IDENTIFICATION IN WESTERN EURASIA: REGIONAL BODY-WAVE CORRECTIONS AND SURFACE-WAVE TOMOGRAPHY MODELS TO IMPROVE DISCRIMINATION

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ABSTRACT

Our identification research is focused on the problem of correctly discriminating small magnitude explosions from a background of earthquakes, mining tremors, and other events. Small magnitude monitoring leads to an emphasis on regional waveforms. The goal is to reduce the variance within the population of each type of event, while increasing the separation between the explosions and the other event types. We address this problem for both broad categories of seismic waves, body waves, and surface waves. First, we map out the effects of propagation and source size in advance so that they can be accounted for and removed from observed events. This can dramatically reduce the population variance. Second, we try to optimize the measurement process to improve the separation between population types.

For body waves we focus on the identification power of the short-period regional phases Pn, Pg, Sn and Lg, and coda that can often be detected down to very small magnitudes. It is now well established that particular ratios of these phases, such as 6- to 8-Hz Pn/Lg, can effectively discriminate between closely located explosions and earthquakes. To extend this discrimination power over broad areas, we developed a revised Magnitude and Distance Amplitude Correction (MDAC2) procedure (Walter and Taylor, 2002). This joint source and path model fits the observed spectra and removes magnitude and distance trends from the data. The MDAC2 procedure makes use of the extremely stable coda estimates of Mw for source magnitude and can also use independent Q tomography to help reduce trade-offs in fitting spectra. We can then apply the Kriging operation (e.g. Schultz *et al*., 1998) to the MDAC2 residuals to provide full 2-D path corrections by phase and frequency band. These corrections allow the exploration of all possible ratios and multivariate combinations of ratios for their discrimination power. We also make use of the MDAC2 spectra and the noise spectra to determine the expected signal-to-noise value of each phase and use that to optimize the multivariate discriminants as a function of location. We quantify the discrimination power using the misidentified event trade-off curves and an equiprobable measure. In addition to the traditional phases, we are also exploring the application of coda amplitudes in discrimination. Coda-derived spectra can be peaked due to Rg-to-coda scattering, which can indicate an unusually shallow source.

For surface waves we continue to make improvements in our regional group velocity tomography models of Western Eurasia and North Africa. The tomography models provide high-resolution maps of group velocity from 10- to 100-s period. The maps also provide estimates of the expected phase spectra of new events that can be used in phase-match filters to compress the expected signals and improve the signal-to-noise ratio on surface wave magnitude (Ms) estimates. Phase match filters in combination with regional Ms formulas can significantly lower the threshold at which Ms can be measured, extending the M_s:m_b discriminant. We have measured Ms in western Eurasia for thousands of events at tens of stations, with and without phase match filtering, and found a marked improvement in discrimination. Here we start to quantify the improvement to both discrimination performance and the Ms threshold reduction.

OBJECTIVE

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. Here, we briefly review three of these efforts: 1) MDAC2 - a revised spectral normalization technique to improve regional body-wave discrimination, 2) regional coda envelope based spectral peaking as an indicator of shallow depth events and 3) Improved M_s:m_b discrimination using high-resolution surface wave tomography.

MDAC2

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; Rodgers and Walter, 2002; Taylor *et al*., 2002; and many others). When similarly 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. For example, in Figure 1, we compare pairs of earthquakes and explosions of similar size and location and recorded at a common station. The traces have been high-frequency band passed at 6-8 Hz and show the characteristic discrimination difference, where in each case the explosion has larger P wave amplitudes relative to the S waves when compared to the earthquake.

The availability of such reference events, particularly nuclear tests, to compare to a new event in question is highly non-uniform and limited. Therefore, in real monitoring cases, we are often interested in comparing events that are not co-located, not recorded at the same station and may have quite different sizes. In order to make sure any observed differences between a new event in question and the reference events (or models) are not due to differences in path or magnitude, we must correct for these effects. For the past several years, we have been working with our colleagues at Los Alamos National Laboratory on the best ways to model and remove magnitude and distance trends from regional amplitudes. The original MDAC (Magnitude and Distance Amplitude Correction) procedure involved estimating and removing a simple theoretical earthquake spectrum from the data to remove any magnitude and distance trends in the regional phase amplitudes and any discriminants formed from those amplitudes (Taylor *et al*., 2002). We have just completed a refined and improved version of the procedure (MDAC2) by generalizing the source model, taking advantage of independent moment estimates and reducing some of the free parameters (Walter and Taylor, 2002).

The source spectrum depends upon the seismic moment and stress drop and can have additional complications due to non-constant stress drop scaling and differential P/S corner frequency effects. We require the different phases for the same event recorded at the same station to have the same moment and apparent stress (or stress drop) values and other source parameters, such as corner frequencies to be related to each other. This requirement effectively imposes some of the ratio constraints discussed in Rodgers and Walter (2002) on the amplitudes and improves discrimination performance. While such models of source spectra are certainly oversimplified, they have proven track records of providing good first-order fits to real earthquakes. In addition they also provide simple theoretical models to use in aseismic areas.

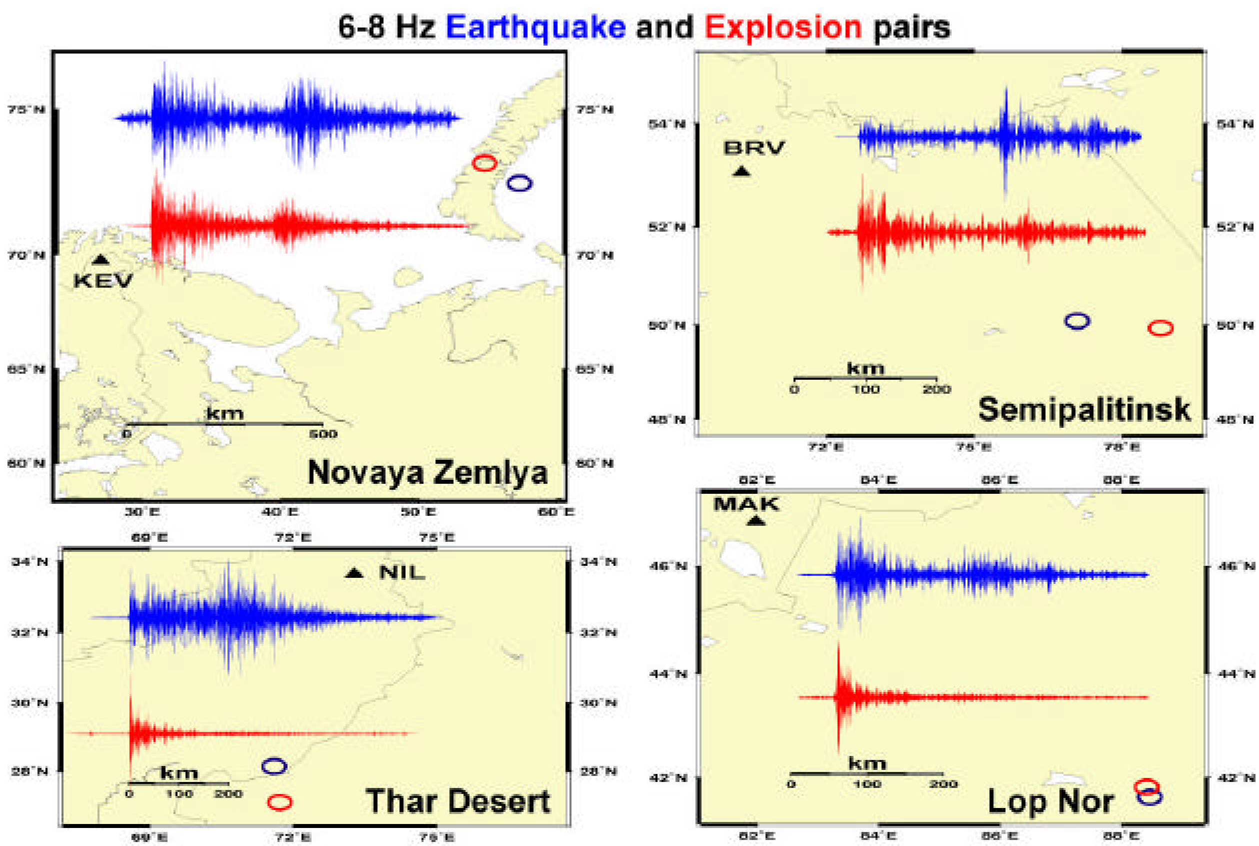

Figure 1. 6- to 8-Hz bandpass seismograms of earthquakes (blue) and explosions (red) show relative P to S wave amplitude differences that allow discrimination between the two source types.

The details of the MDAC2 formulation are given in Walter and Taylor (2002). The predicted spectrum is a convolution of the revised source terms and the previously used geometrical spreading, site, and apparent attenuation terms. We can write the log of the MDAC2 predicted spectrum as (Walter and Taylor, 2001):

$$\log P(f,R) = \log(S_o) - \log\left(1+\left(\frac{w}{w_c}\right)^2\right) + \log G(R) + Site(f) - \frac{pR}{Q_o c} f^{(1-g)} \log(e) \qquad (1)$$

for a regional phase with velocity c. Here S_o is the source low-frequency spectral level and w_c is the source corner frequency. These terms are set by the input moment (we use the stable coda measures, see Mayeda *et al*, this volume), the apparent stress scaling and material property terms. Apparent stress, geometrical spreading (*G(R)*), site effect, and attenuation (Q_o, g) terms are typically solved for using a grid search technique that simultaneously minimizes the spectral fit residual and residual magnitude and distance trends. In this way, *a priori* information such as previous studies on geometrical spreading or Q-tomography results can be easily incorporated.

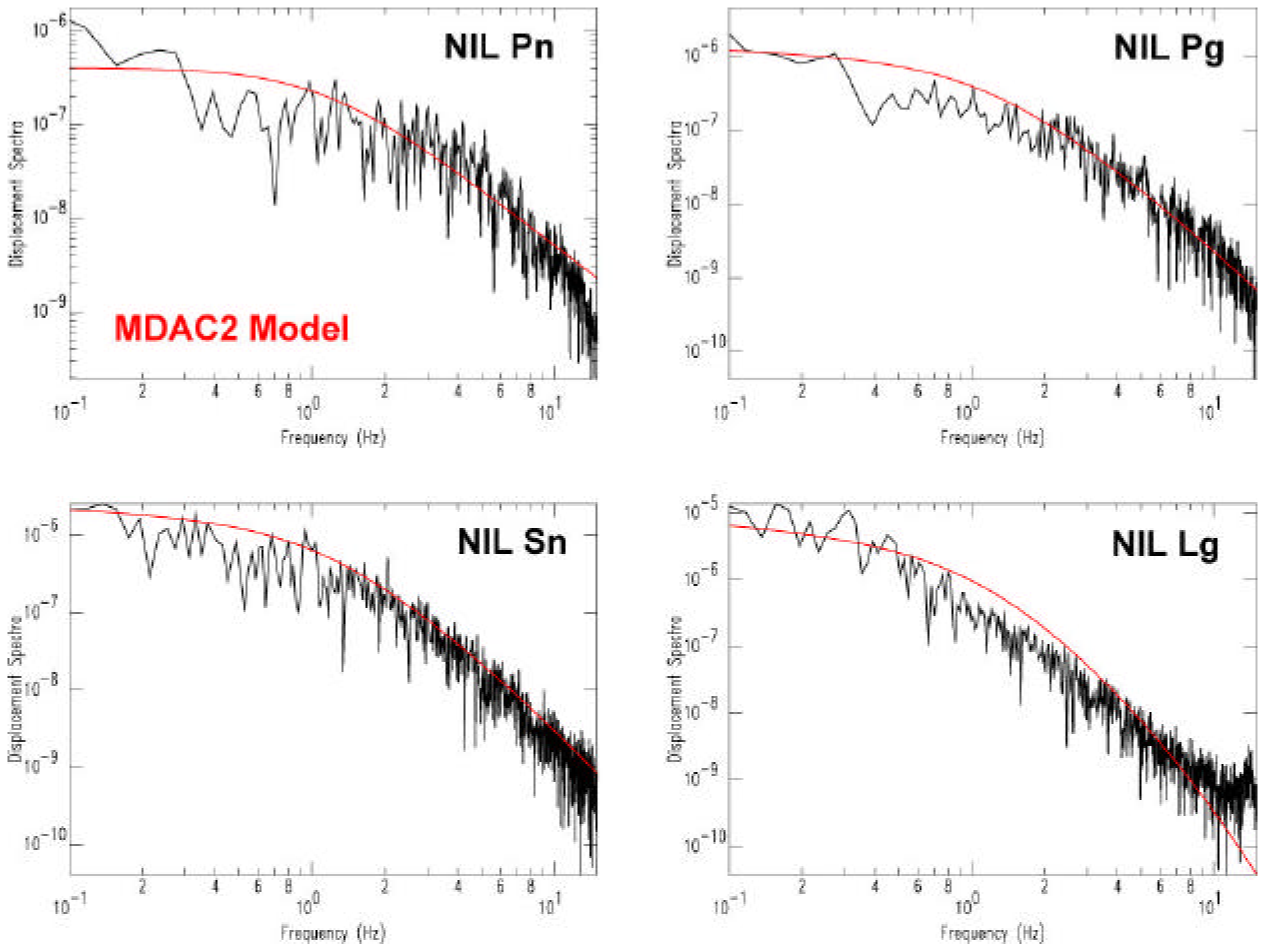

Figure 2. Comparison of observed (black) and MDAC2 model (red) spectra for a regional earthquake recorded at NIL.

In Figure 2 we show a comparison of the observed regional phase spectra (Pn, Pg, Sn and Lg) for a regional earthquake recorded at station NIL with the model spectra. Overall, the match is reasonable, though the Lg attenuation and site terms could use further refinement. By subtracting these model spectra, we essentially normalize the observations for effects of source, 1-D path, and site. However, 3-D path effects remain in the residuals. We can further reduce the MDAC2 residual amplitude variance by using the Bayesian kriging method of Schultz *et al* (1998) on the results. For each phase and frequency band we create kriged residual surfaces. These surfaces can then be used to create any discriminant measurement of choice. For example we can make phase, spectral and cross-spectral ratio measurements between any phase and frequency combination. In practice it is found that the best discriminant performance comes from combining several different ratio measurements (e.g. Taylor, 1996).

We test these ideas on a dataset of regional events with magnitude greater than 3.5 recorded at NIL (e.g., Rodgers and Walter, 2002). In Figure 3, we show the raw measurements, MDAC2 corrected measurements, and the kriged MDAC2 residual measurements as a function of the equiprobable measure. The equiprobable point provides a measure of the overlap of the earthquake and explosion populations. It is the point on a receiver-operator tradeoff curve of the error rates where the error rates are equal. For example an equiprobable measure 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 choose 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. We plot this against the number of optimal combinations of measurements, using the LDA (Linear Discriminant

Analysis) rule. For example the best single measurement, the best combination of two measurements and so forth. From this plot we can see at a glance that MDAC2, kriging, and multivariate combinations of measures each contribute to a significant improvement over the best single raw measure, and the overall result is an order of magnitude improvement in discrimination capability.

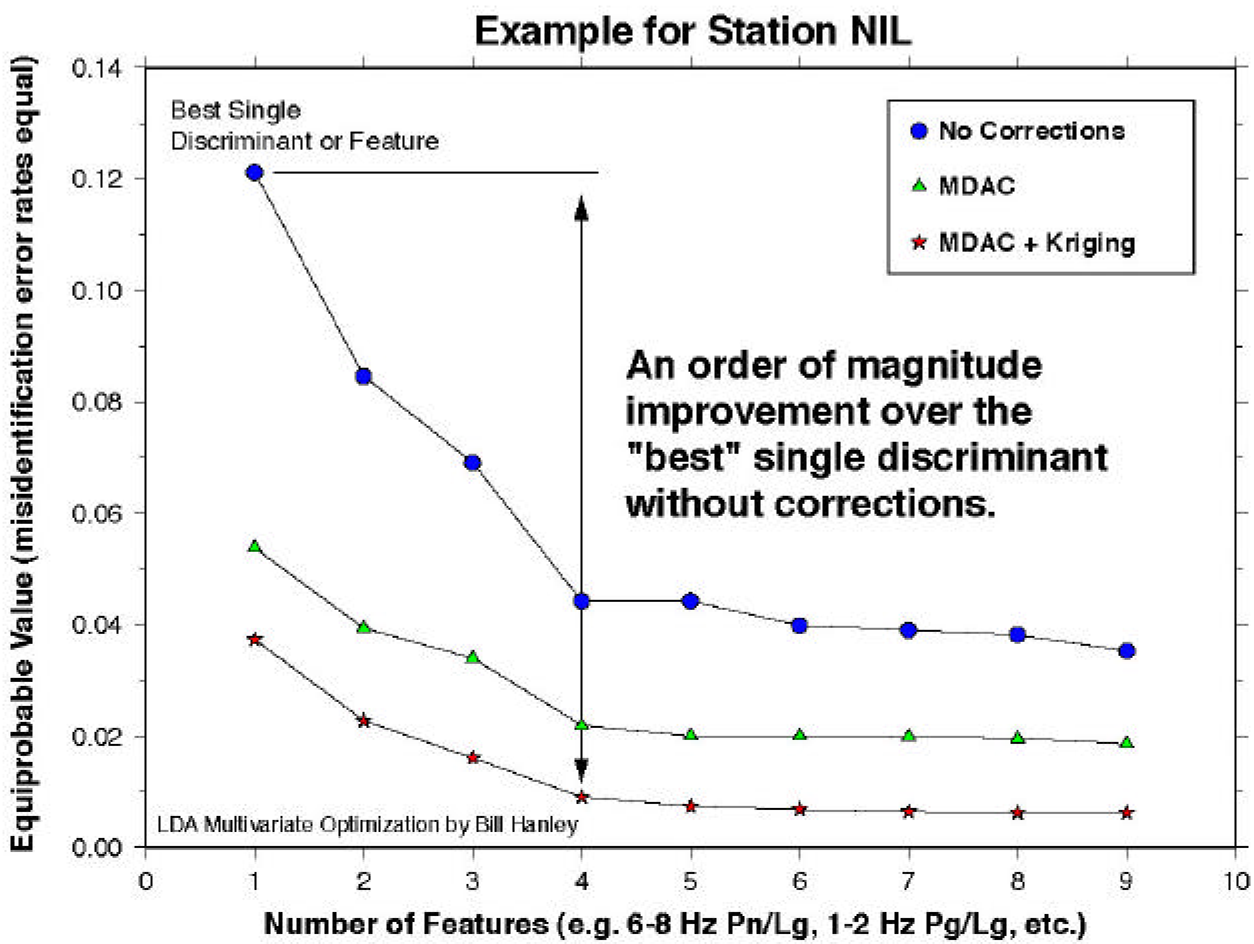

Figure 3. Plot of raw, MDAC corrected and kriged MDAC residual equiprobable values versus the number of feature measurements that go into an LDA discriminant. Feature measures are individual ratios such as 6- to 8-Hz Pn/Lg or 6- 8-Hz Pg / 1- to 2-Hz Sn (after Rodgers, Hanley, Sicherman and Walter, paper in preparation).

Coda Spectral Peaking as a Depth Indicator

In previous work we found that regional coda envelopes could be used to estimate source spectra and seismic moments from earthquakes down to very small sizes (Mayeda and Walter, 1996). These regional coda-derived spectra also show unusual peaking for very shallow events that we attribute to Rg-to-S coda scattering (Myers *et al*., 1999). We are continuing to explore this idea as a better way to identify very shallow events than by direct Rg identification. The Rg phase usually scatters and attenuates to the point at which it can no longer be identified within a few hundred kilometers of the source or less. However, its imprint remains on the coda spectra at much greater distances, and, by examining the size and frequency of the coda-based spectral peak, we hope to be able to use it as an indicator of very shallow events such as explosions. As an example we show in Figure 4 the coda spectra of the May 11, 1998, Indian nuclear test compared with a number of nearby earthquakes. Note the strong spectral peak in the explosion spectra at about 1.5 Hz when compared with the earthquakes. We are also testing various ways to use this property and a depth discriminant. The left hand side of Figure 4 shows one such measure, moment versus m_b, both derived from the coda spectra, which appears to separate the explosion from the earthquakes.

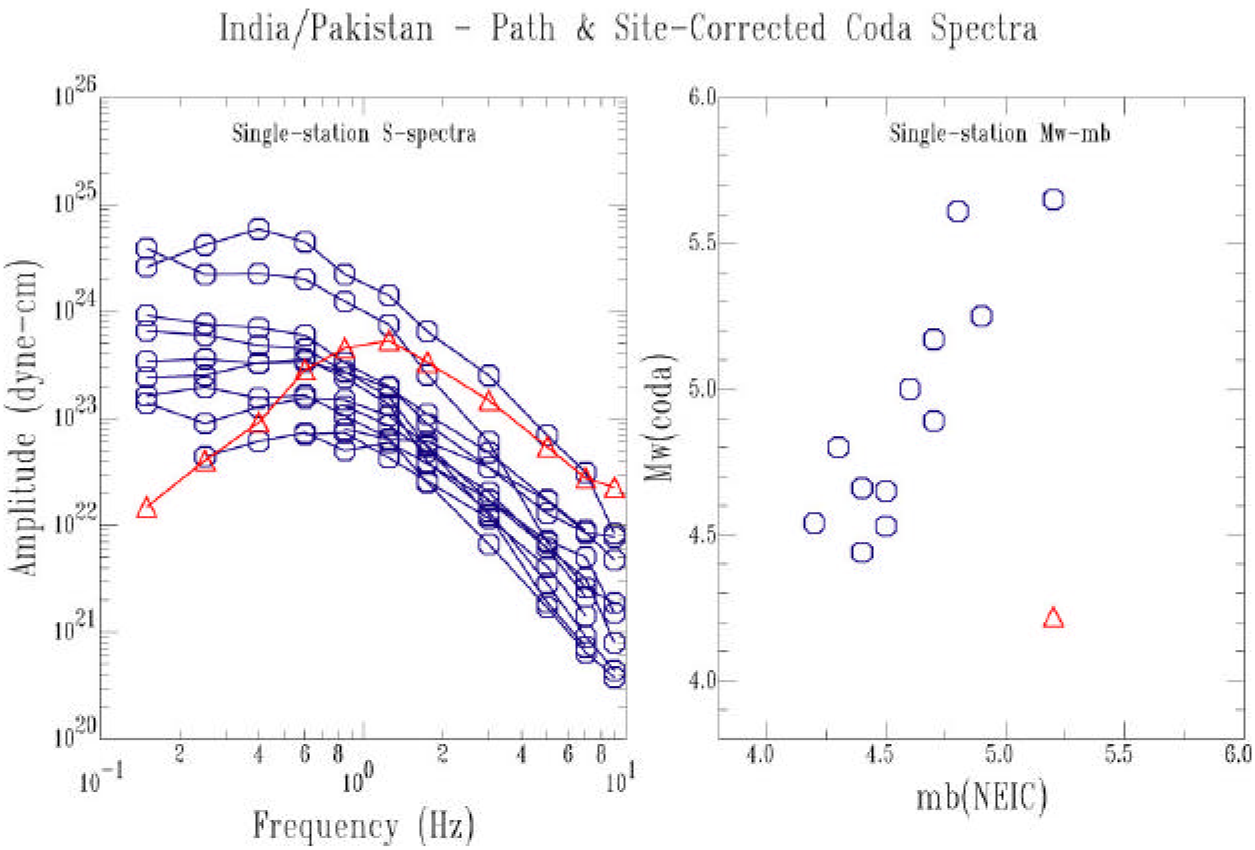

Figure 4. Regional coda envelope based spectra of regional events recorded at station NIL. The Indian test of May 11, 1998, is shown in red triangles. The right hand side shows discrimination on a moment-magnitude plot.

Phase-Matched M_s-m_b

The teleseismic magnitude ratio M_S:m_b is one of the best understood and most effective discriminants known (e.g. Stevens and Day, 1985). Several studies have also shown that it appears to be effective down to as small magnitudes as can be measured regionally (e.g., Denny *et al*., 1987). The problem is that the 20-s surface wave amplitude on which M_S is based can be below the noise even at regional distances. We are researching several ways to allow M_S measurements on smaller magnitude events to be made and used to improve discrimination. One way is to allow regional M_S measurements at periods between 10 and 20 s where the regional Airy phase produces the largest amplitudes (e.g., Denny *et al*., 1987). Additionally we can improve signal-to-noise by making use of phase-match filters (e.g. Herrin and Goforth, 1977). This is particularly attractive because in addition to reducing the noise level in the signal, it can provide an accurate maximum Ms estimate even on a very noisy trace. For small explosions that have reduced M_S excitation to start with and may not have observable surface waves, this method can still provide some discrimination power relative to earthquakes of the same mb that do have measurable M_S.

For the past several years, we have been carrying out systematic measurements of Rayleigh and Love wave group velocities in Western Eurasia with the goal of creating high-resolution tomography models (Pasyanos *et al*., 2001).

We follow the guidelines for measurements laid out in the 1998 surface wave workshop (Walter and Ritzwoller, 1998) and we have exchanged group velocity curves with groups at the University of Colorado and SAIC/Maxwell. The tomography maps that we have created are thus formed from both our own regional measurements and the broader measurements provided by those two groups. Overall, we have examined more than 20,000 seismograms and made more than 9,900 Rayleigh wave measurements and 5,400 Love wave measurements at periods from 10-100 seconds. These numbers apply to the middle period range and the number of good measurements decreases at the shorter and longer periods. In addition we have incorporated more than 3,000 path measurements from the University of Colorado (Ritzwoller, written communication) and SAIC/Maxwell (Stevens, written communication). We are currently using the surface wave tomography model in conjunction with receiver functions to estimate velocity structure in Western Eurasia (see Ammon *et al*., this volume).

The Rayleigh wave group velocity tomography described above can be used to provide predicted group velocity curves for input to a phase-match filtering routine. We can pre-calculate the expected group velocity at a station for any nearby event using the tomography model. In Figure 5, we show such a surface for station KEV in Norway. In addition we can use the measurements to provide an additional refinement to the model predictions using an intelligent interpolation technique. Here we use the Bayesian kriging technique of Schultz *et al*. (1998) on the measured residuals and add these back to the surface. Pasyanos (2000) previously demonstrated that this model plus a kriging approach provides better estimates of group velocity than either the model or kriging alone. Figure 5 shows an example of a PDE explosion and compares the raw data, a bandpass-filtered signal, and a re-dispersed seismogram from a phase-match filter. Note the improved signal-to noise ratio in the phase-match trace.

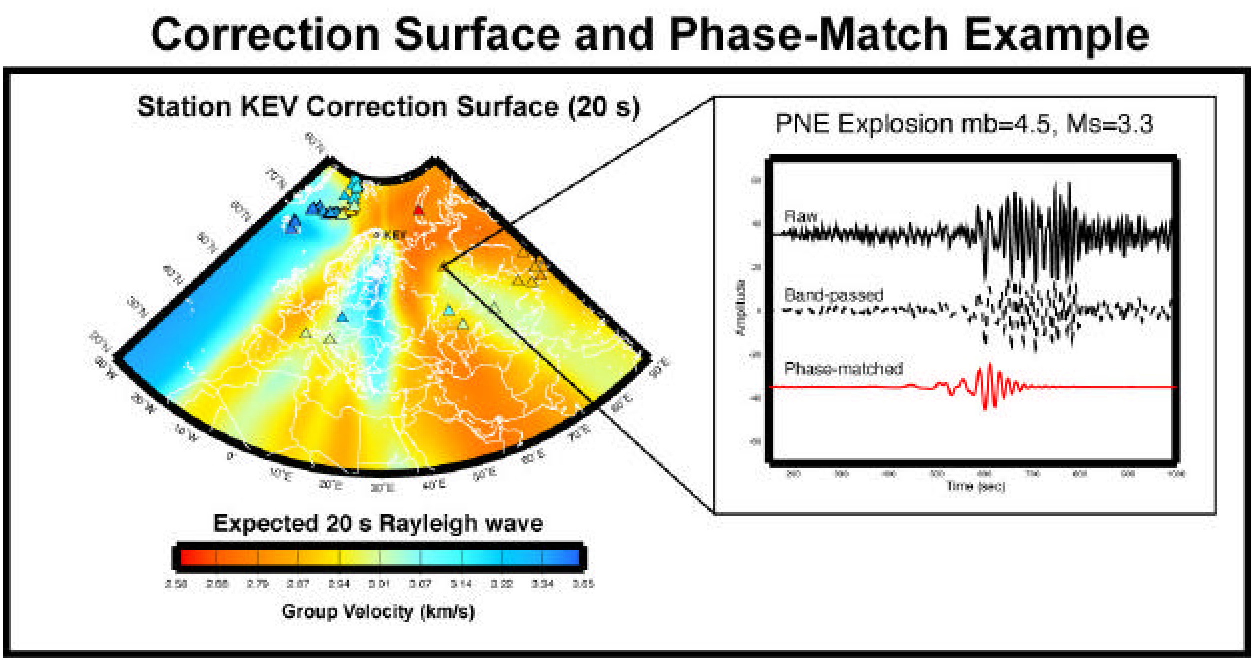

Figure 5. Correction surface for KEV showing predicted 20-s Rayleigh group velocities as a function of event location. The inset compares the results of three different sets of processing on a seismogram from a peaceful nuclear explosion. The phase-match re-dispersed seismogram result comes from using the correction surface.

To test the improvement provided by phase match filtering on M_s:m_b, we performed a test on a large dataset in Western Eurasia. We examine events with m_b from the National Earthquake Information Center larger than 3.5 where at least four stations record the event with a signal to pre-event noise ratio greater than 1.5. In the western Eurasia region covered by the tomography, this resulted in 1600 earthquakes and 11 explosions. Decreasing the number of stations or the signal-to-noise floor would allow more events. For these events we measured Ms using the formula of Rezapour and Pearce (1998). The maximum likelihood M_s was measured both by traditional band pass filtering and after phase matching filtering using the high-resolution tomography model. We tried a variety of tests in which we varied the SNR or number of stations we found that in almost all cases, phase match filtering improves the M_s:m_b discrimination. We show an example in Figure 6 below for the parameters discussed above.

The left hand side shows M_s versus m_b. We then remove the linear trend to form an M_s:m_b measure in the middle plot. From this scatter plot, we determine the receiver operator curve of the types of misidentification error. The phase match based M_s improves the overall discrimination performance by nearly a factor of two. Here we hold the dataset in common, but in further testing, we estimate that the phase match is able to lower the M_s detection measurement threshold by roughly 0.3 magnitude units or a factor of two. Both of these effects, improved discrimination performance and lower Ms measurement thresholds, indicate that using phase-match filtering for the M_s measurement can significantly improve discrimination performance.

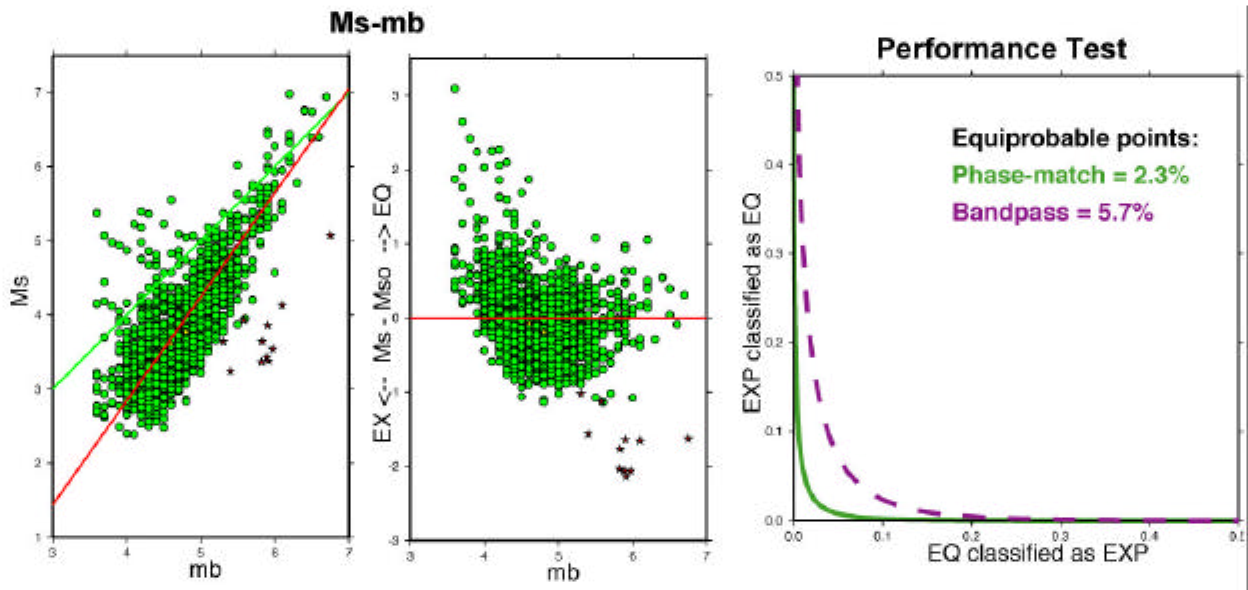

Figure 6. A Western Eurasia dataset test of M_s:m_b on left. Earthquakes are green circles and explosions are red stars. We remove the earthquake data trend from all data in the middle plot to form a magnitude independent measure of discrimination. The right hand plot shows the error rates from the de-trended data and the discrimination improvement provided by phase match filtering versus bandpass filtering.

CONCLUSIONS AND RECOMMENDATIONS

Regional discrimination algorithms require calibration at each seismic station to be used for nuclear explosion monitoring. We have developed a revised 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 to form multivariate discriminants that can have significantly better performance. We have also developed surface wave group velocity maps and correction surfaces for phase-match filtering to improve Ms:m_b discrimination and lower its effective threshold. Calibrating seismic stations to monitor for nuclear testing is a challenging task that will require processing large amounts of data, and collaboration with government, academic and industry researchers and incorporation of the extensive R&D results both within and outside of NNSA.

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