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W.R. Walter
A.J. Rodgers
A. Sicherman
W. Hanley
K. Mayeda
S.C. Myers
M. Pasyanos

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LLNL's REGIONAL SEISMIC DISCRIMINATION RESEARCH

William R. Walter, Arthur J. Rodgers, Alan Sicherman, William Hanley, Kevin Mayeda Stephen C. Myers, and Michael Pasyanos
Geophysics and Global Security Division,
Lawrence Livermore National Laboratory

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ABSTRACT

As part of the Department of Energy's research and development effort to improve the monitoring capability of the planned Comprehensive Nuclear-Test-Ban Treaty international monitoring system, Lawrence Livermore Laboratory (LLNL) is testing and calibrating regional seismic discrimination algorithms in the Middle East, North Africa and Western Former Soviet Union. The calibration process consists of a number of steps: 1) populating the database with independently identified regional events; 2) developing regional boundaries and pre-identifying severe regional phase blockage zones; 3) measuring and calibrating coda based magnitude scales; 4a) measuring regional amplitudes and making magnitude and distance amplitude corrections (MDAC); 4b) applying the DOE modified kriging methodology to MDAC results using the regionalized background model; 5) determining the thresholds of detectability of regional phases as a function of phase type and frequency; 6) evaluating regional phase discriminant performance both singly and in combination; 7) combining steps 1-6 to create a calibrated discrimination surface for each stations; 8) assessing progress and iterating. We have now developed this calibration procedure to the point where it is fairly straightforward to apply earthquake-explosion discrimination in regions with ample empirical data. Several of the steps outlined above are discussed in greater detail in other DOE papers in this volume or in recent publications. Here we emphasize the results of the above process: station correction surfaces and their improvement to discrimination results compared with simpler calibration methods.

Some of the outstanding discrimination research issues involve cases in which there is little or no empirical data. For example in many cases there is no regional nuclear explosion data at IMS stations or nearby surrogates. We have taken two approaches to this problem, first finding and using mining explosion data when available, and second using test-site based models to transport earthquake-explosion discrimination behavior to new regions.

Finally an important component of our research is assessing improvement in the ability to discriminate events. By combining the multivariate discriminants with the threshold detection curves for the regional seismic phases used in those discriminants, we have started to make maps of the probability an event will be identified properly. These maps serve a broad range of purposes from demonstrating progress to funding agencies to prioritizing research and calibration efforts.

Key Words: seismic, discrimination, explosion, Middle East, North Africa, India

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OBJECTIVES

Monitoring of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) requires characterizing seismic events and discriminating between earthquakes, mining activities and banned nuclear tests. LLNL is evaluating and calibrating regional discriminants in the uncalibrated Middle East, North Africa, Southwest Asia, Western Russia and other regions of interest to improve CTBT monitoring capability.

RESEARCH ACCOMPLISHED

As part of the overall Department of Energy CTBT Research and Development program, LLNL is pursuing a comprehensive identification research effort to improve our capabilities to seismically characterize and discriminate banned underground nuclear tests from other natural and man-made sources of seismicity. Over the past several years we have developed, tested, and refined a regional seismic discrimination calibration procedure for seismic regions. Here we will give an overview of the procedure as applied to regional seismic body-wave (Pn, Pg, Sn, Lg, coda) discriminants. Surface-wave discriminant techniques, such as Ms-mb using phase-match filters derived from group velocity tomography results, are described in Pasyanos et al (this volume). The procedure is shown in Figure 1 in flowchart form and described in words in the abstract. We will give a brief description of each part below and summarize the recent progress.

A) Database

The first step in the calibration is to populate a database with independently identified (source ground truth) events to use in calibration and testing. LLNL has created an extensive research database (see Ruppert et al., this volume) of both earthquakes and explosions from public data repositories, catalogs and publications. In addition we have made use of waveform correlation techniques, spatial and temporal clustering and site visits to build up catalogs of ground truth mine blasts (Harris et al., this volume).

B) Regionalization

The Middle East and North African region encompasses the full range of tectonic processes and with a correspondingly heterogeneous lithosphere. This in turn can dramatically affect regional seismic phase propagation producing a large variability in expected amplitudes. In some cases phases such as Lg can be "blocked" (amplitude attenuated to below background noise) due to structural effects. Because relatively small amplitude S-wave phases (Sn or Lg) are potential discriminants it is important to identify when structural rather than source effects reduce their amplitudes in order to avoid false alarms. We developed a new, more quantitative, empirical procedure to better map the efficiency of Lg propagation in the greater Mediterranean region (McNamara and Walter, 1999). The technique plots the maximum observed Lg/Pcoda amplitude in a one by one-degree or smaller cells for several thousand paths in the region. In seismic areas these empirical techniques can be effective, but there are also large aseismic regions (e.g. north Africa, Arabia, India) in our region. To help intelligently extrapolate of empirical calibrations we developed a first-order regionalization for the Middle East and North Africa (Sweeney and Walter, 1998) based on tectonic maps, and a review of published and unpublished literature. There are many ongoing studies to better determine seismic structure in aseismic areas of the Middle East and North Africa both at LLNL (see Rodgers et al., this volume and Hazler et al this volume) and in academia and industry (e.g. Sandvol et al, 1998).

C) Coda Magnitudes

Previous studies have shown the great stability of regional coda magnitudes (Mayeda, 1993; Mayeda and Walter 1996). Regional coda amplitudes show four to eight times less interstation scatter than the amplitudes of direct phases such as Lg and Pn. This means that a single station coda magnitudes can have the same precision as a direct phase magnitude using 16 to 64 station networks. This is particularly useful for characterizing small magnitude events recorded at just a few stations. Coda magnitudes can also be calibrated to give accurate independent seismic moments, which are critical for obtaining accurate source scaling corrections as discussed in the next section. Mayeda et al (this volume) describe how to calibrate regional coda magnitude scales using Middle East stations as examples.

D) Amplitude Corrections

Regional amplitudes are strongly affected by source-size scaling and path propagation effects. Source-size scaling effects include the corner frequency or source dimension effects (e.g. Taylor and Denny, 1991; Walter and Priestley, 1991) and can appear as magnitude dependent discrimination results. Path propagation effects include geometrical spreading and attenuation and can appear as distance dependent discrimination results. Removing these effects allows the comparison of events of different sizes and distances and facilitates combining individual discriminant measures to form more effective multivariate discriminants. For these reasons we are applying a Magnitude and Distance Amplitude Correction (MDAC) technique to the regional measurements (see Taylor et al, this volume; Taylor et al, 1999). The MDAC technique uses a Brune (1970) type source model and simple 1-D path corrections to remove gross magnitude and distance trends from earthquake data at each station. These corrections are then applied to all future measurements at that station.

After applying the MDAC process there remain amplitude variations due to heterogeneous structural effects. In a recently completed study (Rodgers et al, 1999) we used a common data set to compare a variety of techniques to correct for 2-D path effects and found that nonstationary Bayesian kriging (Schultz et al., 1998) gave the best results and has particular advantages in the way it handles uncertainties. These results are demonstrated in Figure 2. Phillips (1999) reached similar conclusions. To correct for heterogeneous structure we krig the MDAC residuals and make use of a priori background models to fill in the larger aseismic regions.

E) Detection

To use a regional discriminant with confidence we need to know whether the regional phase amplitudes can be detected at each station. This is particularly important for discriminants that rely on the relatively low amplitude or absence of a phase to identify explosions. We are currently exploring two-dimensional generalizations of a 1-D detectability functions (e.g. Sereno and Bratt, 1989; Taylor and Hartse, 1996) for each phase as a function of frequency.

F) Discrimination

After determining the frequency bands at which regional phase amplitudes can be measured, and correcting for first-order effects of source size and distance, we can examine the combinations of amplitudes separate explosions from earthquakes. The May 11, 1998 Indian tests provide a good underground nuclear explosion data-point to test our calibration procedure and evaluate discriminants. We have recently completed a regional discrimination study using this Indian test (Rodgers and Walter, 1999). We measured 1-2 Hz Pn/Lg amplitudes for several hundred earthquakes recorded at regional distances at the IRIS station NIL (Nilore, Pakistan). Ratios of Pn/Lg have shown good regional discrimination performance at other nuclear test sites (e.g. Walter et al. 1995; Hartse et al, 1997). The 1-2 Hz Pn/Lg values show great variability as a function of location as shown in Figure 3. After correcting for a first-order distance effect we krig the amplitudes giving the correction surface shown on the left-hand side of Figure 3. On the right-hand side of Figure 3 we compare the effect on the separation of the Indian test from surrounding explosions before and after the distance+kriging correction. Note the scatter of the earthquake population is significantly reduced and the explosion separates form the earthquakes more cleanly. In the Assessment section we will quantify this improvement.

G) Station Surfaces

This step combines all the information in steps A-F to create discrimination surfaces for each station. It is important to note that we have developed each of the calibration steps in such a way as to allow this kind of combination. For example the kriging of empirical data can easily be done on top of a background model for regionalization and/or after applying 1-D MDAC corrections. The kriging algorithm can also incorporate a priori boundaries where parameters such as correlation length change to accommodate structural discontinuities.

H) Assessment

After regional discrimination correction surfaces are created for each station we need to be able to assess progress. For example the right-hand side of Figure 3 shows clear improvement in a scatter plot after the calibration corrections are applied. We want to quantify these results and make them more useful to policy makers and other non-technical people. One standard way to quantify discrimination is using Mahalanobis distance (e.g. Hartse et al, 1997), a measure of separation of the means divided by a sum of the variances, and these numbers are given as D2 on the right-hand side of Figure 3. Bigger Mahalanobis distances are better and we show an improvement of about a factor of three in D2. However these numbers are not intuitively useful by themselves, don't easily allow tradeoffs in error rates and are hard to convey to policy makers and funding agencies. We think a better approach is to use Receiver Operator Curves (ROC). We are currently writing up a report documenting these ideas (Sicherman et al., 1999, written communication).

An example of converting the scatter plots shown in Figure 3 into ROC or tradeoff curves is shown in Figure 4. The probability densities of the two population types are calculated and the "decision line" is swept through all possible values tracing out a tradeoff curve as shown in Figure 4. The tradeoff curves plot the two possible error types in identifying events drawn from populations of two types of events against each other. The error types are mislabeling an explosion and an earthquake (missed event) and mislabeling an earthquake as an explosion (false alarm or reported event). This explicitly allows tradeoff of this error type if political or other costs way one type of mislabeling higher than the other. It also easily allows the creation of multiple categories of labels, for example creating a "needs further investigation" label between "earthquake" and "explosion" labels.

In this example, we have only one explosion, and we've assumed the Indian test is the mean of the explosion population and the variance is the same as the earthquakes. Under the equal variance assumption Mahalanobis distance can be explicitly related to the equiprobable point (EPP) on the ROC, this is the point where the two errors are equal. So in this example the EPP goes from 19.8% to 8.6%. This also quantifies improvement but in a clearly understandable way, the mislabeling for each event type drops from 19.8% to 8.6% after calibration. It is important to note that 1-2 Hz Pn/Lg is just one discriminant measure and that the EPP value can be reduced much further by combining several discriminant measures.

We are currently developing procedures to combine detection maps, discrimination surfaces and ROC results to map error rates as a function of location for each station. This will allow us to better assess areas that are well calibrated and areas that need more work. Similar work has already been done for the location problem (see Schultz et al., this volume).

I) Iterate

It is important to note that discrimination procedures can always be improved. The assessment process lets us evaluate how we are doing for each station and reallocate resource and priorities in a more cost-effective manner. As stations become calibrated we will continually assess how well they do and how improvements can be made by obtaining new data, doing a calibration experiment or through other means.

CONCLUSIONS AND RECOMMENDATIONS

Regional discrimination algorithms require calibration at each seismic station to be used for CTBT monitoring. LLNL is pursuing a comprehensive discrimination effort in the Middle East, North Africa and other regions of interest. In addition we are engaged in ongoing physical basis studies to understand and model discriminants in new regions. Calibrating seismic stations for monitoring the CTBT is a challenging task and 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 DOE.

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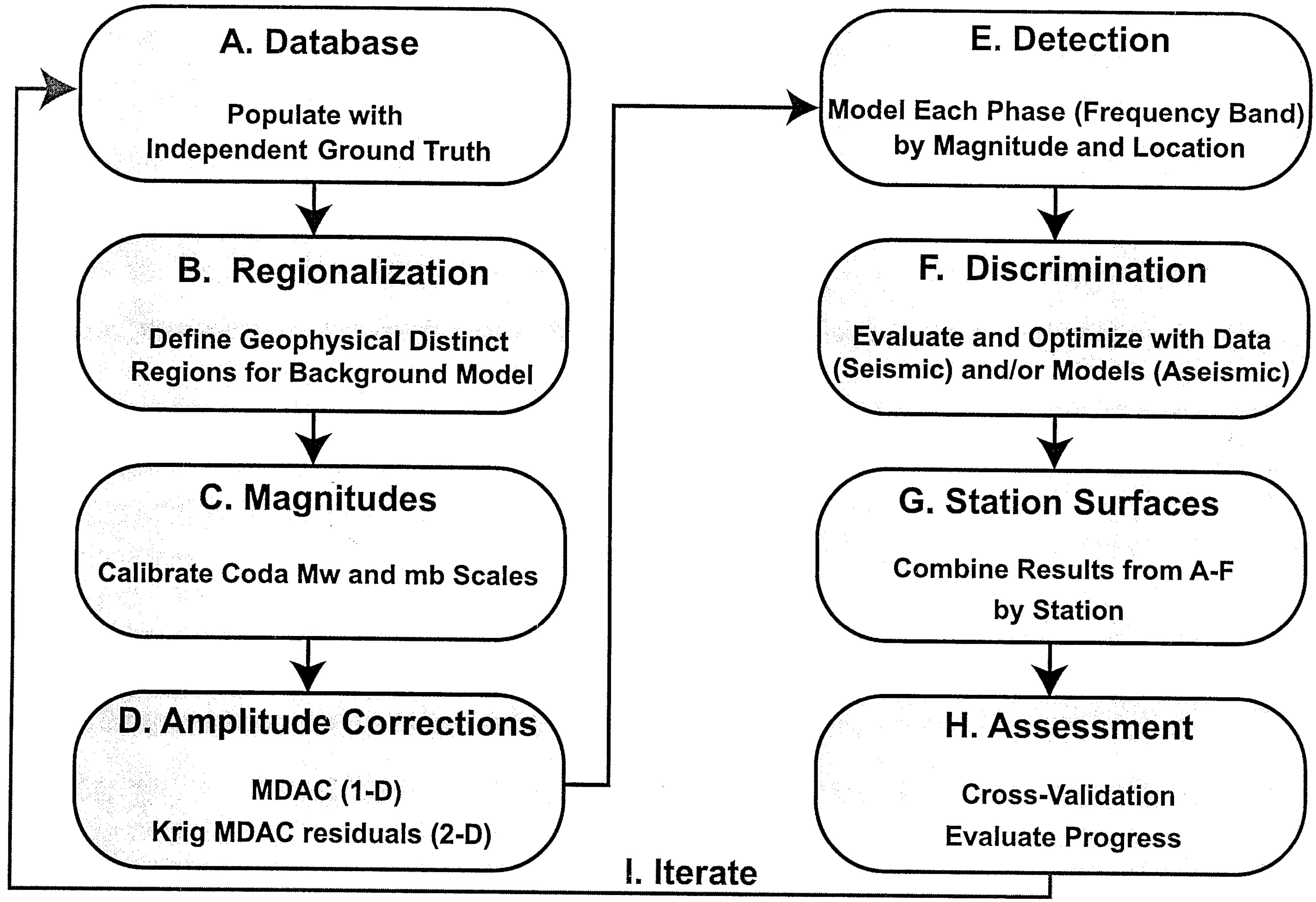

Fig. 1. Flowchart showing regional seismic discrimination calibration procedure as dicussed in the text.

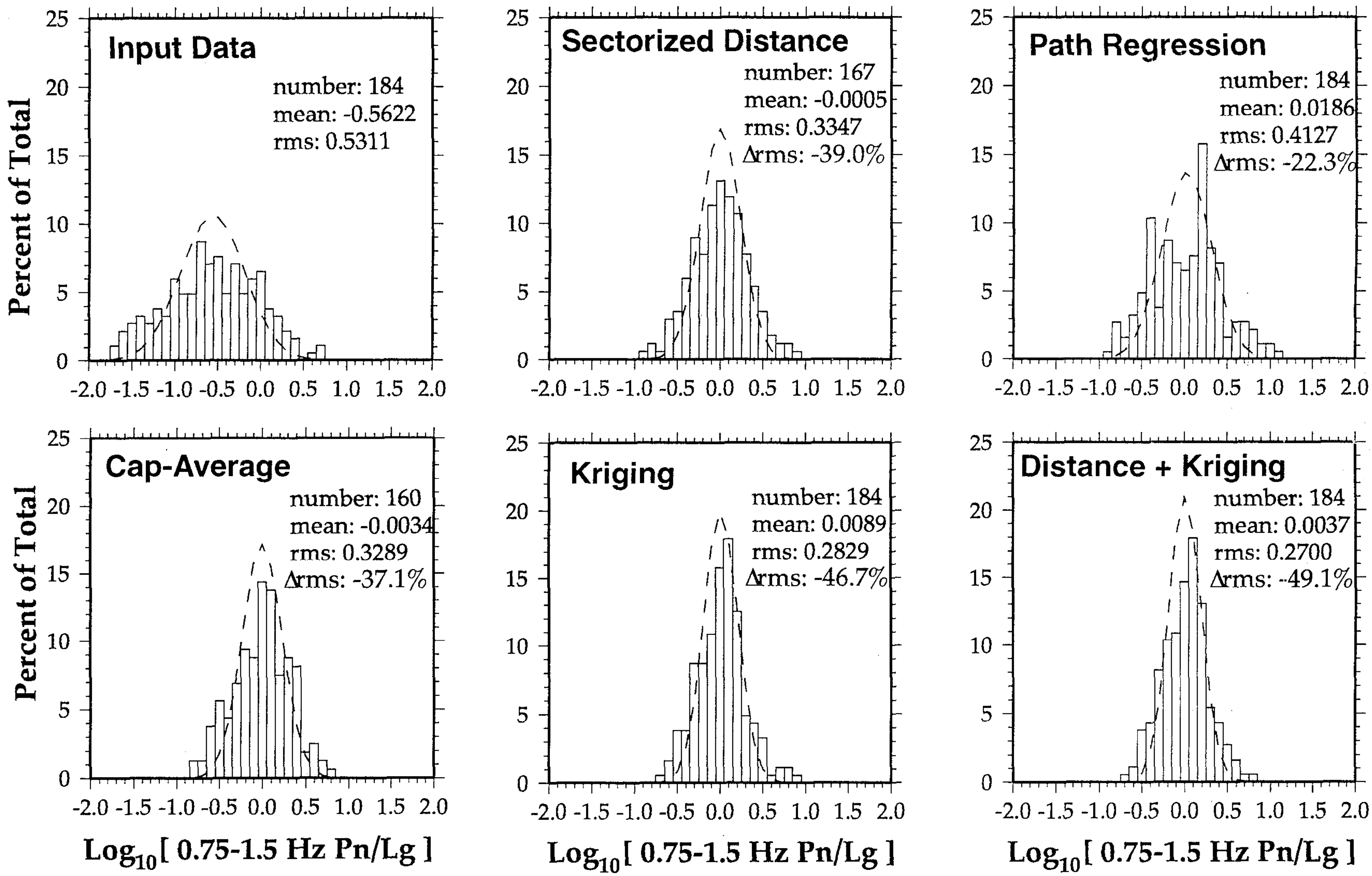

Fig. 2. Comparison of path correction techniques applied to the 0.75-1.5 Hz Pn/Lg regional seismic discrimination measure at the IRIS station ABKT (site of IMS primary stations GEYT). Upper left shows the uncorrected earthquake population; upper model shows the reduction in scatter after several 1-D distance corrections sectorized by azimuth were applied; upper right shows scatter after path-specific corrections from the best regression against crustal parameters such as topography and sediment thickness were applied; lower left shows the effect of applying a circular area smoothing process, lower middle shows the application of the DOE kriging algorithm, and lower right shows the best reduction after kriging is applied to a simple distance corrected data. Note that kriging alone give the best results and that any additional corrections desired (e.g. distance) can be applied prior to kriging. In addition kriging gives accurate estimates of the error of any point on the surface, (after Rodgers et al., 1999).

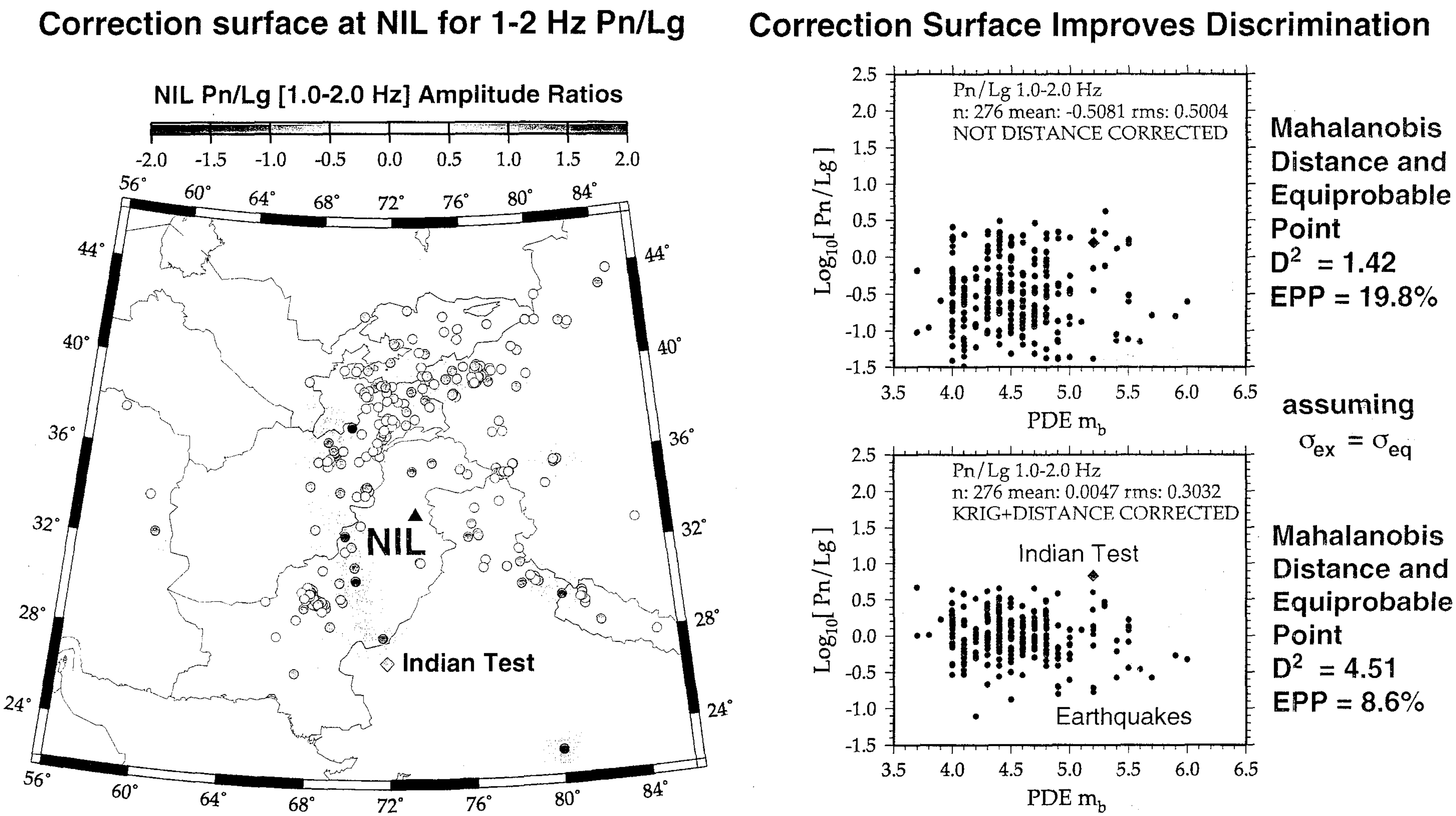

Fig. 3. The left-hand side shows an example of a kriged correction surface for a particular regional seismic discrimination measure (after correcting for a 1-D distance effect) at the IRIS station NIL, site of the IMS primary station PRPK. The right hand side shows the improvement in separating the May 11, 1998 Indian underground nuclear test from the earthquake population after the distance+kriging correction is applied (after Rodgers and Walter, 1999).

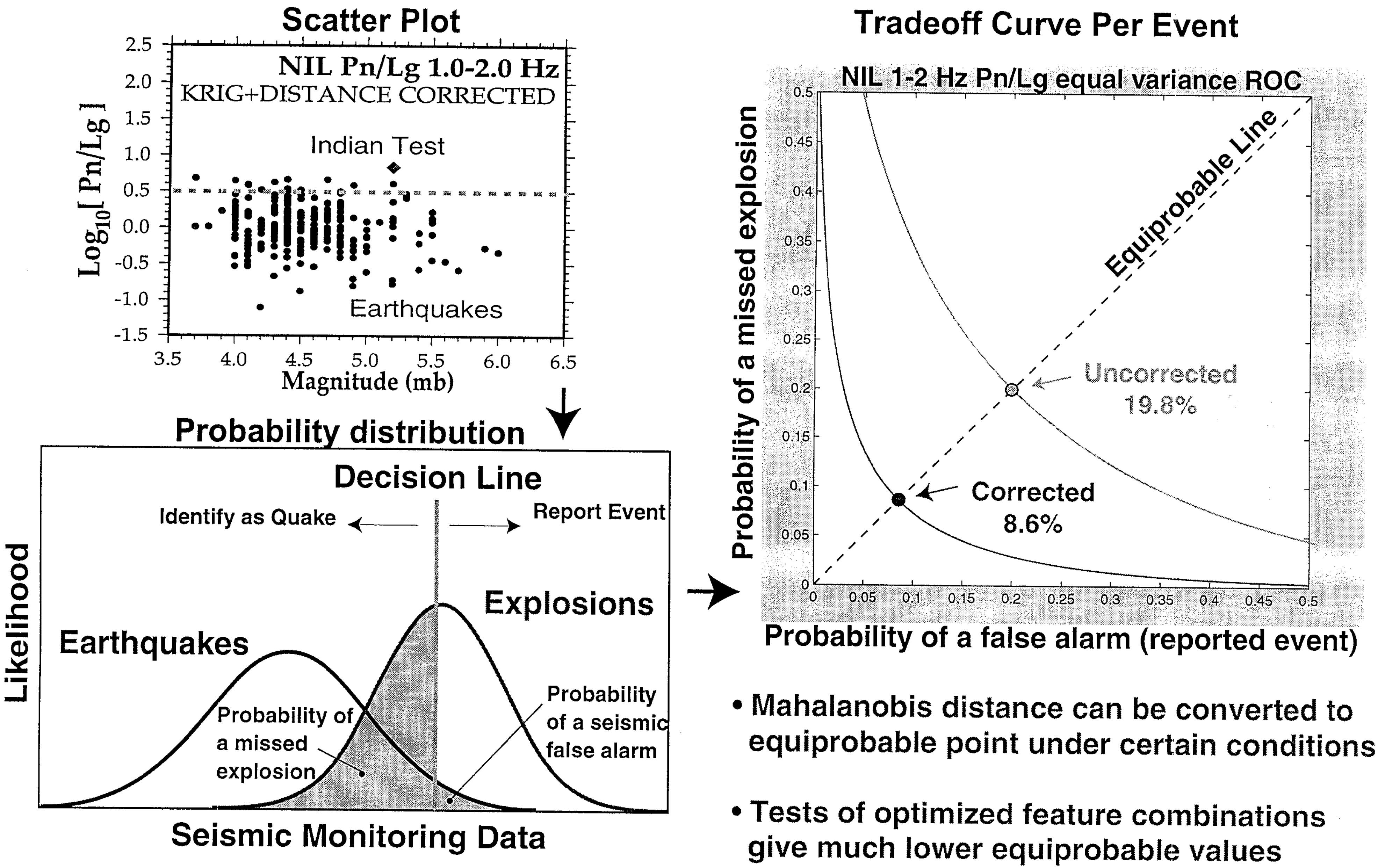

Fig. 4. Example showing how discrimination scatter plots can be converted to Receiver-Operator Curves (ROC) which explicitly show the tradeoff between misidentifying an explosion as an earthquake (missed explosion) and reporting an earthquake as suspicious (false alarm). The relative costs of these two error types depend on political and other non-technical factors. ROC curves allow these factors to be incorporated and give a more general and complete assessment of discrimination potential.