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REGIONAL SEISMIC CHEMICAL AND NUCLEAR EXPLOSION DISCRIMINATION: WESTERN U.S. EXAMPLES

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ABSTRACT

We continue exploring methodologies to improve regional explosion discrimination using the western U.S. as a natural laboratory. The western U.S. has abundant natural seismicity, historic nuclear explosion data, and widespread mine blasts, making it a good testing ground to study the performance of regional explosion discrimination techniques. We have assembled and measured a large set of these events to systematically explore how to best optimize discrimination performance. Nuclear explosions can be discriminated from a background of earthquakes using regional phase (Pn, Pg, Sn, Lg) amplitude measures such as high frequency P/S ratios. The discrimination performance is improved if the amplitudes can be corrected for source size and path length effects. We show good results are achieved using earthquakes alone to calibrate for these effects with the MDAC technique (Walter and Taylor, 2001). We show significant further improvement is then possible by combining multiple MDAC amplitude ratios using an optimized weighting technique such as Linear Discriminant Analysis (LDA). However this requires data or models for both earthquakes and explosions. In many areas of the world regional distance nuclear explosion data is lacking, but mine blast data is available. Mine explosions are often designed to fracture and/or move rock, giving them different frequency and amplitude behavior than contained chemical shots, which seismically look like nuclear tests. Here we explore discrimination performance differences between explosion types, the possible disparity in the optimization parameters that would be chosen if only chemical explosions were available and the corresponding effect of that disparity on nuclear explosion discrimination.

Even after correcting for average path and site effects, regional phase ratios contain a large amount of scatter. This scatter appears to be due to variations in source properties such as depth, focal mechanism, stress drop, in the near source material properties (including emplacement conditions in the case of explosions) and in variations from the average path and site correction. Here we look at several kinds of averaging as a means to try and reduce variance in earthquake and explosion populations and better understand the factors going into a minimum variance level as a function of epicenter (see Anderson *et al.* this volume). We focus on the performance of P/S ratios over the frequency range from 1 to 16 Hz finding some improvements in discrimination as frequency increases. We also explore averaging and optimally combining P/S ratios in multiple frequency bands as a means to reduce variance. Similarly we explore the effects of azimuthally averaging both regional amplitudes and amplitude ratios over multiple stations to reduce variance. Finally we look at optimal performance as a function of magnitude and path length, as these put limits the availability of good high frequency discrimination measures.

OBJECTIVES

Monitoring the world for potential nuclear explosions requires characterizing seismic events and discriminating between natural and man-made seismic events, such as earthquakes and mining activities, and nuclear weapons testing. We continue developing, testing, and refining size-, distance-, and location-based regional seismic amplitude corrections to facilitate the comparison of all events that are recorded at a particular seismic station. These corrections, calibrated for each station, reduce amplitude measurement scatter and improve discrimination performance. We test the methods on well-known (ground truth) datasets in the U.S. and then apply them to the uncalibrated stations in Eurasia, Africa, and other regions of interest to improve underground nuclear test monitoring capability.

RESEARCH ACCOMPLISHED

As part of the overall National Nuclear Security Administration Ground-based Nuclear Explosion Monitoring (GNEM) Research and Engineering program, we continue to pursue a comprehensive research effort to improve our capabilities to seismically characterize and discriminate underground nuclear tests from other natural and man-made sources of seismicity. To reduce the monitoring magnitude threshold, we make use of regional body and surface wave data to calibrate each seismic station. Our goals are to reduce the variance and improve the separation between earthquakes and explosion populations by accounting for the effects of propagation and differential source size, and by optimizing the types and combinations of amplitude measurements used.

Western U.S Data Corrected for Magnitude and Distance Effects

We continue to re-examining the large database of the western United States (U.S.) underground nuclear tests and earthquakes we assembled under a prior year BAA (Walter et al. 2003). This western U.S. nuclear explosion data covers a wide range of depths and material properties and has excellent ground truth information (Springer et al. 2002). This is unlike the situation in most of the world where regional recordings of nuclear tests are scarce and discrimination optimization needs to be done in their absence. In addition we have chemical explosions recorded at the same stations from the Arizona Source Phenomenology Experiment (AZSPE). The AZSPE carried out dedicated single shot chemical explosions under a variety of depth and confinement conditions in two mining regions, a soft rock coal mine and a hard rock copper mine (e.g. Bonner et al. 2005). These mining regions also routinely detonate ripple-fired production blasts that can be observed at regional distances. The availability of both nuclear and chemical explosions lets us examine the differences in optimization and performance of the two source types relative to the earthquakes. The locations of the data and stations discussed in this paper are shown in Figure 1.

Effective earthquake-explosion discrimination has been demonstrated in a broad variety of studies using ratios of regional amplitudes in high-frequency (primarily 1-to 20-Hz) bands (e.g. Walter et al., 1995, Taylor, 1996, Hartse et al. 1997, Rodgers and Walter, 2002, Taylor et al., 2002, Battone et al. 2002 and many others). When similar-sized earthquakes and explosions are nearly co-located, we can understand the observed seismic contrasts, such as the relative P-to-S wave excitation, in terms of depth, material property, focal mechanism and source time function differences. However, it is well known that path propagation effects (e.g. attenuation, blockage) and source scaling effects (e.g. corner frequency scaling with magnitude) can make earthquakes look like explosions and vice versa. We have developed a technique called MDAC (Magnitude and Distance Amplitude Corrections, Walter and Taylor, 2002) that can account for these effects with proper calibration. We use the earthquakes alone to determine the MDAC parameters such as geometrical spreading, frequency dependent Q and the average apparent stress. After calibration the MDAC formulation provides expected spectral amplitudes as a function of phase, magnitude and distance. These can then be subtracted from the actual observations. For earthquakes the corrected data should exhibit a close zero mean, and a magnitude and distance detrended population. Explosions should have significant non-zero mean residuals, leading to improved discrimination.

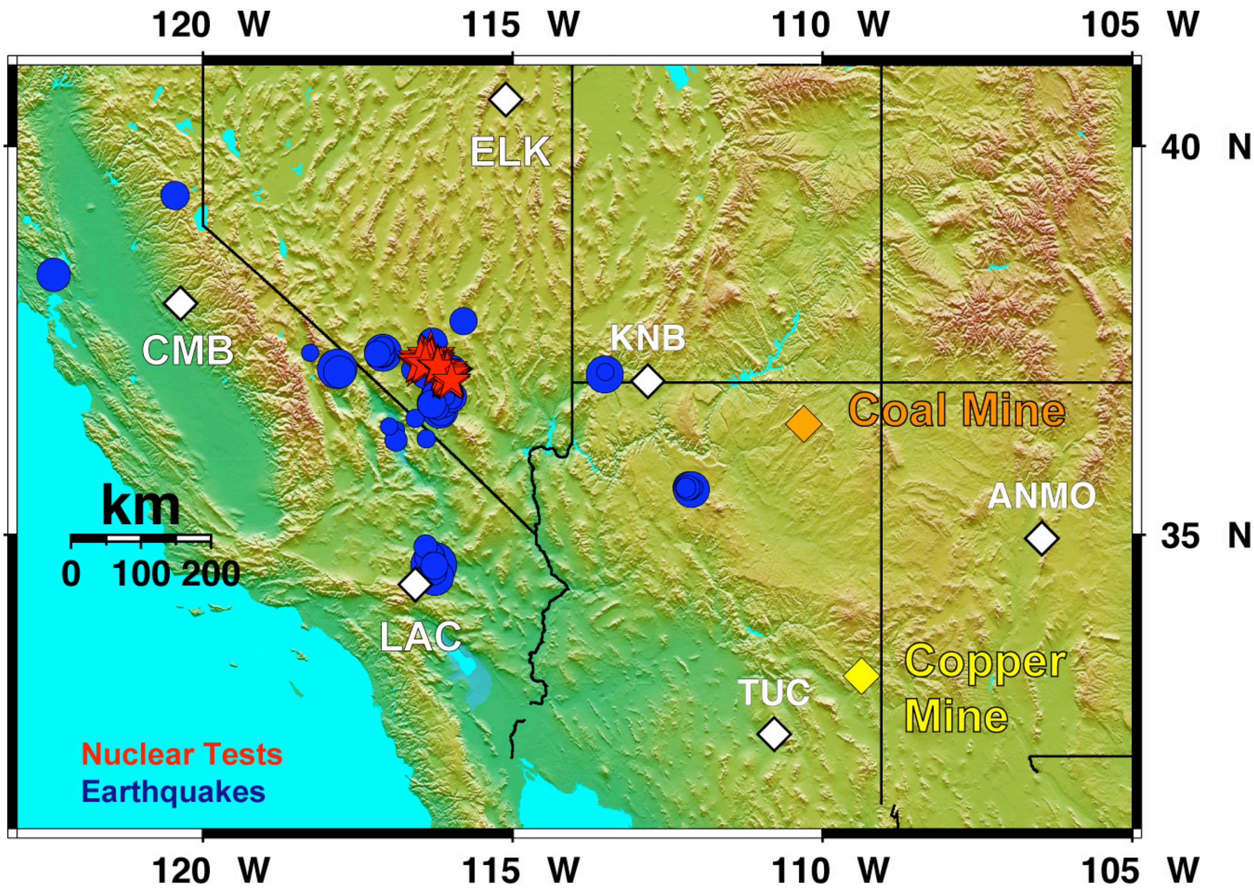

Figure 1. Map showing the location of earthquakes, historic nuclear explosions, mining explosions and stations used in this paper.

After the MDAC correction we can explore optimal combinations of particular regional discriminants (e.g. Taylor 1996). We use the linear discriminant analysis method (LDA) to find the optimal coefficients to combine the measurements. Last year we showed an example of this at KNB of three different regional phase and spectral ratios (Walter et al. 2005). The metric of performance we use is the equiprobable point, which provides a measure of the overlap of the earthquake and explosion populations. It is the point on a receiver operating characteristic (ROC) tradeoff curve where the error rates are equal. For example an equiprobable point of 0.1 implies that 10% of the earthquakes are misclassified as explosions and 10% of explosions are misclassified as earthquakes. In practice one might chose a decision line with unequal error rates, such as by picking a low probability of misclassifying an explosion. The equiprobable point provides a single numerical measure of performance that is much more intuitive than other measures such as Mahalanobis distance, though it can be related to that measure.

Chemical versus Nuclear Explosion Discrimination

Routine industrial mining explosions play two important roles in seismic nuclear monitoring research: (1) they are a source of background events that need to be discriminated from potential nuclear explosions; (2) as some of the only explosions occurring in the current de facto global moratoria on nuclear testing, their signals should be exploited to improve the calibration of seismic monitoring systems. A common issue arising in both of these roles is our limited physical understanding of the causes behind observed differences and similarities in the seismic signals produced by routine industrial mining blasts and small underground nuclear tests. The AZSPE provides an opportunity to compare chemical and nuclear explosion regional amplitudes at common stations to better understand their similarities and differences.

The two different types of chemical explosions (single contained shots versus ripple fired production blasts) show some interesting similarities and differences to the nuclear explosions. They all have similar high frequency P/S ratios, as the 6-8 Hz Pg/Lg example in Figure 2 shows. However in looking at regional seismic coda derived spectra (e.g. Mayeda and Walter, 1996, Mayeda et al. 2003) in Figure 2 we find the production shots have steeper spectral decay between 1-8 Hz and this accounts for the differences we see in the low to high frequency ratios. For this reason it is clear that optimizing discrimination performance (such as finding LDA coefficients) using industrial explosions may not be optimal when low to high frequency spectral or cross spectral ratios are involved. This is an area of research we are actively exploring.

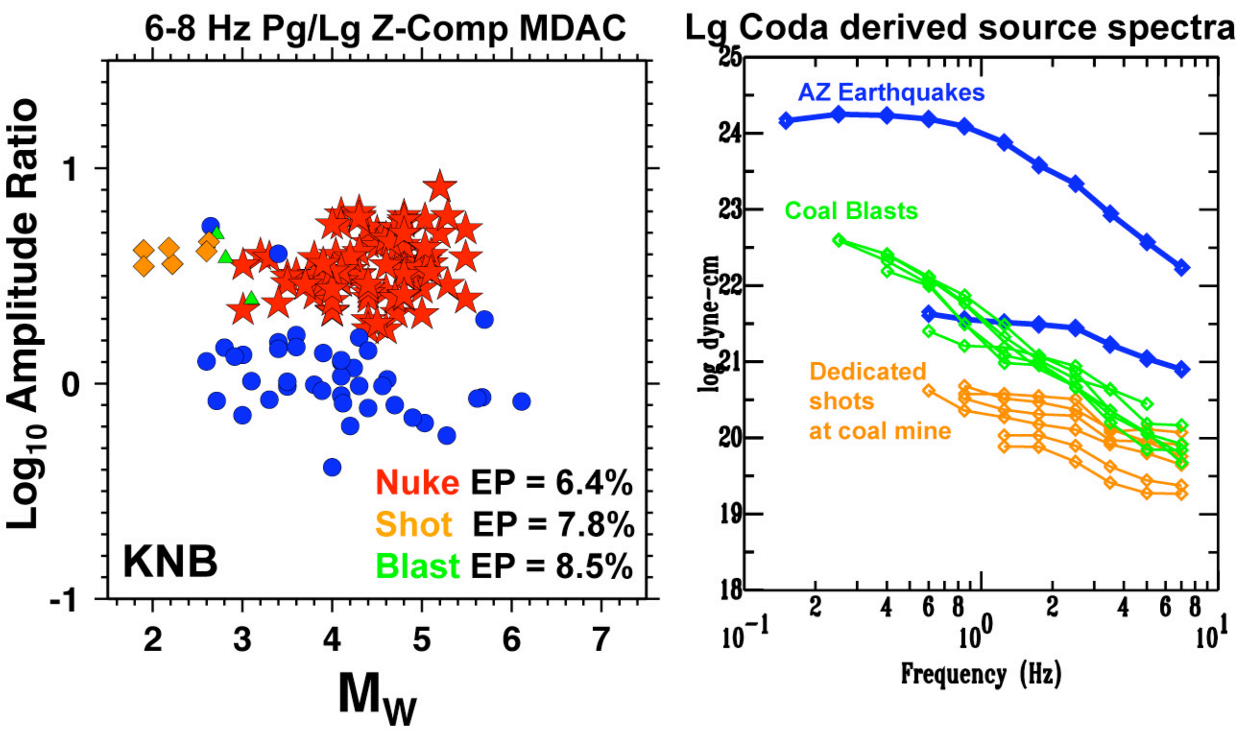

Figure 2. Here we compare the behavior of various explosion types against earthquakes (blue circles and lines) at station KNB. On the left hand side we show explosion discrimination from earthquakes for the 6-8 Hz Pg/Lg ratio after MDAC corrections were applied. The equiprobable measure of discrimination of each explosion type relative to earthquakes is given and they are quite similar for this ratio. On the right hand side we show regional coda envelope derived S-wave spectra of earthquakes (blue) and dedicated single shot chemical explosions (orange) and normal mine production blasts (green). The coda calibrations were done using the Colorado Plateau earthquakes shown. Note that most of the ripple-fired shots have much steeper spectral falloff than the single shots.

<u>P/S Discrimination versus Frequency</u>

Many previous studies of regional nuclear explosion discrimination using P/S ratios have noted that discrimination improves as the frequency increases, with the largest improvement often occurring as frequencies get above about 4 Hz (e.g. Dysart and Pulli, 1987, Baumgardt and Young, 1990, Walter et al., 1995, Taylor et al 1996; Hartse et al. 1997, and many others). Few of these studies looked at frequencies above 10 Hz. Some studies utilizing chemical explosions have looked at discrimination at frequencies above 10 Hz (e.g.

Kim et al 1993, Kim et al 1997) finding good separation at all frequencies above about 5 Hz. However for the western U.S. nuclear data we have previously limited our analysis to 10 Hz and less (Walter et al. 1995, Taylor et al 1996) due both to quality control issues at the higher frequencies and an eye towards the limited number of stations at that time with sample rates greater than 20 sps. As the number of stations with sample rates of 40 sps continues to increase it is worth revisiting the behavior of the P/S ratio discriminants with frequency for the western U.S. nuclear explosion dataset.

Great care must be taken when using historical data to look at high frequency discrimination. Because most of the nuclear testing occurred prior to the deployment of 24 bit recorders, much high frequency amplitude data is corrupted. For example while the LLNL Nevada Network (LNN) stations sampled at 40 sps since digital telemetry was started in 1979, they utilized 12-bit gain ranging prior to September 1987 (Jarpe, 1989). This works fine for data up to 8-10 Hz in most cases but above that frequency the data shows signs of signal generated noise that we suspect is related to the gain ranging. In September 1987 the LNN recorders were upgraded to 16 bit and S-13 seismometers installed with a concerted effort to record good high frequency data. For this reason we have focused our analysis only on the LNN nuclear explosion data from September 1987 to the end of testing in 1992. In the summer of 1992 the instruments were upgraded to 24 bit recorders and Guralp boradband 3T seismometers giving very high quality data. We make use of earthquakes from 1987 through 2005. Finally there still remain problems with glitches, clipping and dropouts. Each seismogram was carefully reviewed by a seismologist, problem data were identified and not used. We are still analyzing data and here show results only for station ELK. The results for Pn/Lg in 8 frequency bands from 0.5 up to 16 Hz are given in Figure 3 and similar results for Pg/Lg are given in Figure 4. We used a signal to pre-event noise threshold of 2.0 for the P-wave phases and 1.3 for the S-wave phases. Note that there is a general improvement in discrimination as the frequency increases as measured by the equiprobable point. However the number of events at the lowest and highest frequency bands drops off due to poor signal to noise.

In order to make a fairer comparison of the effect of frequency on P/S discrimination we restricted the data to those events where all 8 frequency bands were available. In general this raises the threshold to about magnitude 4 and greater. These results are shown in Figure 5 and indicate that the big improvement in both P/S ratios occurs at 4 Hz and higher. In fact the frequency bands between 4 and 10 Hz seem to occupy an effective niche for discrimination without big drop off in the number of events that can be measured. At frequencies above 10 Hz we see two complications start to become significant. First the number of events starts to decease substantially due to signal to noise issues. This is a problem in tectonic regions like the western U.S. with relatively strong regional phase attenuation. Use of frequencies above 10 Hz at ELK will tend to be limited to closer and/or larger events, such as within 300 km or greater than magnitude 4. The second issue is that the Pg/Lg discrimination starts to worsen. Looking at Figure 4 we can see this is primarily due to just two earthquakes. These two events occur in California, one is the Hector Mine mainshock and the other occurs near Lake Tahoe. We believe these events are showing us the limits of the 1-D power law distance correction above 10 Hz, as they are not outliers at lower frequencies. These are the only events above 10 Hz, passing our SNR tests that not within 100 km of the test site. We suspect that using a 2-D attenuation correction could probably reduce the variance (e.g. Mayeda et al. 2005), and expect that P/S has the potential to be a little better discriminant at high frequencies when events are nearly co-located. However in practice getting good 2-D attenuation maps at high frequencies may not be easy unless the region is well instrument and seismically active.

For these reasons frequencies of 4-10 Hz, including the commonly used 6-8 Hz seem to make good practical discriminants. We should note that LDA analysis shows us that there is useful discrimination information even in mediocre discriminants and the best performance comes from combining multiple discriminant ratios. We are currently exploring techniques that average P/S ratios over multiple frequency bands, as averaging multiple bands appears to reduce variance and improve discrimination. Finally we should note that the Pg/Lg discriminant seems to work better than Pn/Lg at most frequencies, particularly the lower frequencies, and the reasons for this need further investigation, but may have to do with amplitude averaging over the source.

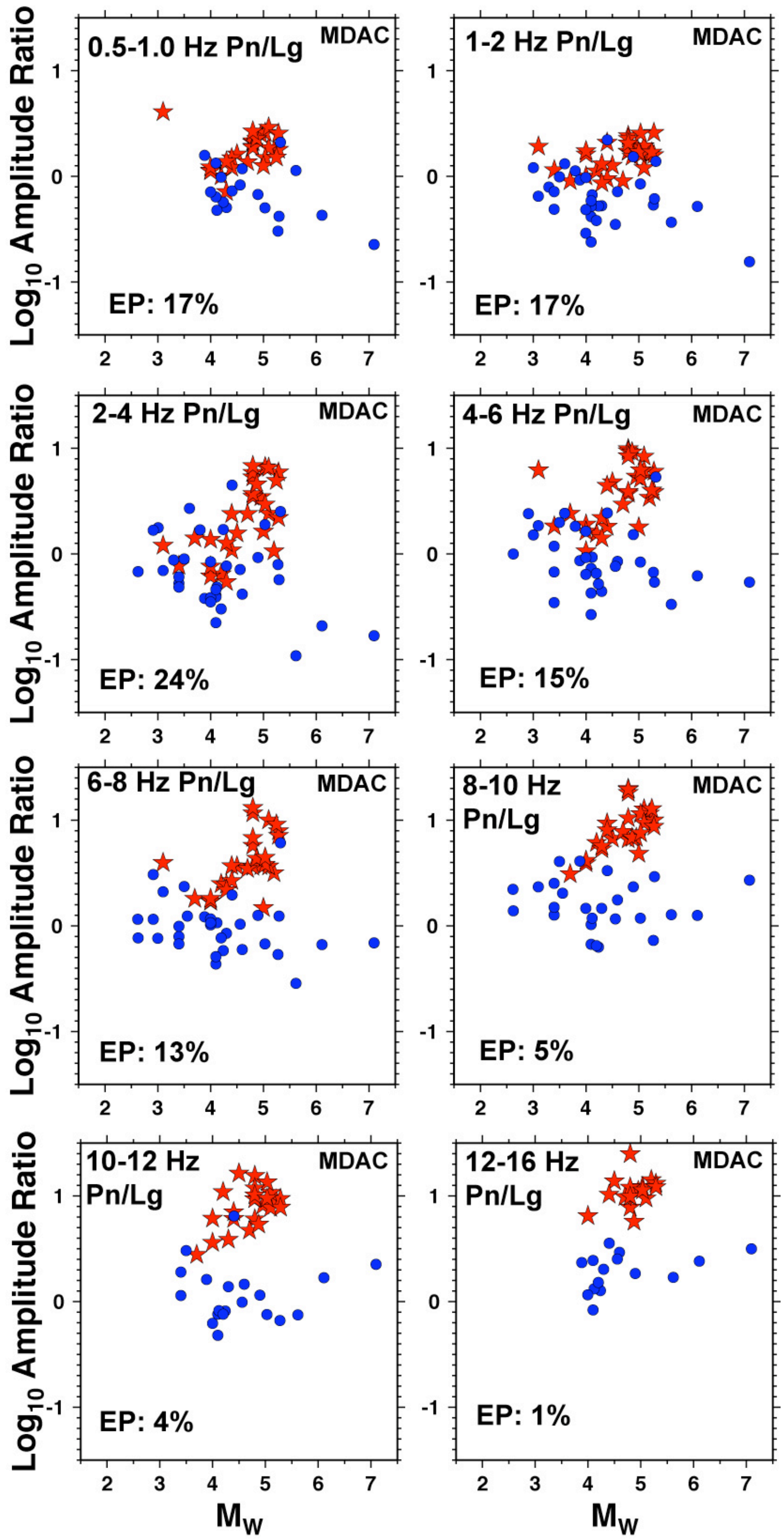

Figure 3. Earthquake (blue circles) and explosion (red stars) discrimination at station ELK for Pn/Lg in eight different frequency bands from 0.5 to 16 Hz. Note the general improvement as frequency increases as measured quantitatively by the equiprobable value, although the number of events decreases.

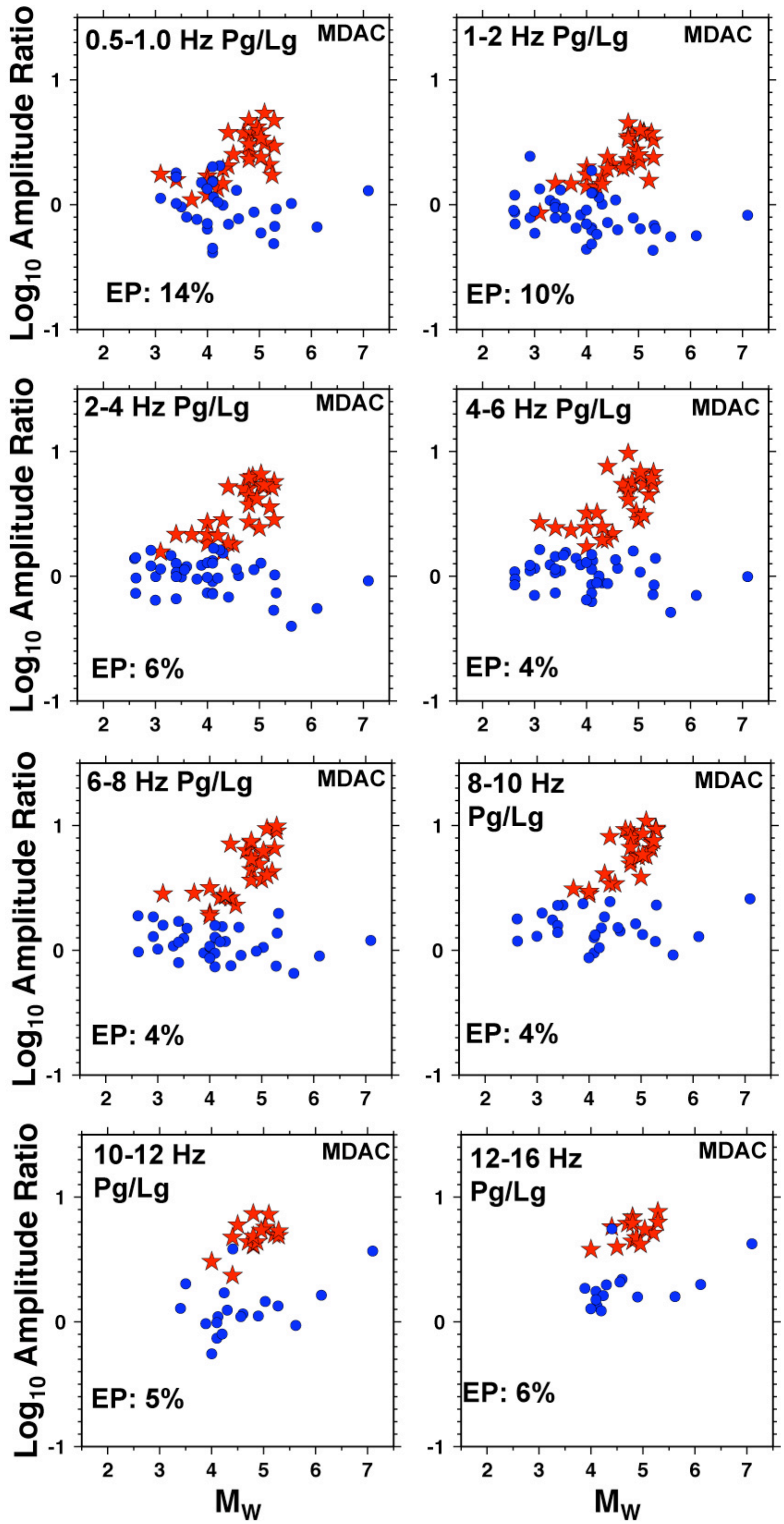

Figure 4. Same as Figure 3 except for Pg/Lg at ELK.

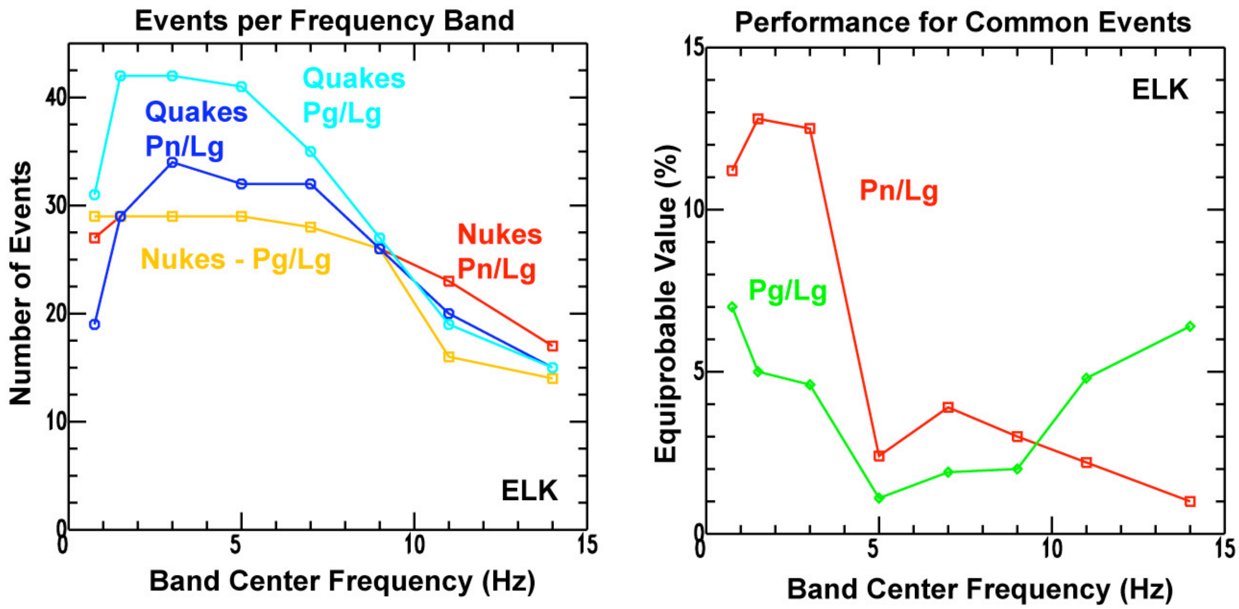

Figure 5. Left-hand side shows the number of events passing the SNR criteria for each ratio at each frequency band. The right-hand side shows the ELK P/S discrimination performance as measured by the equiprobable value for each ratio as a function of frequency using only events where all frequency measures are available.

__Averaging Stations__

It has been observed that events that appear problematic to discriminate at one station may not be a problem at other stations in the same region. We have previously argued qualitatively (e.g. Walter et al. 1995) that averaging over stations improves discrimination performance. We are currently working to quantify this effect. We show a simple two-station example in Figure 6 using just the data from 1987 and later. We are currently testing all 4 LNN stations and other long standing western U.S. stations to better understand the value of multiple station averaging for regional discrimination.

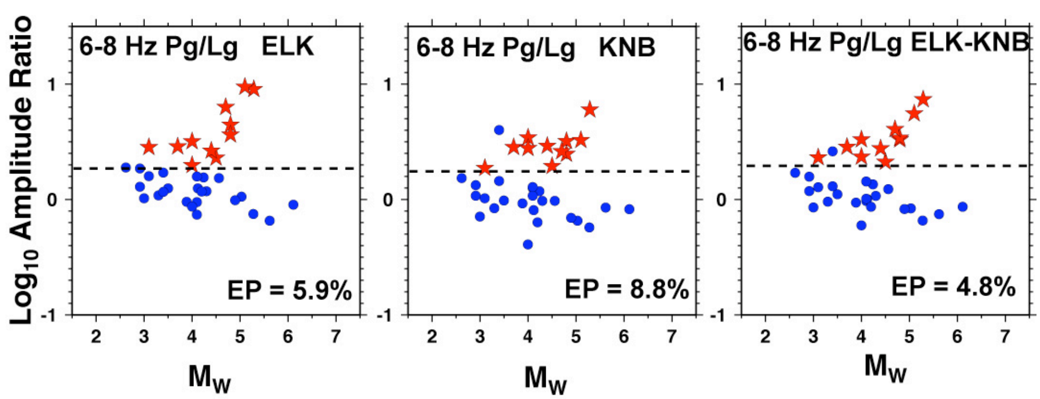

Figure 6. Comparison of 6-8 Hz Pg/Lg discrimination performance at station ELK and KNB for the same events. ELK has better performance than KNB. An earthquake outlier at KNB is not an outlier at ELK indicating that averaging should help reduce variance. A hypothetical decision line has been drawn just below the lowest explosion value in each case. Note that the average of the two stations performs better than either alone as measured by equiprobable value.

CONCLUSIONS AND RECOMMENDATIONS

Regional discrimination algorithms require calibration at each seismic station to be used for nuclear explosion monitoring. We apply a Magnitude and Distance Amplitude Correction procedure to remove source size and path effects from regional body-wave phases. This allows the comparison of any new regional events recorded at a calibrated station with all available reference data and models. This also facilitates the combination of individual measures at multiple stations to form multivariate discriminants that can significantly improve performance over single station individual measures. We are working to quantify the performance of P/S ratio discriminants as a function of frequency and number of stations. We are using the AZSPE data to explore the use of industrial chemical explosions to help calibrate regional discriminants in areas where nuclear explosion data is not available.

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