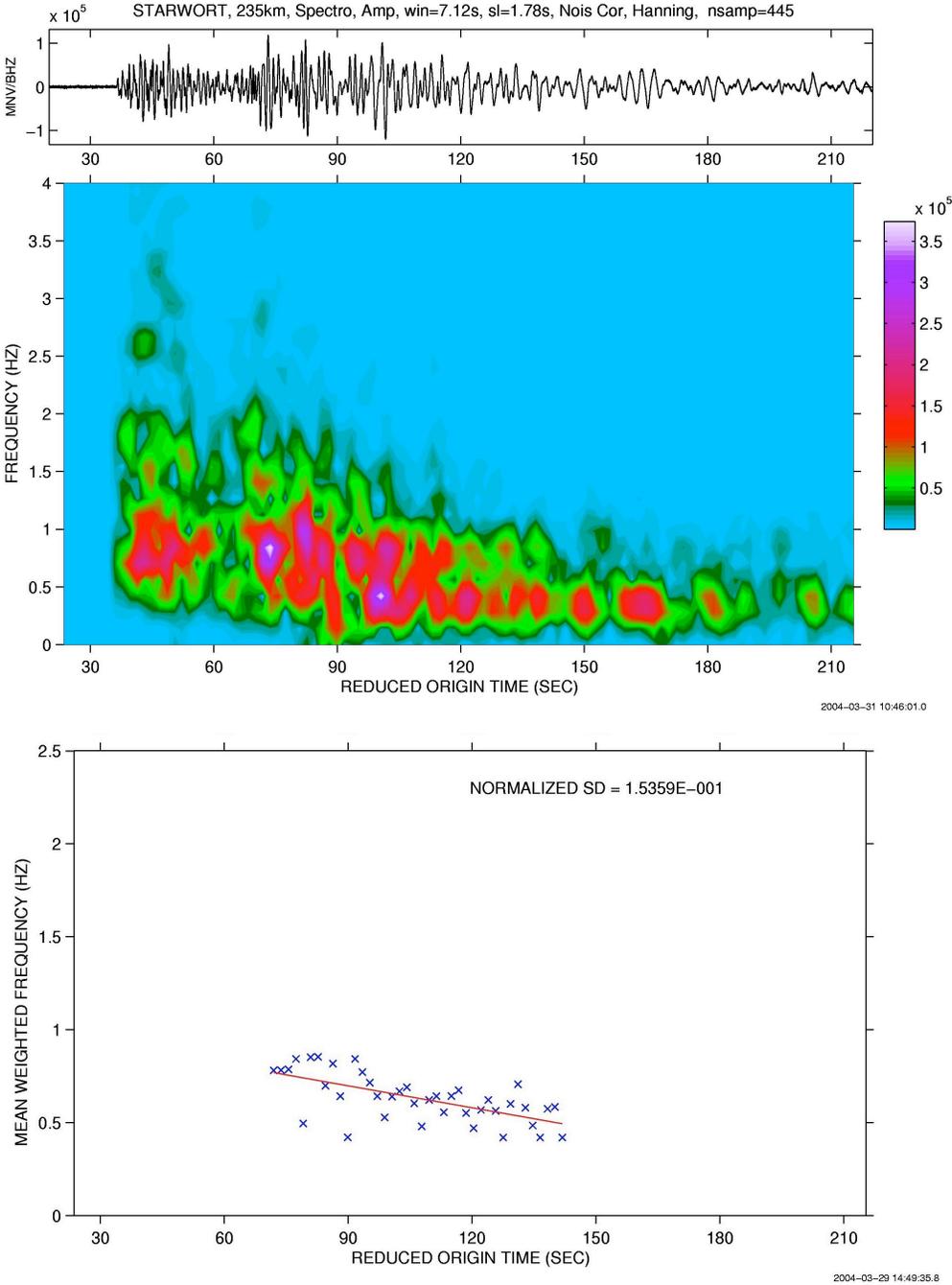


Figure 1. Seismogram (top) and spectrogram of Starwort recorded at MNV. The Lg wavetrain on the explosion spectrogram, starting at about 71 sec, shows several prominent peaks with progressively decreasing frequency content and amplitude. Bottom figure shows the mean weighted frequency versus travel time, within the time window $D/(3.3\text{km/sec})$ and $D/(1.65\text{ km/sec})$, where D is the epicentral distance; linear regression (red line) and the associated normalized standard deviation are indicated.

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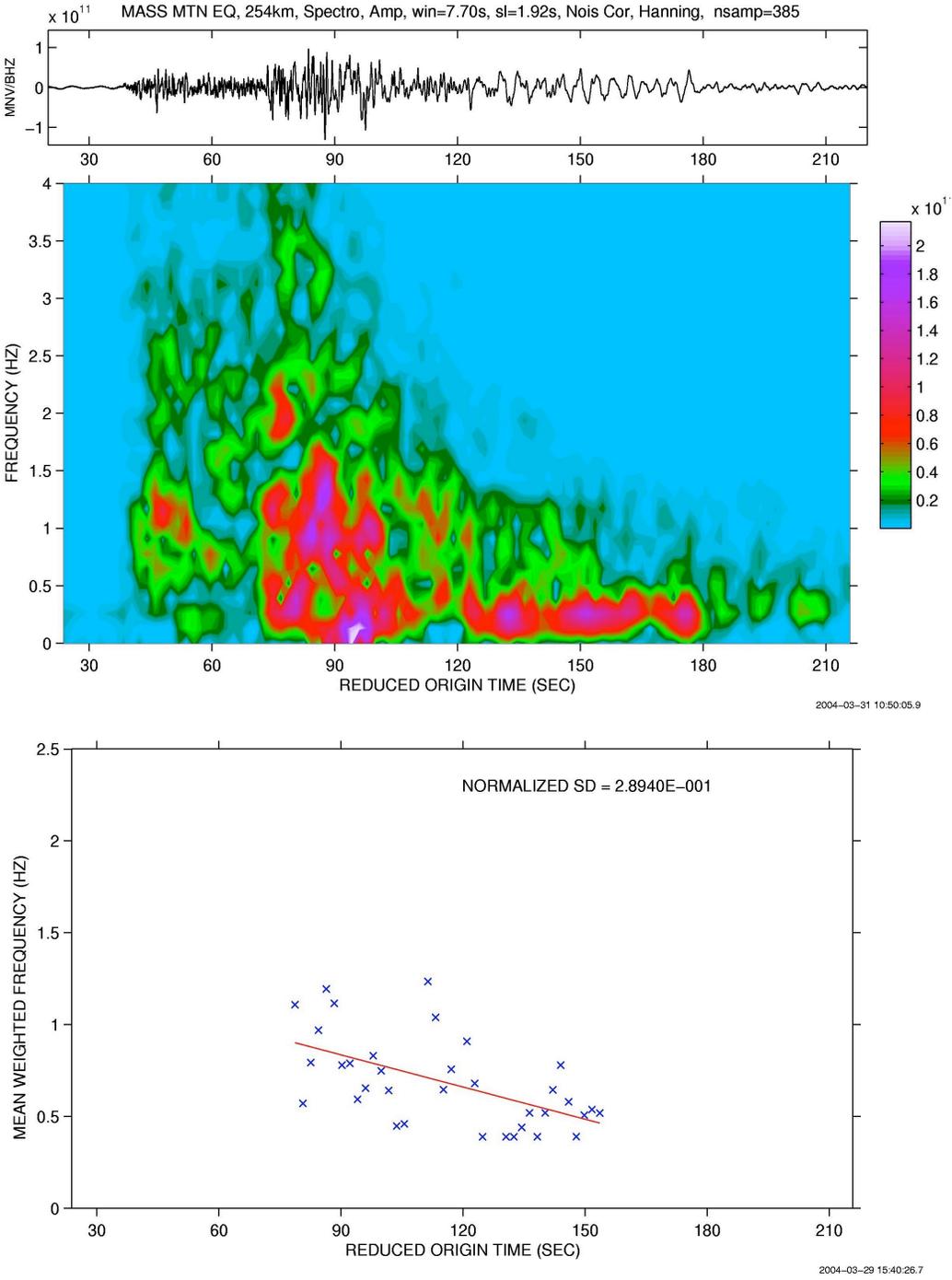


Figure 2. Seismogram (top) and spectrogram of the Massachusetts Mountain earthquake recorded at MNV. The Lg wavetrain, on the earthquake spectrogram, starting at about 77 sec, shows several prominent peaks but these peaks are not as systematically decreasing in frequency content and amplitude as those for the explosion in Figure 1. Bottom figure shows the mean weighted frequency versus travel time, within the time window $D/(3.3\text{km/sec})$ and $D/(1.65\text{ km/sec})$; linear regression (red line) and the associated normalized standard deviation are indicated.

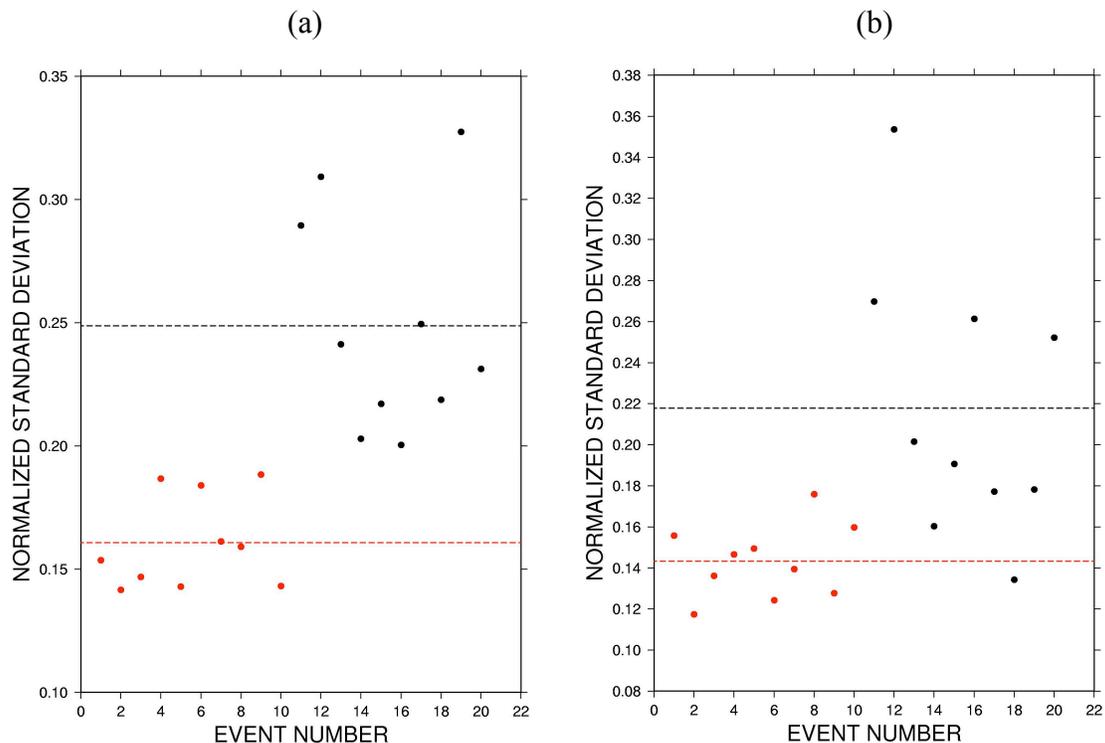


Figure 3. (a) Normalized standard deviation for 10 NTS explosions (red circles) and 10 nearby earthquakes (black circles) recorded at MNV. The earthquake and explosion populations are fairly well separated. The mean value for the earthquake population is about 55% higher than for the explosion population, suggesting that differences in standard deviation values should be useful for source discrimination. (b) Normalized standard deviation for 10 KTS explosions (red circles) and 10 earthquakes (black circles) recorded at WMQ. The earthquake and explosion populations are separated such that the mean value for the earthquake population is about 52% higher than for the explosion population. Considering large differences in propagation paths to WMQ, these results should be useful for source discrimination.

influence the source discrimination results much more than for the U.S. data. This provides a possible explanation for the Soviet discrimination results (Figure 3b) to be not as satisfactory as for the U. S. events (Figure 3a).

Discrimination Based on Lg Spectral Ratios and Spectral Slopes

Several investigators (e.g. Taylor et al., 1988; Gupta and Wagner, 1998) have used Lg spectral ratios for regional discrimination with limited success. There have also been a few studies of spectral slope as a discriminant but with ambiguous results. For example, by analyzing high frequency data, Chael (1988) found the spectral slope of Pg to be a good discriminant for NTS explosions and southwestern earthquakes. Gupta and Wagner (1998) were probably the first to successfully use the spectral slope of Sg and Lg as a source discriminant.

By using the same dataset of 10 NTS explosions and 10 U.S. earthquakes, we obtained spectra of Lg wavetrain starting at a velocity of 3.5 km/sec. Multitapered spectra, corrected for noise, for 25.6 sec long windows were used to obtain mean log amplitudes within several frequency bands. Results for $Lg(0.5-2 \text{ Hz})/(3-7 \text{ Hz})$ are shown in Figure 4a (open symbols). All ten explosions are at nearly the same distance (within 234 to 246 km), whereas the epicentral distances for earthquakes vary from 179 to 300 km. A source-receiver distance correction was therefore computed by assuming linear dependence with distance for the ten earthquake spectral ratios, as by Taylor et al. (1988). Normalizing all data to the mean distance of the ten explosions (i.e. 238 km), the corrected results for all 20 events are also shown in Figure 4a (filled symbols), in which the mean values for the explosion and earthquake populations differ by 0.69 log units.

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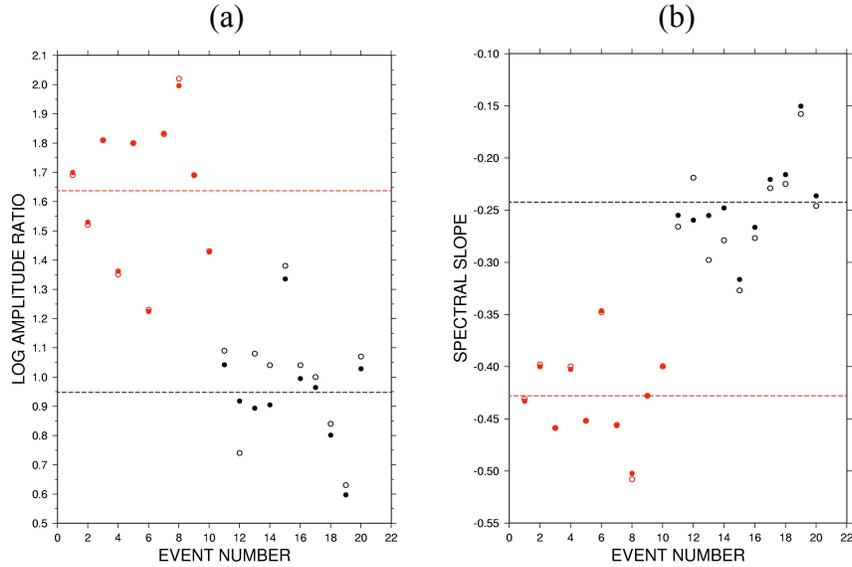


Figure 4. (a) Mean spectral ratio $Lg(0.5-2 \text{ Hz})/(3-7 \text{ Hz})$ for 10 NTS explosions (red circles) and 10 nearby earthquakes (black circles) recorded at MNV. (b) Mean spectral slope of Lg over 0.5-7.0 Hz for the same dataset. In both figures, results without (open symbols) and with distance correction (filled symbols) are shown; the latter show the earthquake and explosion populations to be well separated by (a) 0.69 log units and (b) 0.19 log units. Differences in both (a) Lg spectral ratios and (b) Lg spectral slopes appear to be useful for source discrimination.

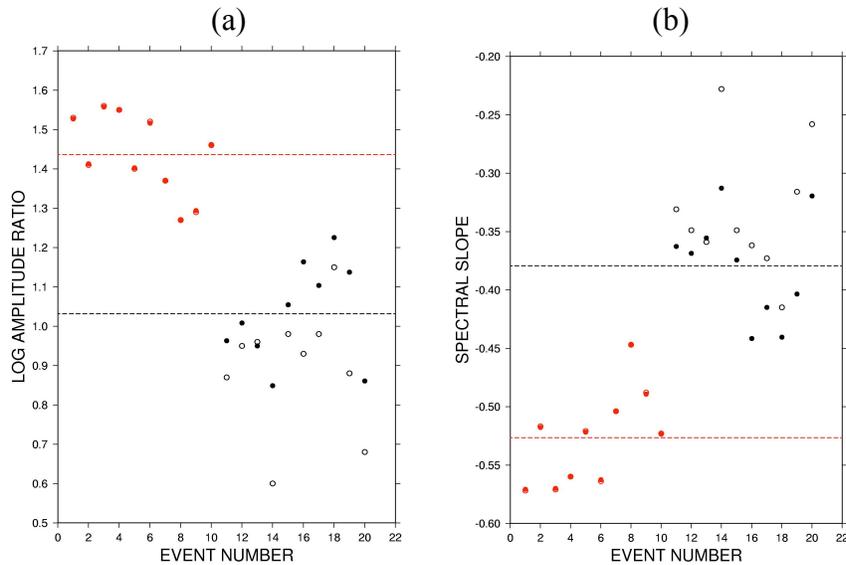


Figure 5. (a) Mean spectral ratio $Lg(0.5-2 \text{ Hz})/(3-5 \text{ Hz})$ for 10 KTS explosions (red circles) and 10 earthquakes (black circles) recorded at WMQ. (b) Mean spectral slope of Lg over 0.5-5.0 Hz for the same dataset. In both figures, results without (open symbols) and with distance correction (filled symbols) are shown; the latter show the earthquake and explosion populations to be well separated by (a) 0.41 log units and (b) 0.15 log units. Differences in both (a) Lg spectral ratios and (b) Lg spectral slopes appear to be useful for source discrimination.

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The mean spectral slopes over the frequency range of 0.5 to 7.0 Hz for all events are shown in Figure 4b, which shows results for both without and with distance correction. The explosion and earthquake populations are well separated (about 0.19 log units). Considering that results in Figures 4a and 4b are from only one recording station, it seems that the observed differences in the Lg spectral ratios and spectral slopes may serve as powerful regional discriminants based on the use of only the Lg phase.

By using the same dataset of 10 KTS explosions and ten earthquakes recorded at WMQ as used earlier, we obtained Lg spectra of 25.6 sec long windows by following the same procedure as for the United States data. Similar to the NTS shots, all ten explosions are at nearly the same distance (within 948 to 963 km). However, the epicentral distances for earthquakes vary from 476 to 975 km. Results for Lg(0.5-2 Hz)/(3-5 Hz), both without and with distance correction, are shown in Figure 5a, after normalizing all data to the mean distance of the ten explosions (about 956 km). The explosion and earthquake populations, with their mean values differing by 0.41 log units, are fairly well separated. The mean spectral slopes over the frequency range of 0.5 to 5.0 Hz for all events are shown in Figure 5b, which also shows results for both without and with distance correction. The explosion and earthquake populations are well separated (about 0.15 log units). Considering that results in Figures 5a and 5b are also from only one recording station, it seems that the observed differences in the Lg spectral ratios and spectral slopes may serve as powerful regional discriminants, similar to the findings for the U.S. data. It is also interesting to note that, although the available Russian and Chinese earthquakes are at significantly different locations as compared to the KTS explosions (unlike the U.S. events), the Lg spectral ratios and spectral slopes are still as effective regional discriminants as for the U.S. data.

Discrimination Based on Skewness and Kurtosis of Lg Spectra

A recent study by Ortiz et al. (2002) found statistical measures such as skewness and kurtosis to be useful for source discrimination at regional distances. Their approach, based on the use of time-series analysis of various regional phases, provided effective discrimination between nuclear explosions and earthquakes. We modified their procedure to frequency domain measurements and applied it to the spectra of Lg from both types of seismic events recorded at a common station.

Following Ortiz et al. (2002), skewness for signal $S(t)$ may be expressed as

$$W(t) = \frac{\sum_i (t_i - t_0)^3 |S(t_i)|}{\left[\sum_i (t_i - t_0)^2 |S(t_i)| \right]^{3/2}} \quad (2)$$

We used the following similar frequency-domain relationship for skewness

$$W(f) = \frac{\sum_i (f_i - f_0)^3 A_i}{\left[\sum_i (f_i - f_0)^2 A_i \right]^{3/2}} \quad (3)$$

The above relationship provides results that vary with the absolute value of the amplitudes, A_i , which, in this study, are in log units. In order to obtain results that only depend on the shape of the spectra (rather than absolute values), all mean amplitudes within a specified frequency range are scaled by assigning the same fixed value for all events. This required all A_i values (in log units) for a given event to be adjusted by the same normalizing amount, which was of course different for different events.

Lg spectra for 25.6 sec long Lg windows, corrected for noise, were obtained for all 20 U.S. seismic events recorded at MNV. For the frequency range of 0.5-7.0 Hz, skewness was computed by using equation (3). Mean values of A_i for 0.5-7.0 Hz for most events were close to 3 so that a normalizing amount of 3.0 was used for all 20 events. Actually, skewness based on the use of equation (3) yielded negative values for all 20 seismic events and Figure 6a shows the absolute (positive) values. The explosion and earthquake populations are remarkably well separated. However, the

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results for kurtosis showed no significant discrimination between the two types of seismic events. A source-receiver distance correction was applied to the skewness and the results are also included in Figure 6a. Furthermore, we also derived the skewness and kurtosis by using a normalizing amount of 5.0 but the results remained almost the same; indicating that the choice of the normalizing amount is not important. Considering that the skewness results in Figure 6a are from only one recording station, it seems that the observed differences in the skewness of Lg spectra serve as an effective regional discriminant.

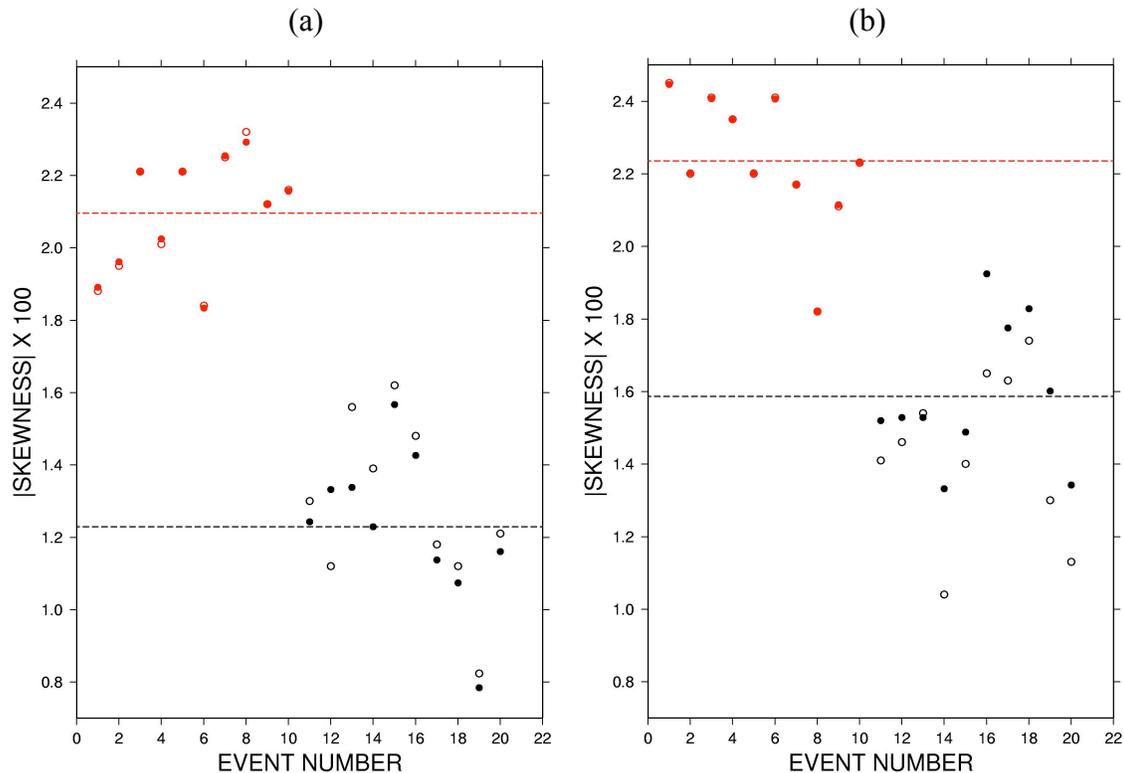


Figure 6. Skewness for (a) 10 NTS explosions (red circles) and 10 nearby earthquakes (black circles) recorded at MNV for the frequency range of 0.5-7.0 Hz and (b) 10 KTS explosions (red circles) and 10 earthquakes (black circles) recorded at WMQ. In both figures, results without (open symbols) and with distance correction (filled symbols) are shown; the latter show the earthquake and explosion populations to be well separated. Differences in skewness appear to provide an effective regional discriminant.

As for the U.S. data, Lg spectra for 25.6 sec long Lg windows, corrected for noise, were also obtained for 10 KTS explosions and 10 nearby earthquakes recorded at WMQ. For most events, mean values of A_i for 0.5-5.0 Hz were close to 3 so that a normalizing amount of 3.0 was used for all 20 events. As for the NTS data, skewness based on the use of equation (3) yielded negative values for all 20 seismic events and Figure 6b shows the absolute (positive) values. The explosion and earthquake populations are well separated. However, the results for kurtosis showed no significant discrimination between the two types of seismic events. A source-receiver distance correction was applied to the skewness and the results are also included in Figure 6b. Considering again that the skewness results in Figure 6b are from only one recording station, it seems that the observed differences in the skewness of Lg spectra serve as an additional regional discriminant, similar to the result for U.S. explosion and earthquake data (Figure 6a).

CONCLUSIONS AND RECOMMENDATIONS

Our analysis of regional data from nuclear explosions from both NTS and KTS and nearby earthquakes suggests the following conclusions: (1) There are several reliable source discrimination methods based on the use of the single seismic phase Lg recorded at regional distances. These should be especially useful for small magnitude seismic events

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for which Lg may be the only well recorded seismic phase. (2) Our preliminary analysis of both NTS and KTS nuclear explosions and nearby earthquakes indicates four possible regional discriminants: (a) normalized standard deviation derived from spectrograms, (b) Lg spectral ratios, (c) Lg spectral slopes, and (d) skewness of Lg spectra. (3) Remarkable similarity of discrimination results from both NTS and KTS nuclear explosions and nearby earthquakes, with entirely different geological settings, indicates that our results should be applicable to other regions of the world. These regional discriminants should be tested and improved by analyzing significantly larger datasets from several regions of the world so that the most effective of these may be incorporated into an automated software system providing identification of small seismic events.

REFERENCES

- Bonner, J. L., 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 25th Seismic Research Review*, 384-393.
- Chael, E. P. (1988). Spectral Discrimination of NTS Explosions and Earthquakes in the Southwestern United States Using High-Frequency Regional Data, *Geophys. Res. Lett.* 15, 625-628.
- 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. Seismol. Soc. Am.*, 82, 352-382.
- Gupta, I. N. and R. A. Wagner (1998). Study of Low and High Frequency Lg from Explosions and its Application to Seismic Monitoring of the CTBT, *AFRL-VS-HA-TR-98-0038*, Air Force Research Laboratory, Hanscom Air Force Base, Massachusetts.
- Gupta, I. N., T. Zhang, and R. Wagner (1997). Low-Frequency Lg from NTS and Kazakh Nuclear Explosions—Observations and Interpretation, *Bull. Seismol. Soc. Am.*, 87, 1115-1125.
- Hartse, H. E., W. S. Phillips, M. C. Fehler, and L. S. House (1995). Single-Station Spectral Discrimination Using Coda Waves, *Bull. Seism. Soc. Am.* 85, 1464-1474.
- Myers, S. C., J. Wagoner, S. Larsen, A. Rodgers, K. Myeda, K. Smith, and W. Walter (2003). Simulation of Regional Explosion S-phases (SIREs) project, *Proceedings 25th Seismic Research Review*, 117-124.
- Myers, S. C., W. Walter, K. Mayeda, and L. Glenn (1999). Observations in Support of Rg Scattering as a Source for Explosion S waves: Regional and Local Recordings of the 1997 Kazakhstan Depth of Burial Experiment, *Bull. Seism. Soc. Am.* 89, 544-549.
- Ortiz, A. M., S. R. Taylor, T. J. Fitzgerald, and T. Wallace (2002). Rediscovering Signal Complexity Discriminants: a Preliminary Study for Application to Regional Seismic and Radio Frequency Signatures, *LA-UR-02-7657*, Los Alamos National Laboratory, Los Alamos, NM.
- Patton, H. J. (2001). Regional Magnitude Scaling, Transportability, and Ms : mb Discrimination at Small Magnitudes, *Pure appl. geophys.*, 158, 1951-2015.
- Patton, H. J., and S. R. Taylor (1995). Analysis of Lg Spectral Ratios from NTS Explosions: Implications for the Source Mechanisms of Spall and the Generation of Lg waves, *Bull. Seismol. Soc. Am.*, 85, 220-236.
- Taylor, S. R., N. W. Sherman, and M. D. Denny (1988). Spectral Discrimination between NTS Explosions and Western United States Earthquakes at Regional Distances, *Bull. Seism. Soc. Am.* 78, 1563-1579.
- Wu, R. S., X. B. Xie, Z. Ge, X. Wu, and T. Lay (2003). Quantifying Source Excitation and Path Effects for High Frequency Regional Waves, *Proceedings 25th Seismic Research Review*, 172-181.