# SOURCES OF ERROR: REGIONAL AMPLITUDE AND TELESEISMIC MAGNITUDE DISCRIMINANTS

Dale N. Anderson

Los Alamos National Laboratory

Sponsored by the National Nuclear Security Administration

Award No. DE-AC52-06NA25396/LA09-ECM-NDD02

**ABSTRACT**

For both regional amplitude and teleseismic magnitude discriminants there are physical effects that diminish identification accuracy and cannot easily be determined and applied as corrections (e.g., focal mechanism and local material properties). We develop a mathematical model to capture these effects as random, giving an error partition of three sources: correction model inadequacy, station noise, and amplitude correlation. This mathematical model is the basis for a new standard error for multi-station discriminants that includes the variances of model inadequacy and station noise, along with amplitude correlation in its formulation. The developed methods are demonstrated for a collection of Nevada Test Site (NTS) events observed at regional stations and teleseismic data acquired from the International Seismological Centre (ISC).

## OBJECTIVES

Source type identification (discrimination) in seismology is unique in that it focuses on the construction of seismic identification features from seismic waveforms and other multi-technology measurements. Most, if not all, statistical classification research begins with the assumption "suppose we have classification features in hand." In contrast, in seismic identification research, significant effort is directed toward the intelligent construction of the identification features, and how to couple to the features most of the associated and relevant sources of error.

Seismic identification features are dynamically adaptable to the number of stations observing an event, the configuration (e.g., geometry) of the observing stations, and the strength of signal at each station. Conceptually, the features are scientifically and statistically constructed to be evidence quality before they are ever combined with a statistical classification method. This paper presents an enhanced construction of the teleseismic $m_b$ versus $M_s$ discriminant and in particular the standard error. Coupled with researched sources-of-error models for a discriminant, a general strategy for the construction of diverse multi-technology discriminants has been developed in Anderson et al. (2007) and Anderson et al. (2009). The revised $m_b$ versus $M_s$ discriminant is illustrated with seismic event data acquired from the ISC and the AWE Blacknest Seismological Centre (BSC), see Figure 1 and description in the following section. These data are available upon request from the author.

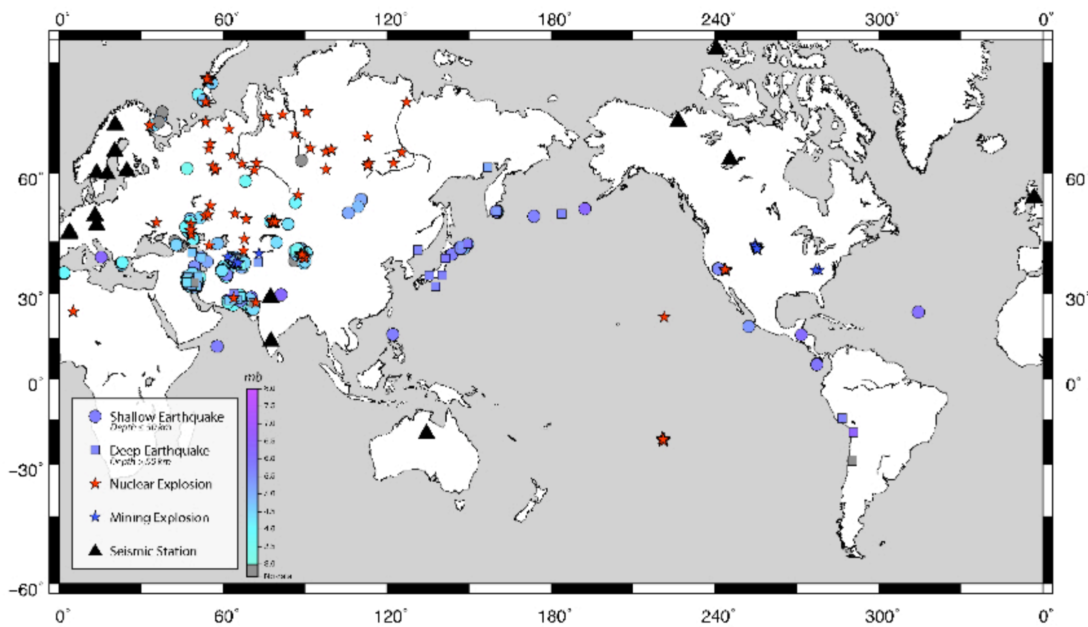


**Figure 1. Teleseismic event and station locations.**

## RESEARCH ACCOMPLISHED

In Anderson et al. (2007), for each teleseismic discriminant a probability model is formulated under a general null hypothesis of $H_0$: Explosion Characteristics. The veracity of the hypothesized model for each discriminant is measured with a calculation that is exactly, or analogous, to a *p*-value. The hypothesis test formulation ensures that seismic phenomenology is tied to the interpretation of the p-value. Most importantly, the hypothesis test formulation ensures that the physical basis of a discriminant is properly integrated into a probability model that describes the most relevant source of error corrupting the physical measurement. Discriminant *p*-values can also be viewed as standardized discriminants, and can be combined into a unified source type identification with a number of statistical classification methods. Making the null hypothesis $H_0$: Explosion Characteristics is also important in the context of treaty verification because seismic events are assumed to be single-point explosions and then inferential evidence is used to reject this hypothesis, if possible. The teleseismic events acquired from the ISC and BSC include nuclear explosions from NTS and the former Soviet Union, global earthquakes, and mining explosions from 1964 to 2000. Necessary signal processing was completed by Rocky Mountain Geophysics (RMG), LLC. Seismic measurements from combinations of stations given in Table 1 are used in the demonstration analysis. Arrays EKA, GBA, WRA and YKA comprise the United Kingdom seismic system. Source type definitions for these data are deep earthquake (DEQ) for a reported depth greater than 50 kilometers, shallow earthquake (SEQ) for a reported depth less than or equal to 50 kilometers and single-point fully contained explosions (EX). The EX population included underground nuclear weapons tests and some single-point fully contained chemical explosions. Acquired data counts are summarized by source type in Table 2. Figure 1 shows the event and station locations.

Teleseismic discrimination between underground nuclear explosions and naturally occurring earthquakes has been summarized in a number of publications (Blandford [1977]; Douglas [1981]; Blandford [1982]; Douglas [2007]). A seismic event couples energy into the earth and this energy is partitioned into waveform phases. The path and distance between event and stations are different and if the phase energy measurements from each station could be reasonably corrected for these effects, the measurements would be quite similar, with differences fundamentally due to near-source and near-station effects. Significant research on correction models includes Mueller and Murphy (1971), Murphy and Mueller (1971) and Patton and Taylor (2008). Current methods model station magnitudes as Gaussian and average to construct an event network magnitude.

**Table 1. Array locations used in $m_b$ versus $M_s$ demonstration analysis.**

| Station | Latitude | Longitude | Description |
|---|---|---|---|
| CLL | 51.31 | 13.00 | Collm, Germany |
| EKA | 55.33 | -3.16 | Eskdalemuir Array, Scotland |
| GBA | 13.60 | 77.44 | Gauribidanur Array, India |
| HFS | 60.13 | 13.70 | Hagfors Array, Sweden |
| INK | 68.31 | -133.52 | Inuvik, Northwest Territories, Canada |
| KHC | 49.13 | 13.58 | Kasperske, Hory, Czech Republic |
| KIR | 67.84 | 20.42 | Kiruna, Sweden |
| LOR | 47.27 | 3.86 | Lormes, France |
| MBC | 76.24 | -119.36 | Mould Bay, Northwest Territories, Canada |
| NDI | 28.68 | 77.22 | New Delhi, India |
| NUR | 60.51 | 24.65 | Nurmijarvi, Finland |
| SSF | 47.06 | 3.51 | Saint Saulge, France |
| UME | 63.82 | 20.24 | Umea, Sweden |
| UPP | 59.86 | 17.63 | Uppsala, Sweden |
| WRA | -19.94 | 134.34 | Warramunga Array, Australia |
| YKA | 62.49 | -114.61 | Yellowknife Array, Canada |

**Table 2. Source type summary for teleseismic events.**

| EX | SEQ | DEQ |
|---|---|---|
| 395 | 452 | 144 |

*Enhanced standard error for the teleseismic $m_b$ versus $M_s$ discriminant.*

Research on the $m_b$ versus $M_s$ discriminant is significant (see Marshall and Basham [1972]; Evernden [1975]; Blandford [1982]; and Stevens and Day [1985]). The null hypothesis is $H_0 = \mu_{m_b} - \mu_{M_S} \geq \Delta_0$. A common test discriminant is formed from the difference of network averaged surface-wave and body-wave magnitudes. Subtracting the historical average of this difference, when the seismic source is an explosion, gives $\Delta_0$. The equal variance for $m_b$ and $M_s$ in the standard error is calculated from historical data and is assumed known. Specifically, a common formulation of the test discriminant is

$$Z = \frac{(\tilde{m}_b - \tilde{M}_S) - \Delta_0}{\sigma\sqrt{1/n_{\tilde{m}_b} + 1/n_{\tilde{M}_S}}} \quad (1)$$

where the "~" denotes network averaged magnitudes. The standard error in Equation (1) is inconsistent with the physical basis in that an event observed by a large number of stations will have an unrealistically small standard error. Conceptually this implies that the path and distance corrections for $m_b$ and $M_s$ are accurately known and applied, and these magnitudes are corrupted only by incoherent (uncorrelated) station noise. However, physical path and distance corrections are specific to an event and realistically can only be approximately modeled. If correction model inadequacy (e.g., variations in attenuation) is treated as random, then with historical event data the variance components for correction model error and station noise can be estimated. The conceptual formulation of the random effects model for a magnitude is

$$Y = Magnitude = \mu(source - type) + Event + Noise \quad (2)$$

where *Event* is a random effect that varies from event to event and represents model inadequacy in physical path and distance corrections. *Noise* represents measurement and station noise. The value $\Delta_0$ in Equation (2) is calculated from calibrated values of $\mu$(*source* − *type*) for the magnitudes $m_b$ and $M_s$. The linear model representation of Equation (2) is

$$Y_{ijk} = \mu_i + E_j + \varepsilon_{(ij)k} \quad j = 1,2,..m_i \; k = 1,2,..n_{ij} \quad (3)$$

Equation (3) reads $Y_{ijk}$ equals a constant source-type mean ($\mu_i$) plus a random event adjustment $E_j$ (model inadequacy) plus a station noise adjustment $\varepsilon_{(ij)k}$. The $E_j$ are iid normal random variables with zero mean and variance $\sigma^2$. The $\varepsilon_{(ij)k}$ are iid normal random variables with zero mean and variance $\tau^2$. $E_j$ and $\varepsilon_{(ij)k}$ are independent across all subscripts. This assumption is consistent with near-source and path effects being uncorrelated with station noise. The intra-class correlation $\tau^2/(\tau^2+\sigma^2)$) has an important interpretation. It implies that large adjustment $E_j$ increases correlation between stations because a significant part of this random effect comes from near-source effects applied to all stations observing an event. Small adjustment $E_j$ implies the correction model is good and is conceptually equivalent to error structure from stations with incoherent noise. Small adjustment $E_j$ implies $\tau^2$ is small and the standard error of a network magnitude is reduced further through the station averaging. From the model Equation (3), the new standard error of the $m_b$ versus $M_s$ discriminant is

$$SE_{\tilde{m}_b - \tilde{M}_S} = \sqrt{\tau^2_{m_b} + \frac{\sigma^2_{m_b}}{n_{m_b}} + \tau^2_{M_S} + \frac{\sigma^2_{M_S}}{n_{M_S}}} \quad (4)$$

for both earthquakes and explosions and the test statistic is

$$Z = \frac{(\tilde{m}_b - \tilde{M}_S) - \Delta_0}{\sqrt{\tau^2_{m_b} + \frac{\sigma^2_{m_b}}{n_{m_b}} + \tau^2_{M_S} + \frac{\sigma^2_{M_S}}{n_{M_S}}}} \quad (5)$$

providing a *p*-value for the hypothesis test $H_0 = \mu_{m_b} - \mu_{M_S} \geq \Delta_0$. Note that this extended formulation of the $m_b$ versus $M_s$ discriminant is analogous to the formulation of regional amplitude discriminants in Anderson et al. (2009).

In addition to observed discrimination properties, both $m_b$ and $M_s$ are biased proxy measurements for the size of an event – seismic moment([=] Newton/meter) for earthquakes and yield ([=] kilotons TNT) for explosions.
The network magnitudes for $m_b$ and $M_s$ are biased measurements for event size with increased precision over single-station magnitudes. For earthquakes, this bias is significantly due to inadequate correction for event depth, the radiation pattern of the earthquake (fault orientation) and near-source earth structure, which in the aggregate, is modeled as the random correction model error $E_j$. For explosions, this bias is significantly due to inadequate correction for event depth, the radiation pattern from tectonic release caused by the explosion, and near-source earth structure, also modeled in the aggregate as random correction model error $E_j$. Applying (apparent performance) the discriminant formulation in Equation (5) to the ISC/BSC teleseismic data gave the *p*-values are shown in Figure 2 for the null hypothesis $H_0 = \mu_{m_b} - \mu_{M_S} \geq 1.35$. Deep earthquakes (DEQ) can attenuate the waves that generate the magnitude $M_s$ and so DEQ events can appear to be single-point explosions. In this case, resolution requires a depth discriminant to eliminate the deeper earthquakes. Note that an interpretation of the $m_b$ and $M_s$ p-value as evidence in support of $H_0 = \mu_{m_b} - \mu_{M_S} \geq 1.35$ leads to no missed explosions. Treating the *p*-value as a standardized discriminant, and choosing a decision line of approximately 0.2 also leads to no missed explosions with a significant reduction in false-alarms.

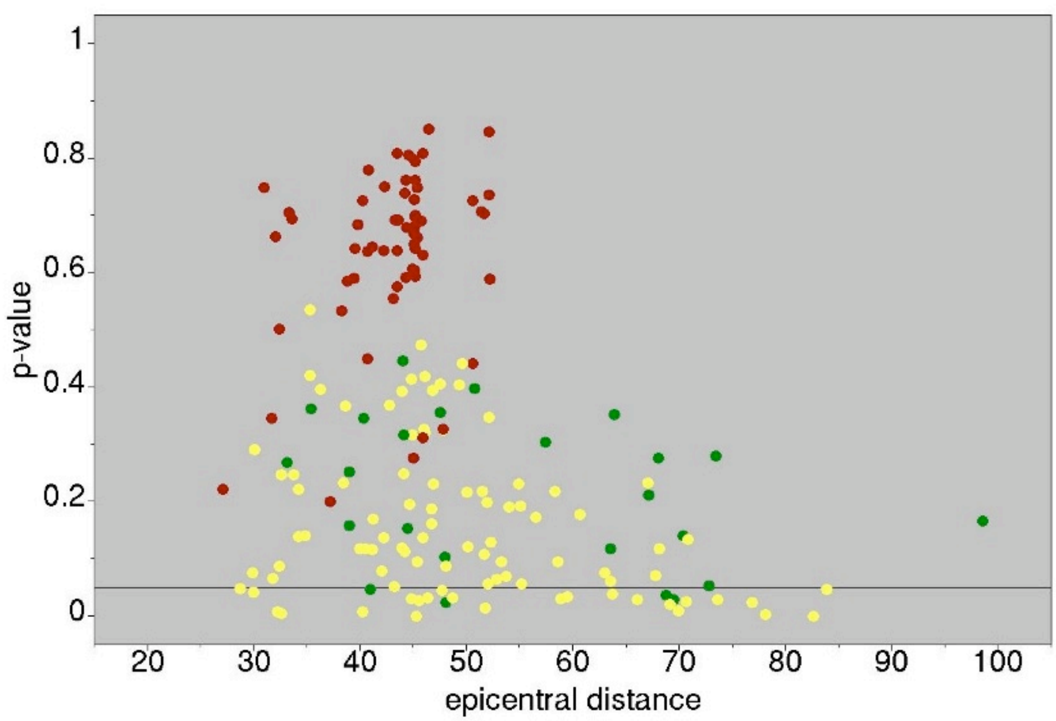


**Figure 2.** ***p*** **-values for** $H_0 = \mu_{m_b} - \mu_{M_S} \geq 1.35$**. The abscissa is the average epicentral distance (degrees) between event and seismic stations observing the event. Single-point fully contained explosions are red, shallow earthquakes are yellow, and deep earthquakes are green.**

## CONCLUSIONS AND RECOMMENDATIONS

A significant aspect of discrimination research should focus on the construction of the discriminants rather than technologies to combine discriminants, as there are many mature technologies for multivariate discrimination (see Hand [2006]). For discriminant research, the fundamental challenge is the mathematical combination of physical basis with probability models to describe sources of error. The criteria for selection of a multivariate discrimination technology are operational utility and relevance. Most seismic discriminants are model-based and as demonstrated in this paper, error partition and characterizing model error should be integral to seismic discriminant construction.

## ACKNOWLEDGEMENTS

The authors acknowledge the support of Leslie A. Casey and the National Nuclear Security Administration Office of Nonproliferation Research and Development for funding this work. Dmitry Storchak, director of the ISC, kindly assisted in the acquisition of the ISC data. Marvin Wetovsky, Los Alamos National Laboratory, provided thorough and objective technical editing support.

## REFERENCES

Anderson, D. N., D. K. Fagan, M. A. Tinker, G. D. Kraft, and K. D. Hutchenson (2007). A mathematical statistics formulation of the teleseismic explosion identification problem with multiple discriminants, *Bull. Seism. Soc. Am.* 97: 1730–1741.

Anderson, D.N., W. R. Walter, D. K. Fagan, T. M. Mercier and S. R. Taylor (2009). Regional multi-station discriminants: Magnitude, distance and amplitude corrections and sources of error, *Bull. Seism. Soc. Am.* 99: 794–808.

Blandford, R. R. (1977). Discrimination between earthquakes and underground explosions, *Ann. Rev. Earth Plan. Sci.* 5: 111–122.

Blandford, R. R. (1982). Seismic event discrimination, *Bull. Seism. Soc. Am.* 72: 69–87.

Douglas, A. (1981). Seismic source identification: a review of past and present research efforts. In Husebye, E. and Mykkeltveit, S., Eds., *Identification of Seismic Sources–Earthquake or Underground Explosion* , pp. 1–48. D. Reidel Publishing Co., Dordrecht, The Netherlands.

Douglas, A. (2007). Forensic seismology revisited, *Surveys of Geophysics* 28: 1–31.

Evernden, J. F. (1975). Further studies on seismic discrimination, *Bull. Seism. Soc. Am*. 65: 359–391.

Hand, D. J. (2006). Classifier technology and the illusion of progress, *Statistical Science* 21: 1–34.

Marshall, P. D. and P. W. Basham (1972). Discrimination between earthquakes and underground explosions employing an improved Ms scale, *Geophys. J. R. Astr. Soc.* 29: 431–458.

Mueller, R. A. and J. R. Murphy (1971). Seismic characteristics of underground nuclear detonations: Part I. Seismic spectrum scaling, *Bull. Seism. Soc. Am.* 61: 1675–1692.

Murphy, J. R. and R. A. Mueller (1971). Seismic characteristics of underground nuclear detonations: Part II. Elastic energy and magnitude determinations, *Bull. Seism. Soc. Am.* 61: 1693–1704.

Patton, H. J. and S. R. Taylor (2008). Effects of shock-induced tensile failure on mb-Ms discrimination: Contrasts between historic nuclear explosions and the North Korean test of 9 October 2006, *Geophys. Res. Lett.* 35: L14301.

Stevens, J. L. and S. M. Day (1985). The physical basis of the mb:Ms and variable frequency magnitude methods for earthquake/explosion discrimination, *J. Geophys. Res*. 90: 3009–3020.