APPLICATION OF A TIME-DOMAIN, VARIABLE-PERIOD SURFACE WAVE MAGNITUDE MEASUREMENT PROCEDURE AT REGIONAL AND TELESEISMIC DISTANCES

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ABSTRACT

Russell (2003) developed a time-domain method for measuring surface waves with minimum digital processing, using zero-phase Butterworth filters. For applications over typical continental crusts, the proposed magnitude equation for zero-to-peak measurements in millimicrons is

$$M_S(VMAX) = log(a_b) + \frac{1}{2}log(sin(\Delta)) + 0.0031\left(\frac{20}{T}\right)^{1.8}\Delta - 0.66\,log\left(\frac{20}{T}\right) - log(f_c) - 0.43 \qquad (1)$$

where

$$f_c \leq \frac{0.6}{T\sqrt{\Delta}}.$$

To calculate M_s(VMAX), the following steps should be taken:

a. Determine the epicentral distance in degrees to the event Δ and the period *T*.
b. Calculate the corner filter frequency f_c using the inequality above.
c. Filter the time series using a zero-phase, third-order Butterworth band-pass filter with corner frequencies $1/T-f_c$, $1/T+f_c$.
d. Calculate the maximum amplitude a_b of the filtered signal and calculate M_s(VMAX).

We demonstrate the capabilities of the method using applications to three different datasets. The first application utilizes a dataset that consists of large earthquakes in the Mediterranean region. The results indicate that the M_s(VMAX) technique provides regional and teleseismic surface-wave magnitude estimates that are in general agreement except for a small distance dependence of -0.002 magnitude units per degree. We also find that the M_s(VMAX) estimates are less than 0.1 magnitude unit different than those from other formulas applied at teleseismic distances such as Rezapour and Pearce (1998) and Vaněk et al. (1962).

In the second and third applications of the method, we demonstrate that measurements of M_s(VMAX) versus m_b provide adequate separation of the explosion and earthquake populations at the Nevada and Lop Nor Test Sites. At the Nevada Test Site, our technique resulted in the misclassification of two earthquakes. We also determined that the new technique reduces the scatter in the magnitude estimates by 25% when compared to our previous studies using a calibrated regional magnitude formula. For the Lop Nor Test Site, we had no misclassified explosions or earthquakes; however, the data were less comprehensive.

A preliminary analysis of Eurasian earthquake and explosion data suggests that similar slopes are obtained for observed surface-wave data at $m_b < \sim 5$. These results suggest that the discrimination of explosions from earthquakes can be achieved at lower magnitudes using the Russell (2005) formula and the M_s(VMAX) measurement technique.

OBJECTIVES

Russell (2005) developed a time-domain method for measuring surface waves with minimum digital processing, using zero-phase Butterworth filters. The method can effectively measure surface-wave magnitudes at both regional and teleseismic distances at variable periods between 8 and 25 seconds. For applications over typical continental crusts, the magnitude equation is

$$M_S(VMAX) = log(a_b) + \frac{1}{2} log(sin(\Delta)) + 0.0031\left(\frac{20}{T}\right)^{1.8} \Delta - 0.66\, log\left(\frac{20}{T}\right) - log(f_c) - 0.43 \qquad (2)$$

where a_b is the amplitude of the Butterworth-filtered surface waves (zero-to-peak in nanometers) and

$$f_c \leq \frac{0.6}{T\sqrt{\Delta}}$$

is the filter frequency of a third-order Butterworth band-pass filter with corner frequencies $1/T-f_c$, $1/T+f_c$. At the reference period T=20 seconds, the equation is equivalent to von Seggern's formula (1977) scaled to Vaněk et al. (1962) at 50 degrees. For periods $8 \leq T \leq 25$, the equation is corrected to T=20 seconds, accounting for source effects, attenuation, and dispersion.

To calculate M_s(VMAX), the following steps should be taken:

a. Determine the epicentral distance in degrees to the event Δ and the period T.
b. Calculate the corner filter frequency f_c using the inequality above.
c. Filter the time series using a zero-phase, third-order Butterworth band-pass filter with corner frequencies $1/T-f_c$, $1/T+f_c$.
d. Calculate the maximum amplitude a_b of the filtered signal and calculate M_s(VMAX).

The objective of this paper is to present the results of applying the Russell (2005) formula at teleseismic and regional distances for variable-period data. First, we applied the formula to a large earthquake dataset to demonstrate the analysis method and to determine if the regional and teleseismic magnitudes are unbiased with respect to each other. We compare the resulting magnitudes from the Russell equation with estimates from the Vaněk et al. (1962) and Rezapour and Pearce (1998). Then, we used the formula to estimate surface-wave magnitudes for explosions and earthquakes in Eurasia and North America to examine if we can improve discrimination performance.

RESEARCH ACCOMPLISHED

We applied the Russell (2005) formula and our M_s(VMAX) technique to three different surface-wave datasets. For the first application of the formula, we estimated surface-wave magnitudes for several large earthquakes in the Mediterranean region of Europe. For the second and third applications, we estimated M_s(VMAX) for earthquakes and explosions in North America and Eurasia, respectively. And finally, we examined all of the data in Eurasia to determine the performance of the M_s-m_b discriminant when our magnitude estimation techniques are used.

Mediterranean Region

We applied the Russell (2005) formula and M_s(VMAX) measurement technique to earthquakes in the Mediterranean region to determine if a) we obtain consistent magnitudes at regional and teleseismic distances and b) our M_s estimates match those obtained using the Vaněk et al. (1962) and Rezapour and Pearce (1998) formulas.

Data. We developed a database of broadband vertical component recordings of 34 earthquakes that occurred in the Mediterranean region of Europe (Figure 1). For this pilot study, we focused on larger events (*mb* > 5.4) with depths of 50 km or less. These restrictions ensured adequate signal-to-noise ratios for the surface waves recorded at regional and teleseismic distances. The data were acquired from the Incorporated Research Institutions for Seismology (IRIS) and consisted of global and regional networks in the study region. The data were all transformed from counts to displacement in nanometers using the Seismic Analysis Code command "transfer" and the SEED response files. The data were decimated from their original sampling rates (> 20 samples/second) to approximately 1 sample/sec for the surface-wave analysis. Down sampling increases the analysis speed and eliminates digital filter problems associated with narrow-band filtering, as discussed in Appendix B of Russell (2005).

Figure 1. Test dataset of events in the Mediterranean region and stations used to test the Russell (2005) formula and M_s(VMAX) measurement technique.

Results. Our first objective in this exercise was to determine if there is a distance dependence in the formula and measurement technique. As mentioned in the introduction of this manuscript, previous research has been unsuccessful at finding a single, variable-period formula valid at both regional and teleseismic distances.

We performed a distance analysis on all 34 events of our test database similar to the one performed in the lower plot of Figure 2. In order to compare events of different magnitudes, we removed the mean magnitude from each event's analysis. Figure 2 shows the results, which include 1,348 M_s(VMAX) magnitude estimates from the events shown in Figure 1. Our objective was to test the formula for a predominance of continental paths; thus, data are at distances less than 70 degrees. A linear regression of the mean-removed magnitude estimates with increasing distance shows a small (0.002 magnitude unit [mu] per degree) decrease in magnitudes. The standard deviation for the regression analysis is 0.21 mu). This suggests that if an event had an M_s(VMAX) magnitude estimate of 6.0 measured at a distance of 5 degrees, the magnitude estimated at a distance of 60 degrees would be ~5.89. This difference is well within the scatter typically observed for surface-wave magnitude estimates resulting from focal mechanisms and path effects.

Because M_s(VMAX) is a variable-period technique, we also examined the periods at which the estimates were formed (Figure 3). There is a general increase in the number of measurements in each bin from shorter to longer periods. This increase is reassuring, since it is consistent with past studies which found that the best period range to measure M_s is between 17 and 23 seconds.

We observe an edge effect associated with ending the surface-wave magnitude analysis at 25 seconds. There are two explanations for this behavior. Because of the spectral shape of earthquakes, they will tend to select longer periods, especially when the events are deeper than the upper crust. In addition, because of the nature of surface wave propagation, we would expect to see a general trend of longer-period measurements with increasing distances. This trend is related to the rapid attenuation of shorter-period amplitudes compared with the longer periods at longer epicentral distances. In Figure 3, we plotted the distances and periods at which the magnitudes were estimated. The plot shows that for the magnitudes estimated at periods of 10 seconds or less, the corresponding epicentral distances were less than 30 degrees. From 10 to 18 seconds, we note a general increase in the cut-out distance from 30 to 60 degrees. For periods greater than 18 seconds, we note that the cut-out distance continues to increase but is less constrained by the available data. The results in Figure 3 suggest that the formula is behaving as we intended. It also hints that the analysis could be improved by increasing the long-period limit to periods greater than 25 seconds.

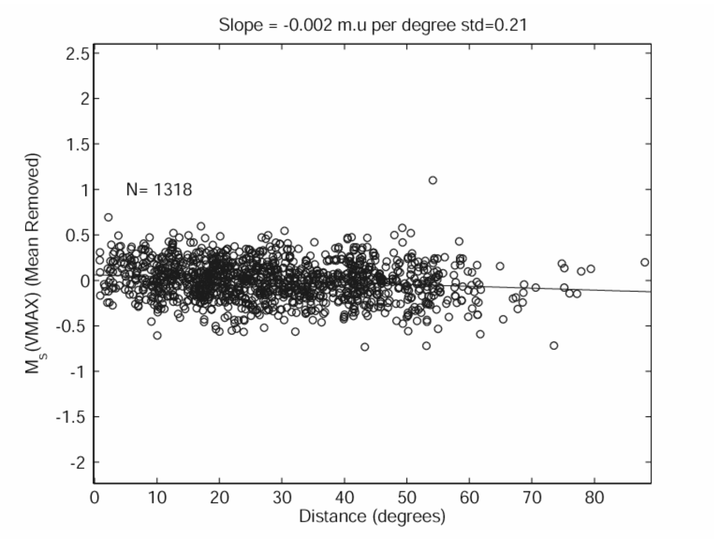

Figure 2. Regression of mean-removed M_s(VMAX) magnitude estimates for the 34 events in Figure 1 with distance. There is a very small decrease in magnitude units (0.002 m.u. per degree) with increasing distance.

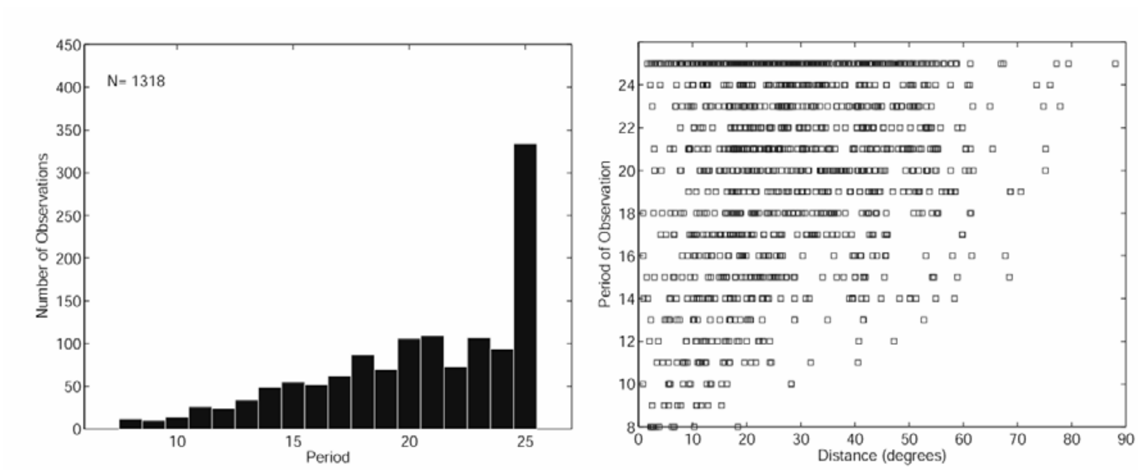

Figure 3. (Left). Bins showing the periods used to estimate the M_s(VMAX) magnitudes at 1348 different station-source pairs. (Right). Comparison of the periods of the M_s(VMAX) estimates compared with the epicentral distance.

As a final step in the analysis of the events in Figure 1, we compared our M_s(VMAX) estimates with magnitude estimates published by the United States Geological Survey (USGS) and the International Data Center (IDC) in Vienna and to the M_w estimates obtained from Harvard's Centroid Moment Tensor (CMT) analysis. The results are shown in Figure 4. We note that the USGS uses the Vaněk et al. (1962) formula, while the IDC uses the Rezapour and Pearce (1998) formula. We performed a fixed slope (slope=1) regression of the M_s(VMAX) estimates against the results from the other organizations to determine the offset between the estimates. The results indicate that the M_s(VMAX) is -0.03 and 0.05 magnitude units different than the Vaněk et al. (1962) and Rezapour and Pearce (1998) formulas, respectively. Differences of this size for all three comparisons are well within the scatter of the observations. Also, the right subplot of Figure 4 shows that the M_s(VMAX) and M_w estimates are approximately equal for $6.0 < M_w < 7.2$.

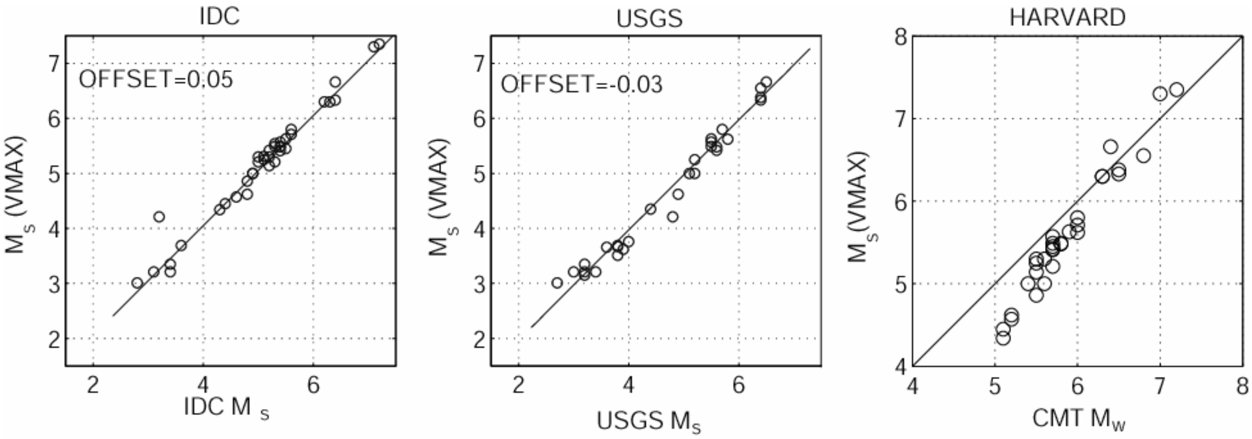

Figure 4. (Left). Fixed slope (slope=1) regression of M_s(VMAX) network-average magnitudes versus the IDC M_s for the Mediterranean events. (Middle). Fixed slope (slope=1) regression of M_s(VMAX) network-average magnitudes versus the USGS M_s. (Right). Comparison of the M_s(VMAX) network-average magnitudes versus the Harvard CMT M_ws.

Nevada Test Site Earthquake and Explosion Discrimination.

Next, we examined the performance of the Russell (2005) formula and M_s(VMAX) measurement technique on earthquake and explosion discrimination at the Nevada Test Site in the western United States (Figure 5). Figure 6 shows the regression of the M_s (VMAX) versus the Denny et al. (1987; 1989) m_b for both the earthquake and explosion populations in our test dataset (Figure 5). The best-fitting regression lines are plotted as solid lines, and the slope and intercepts for the lines are presented in the left subplot. The populations plotted in Figure 6 suggest that M_s and m_b will be fitted well by linear regressions, with approximately equal slopes assumed for the earthquake and explosion populations. While we did observe slightly different slopes in the regression analyses for the two populations, we believe that this is due to inadequate sampling of earthquakes at m_b magnitudes greater than 5.2. Our dataset does not present any evidence that the two populations are converging at smaller magnitudes, although other M_s-m_b studies (Stevens and McLaughlin, 2001) suggest that convergence does occur. The classification equation based on the parallel-slope assumption becomes

$$d = M_s(\text{VMAX}) - 1.3m_b \quad (3)$$

where d is the decision value. We chose to use the explosion slope, as we believe that it is better constrained with the available data, and synthetic studies suggest (Bonner and Herrmann, 2004) that it does not change with increasing magnitude. If d < -2.30, the event will reside in the explosion population. We note that this does not require the event to be a nuclear explosion, as additional testing is needed to ensure the event is shallow enough to be a candidate explosion. If d > 2.30, the event falls into the earthquake classification. We misclassified two earthquakes in the explosion population. In our previous studies based on 7-second data (Bonner et al., 2003), we misclassified four earthquakes as explosions.

Lop Nor Test Site Earthquake and Explosion Discrimination.

In our third application of the Russell (2005) formula and M_s(VMAX) measurement technique, we examined earthquake and explosion discrimination at the Lop Nor nuclear test site in China (Figure 7). As shown in Figure 8, we regressed the M_s (VMAX) versus the USGS m_b for both the earthquake and explosion populations in our test dataset. The best-fitting regression lines are plotted as solid lines. The slope and intercepts for the lines are presented in the left subplot.

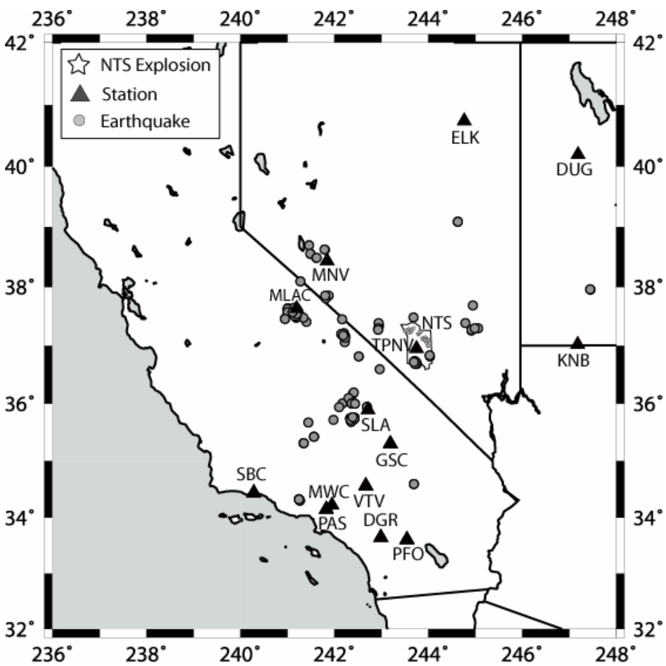

Figure 5. Test dataset consisting of NTS explosions recorded on the LNN dataset together with western United States earthquakes recorded on at least one LNN station and other regional networks.

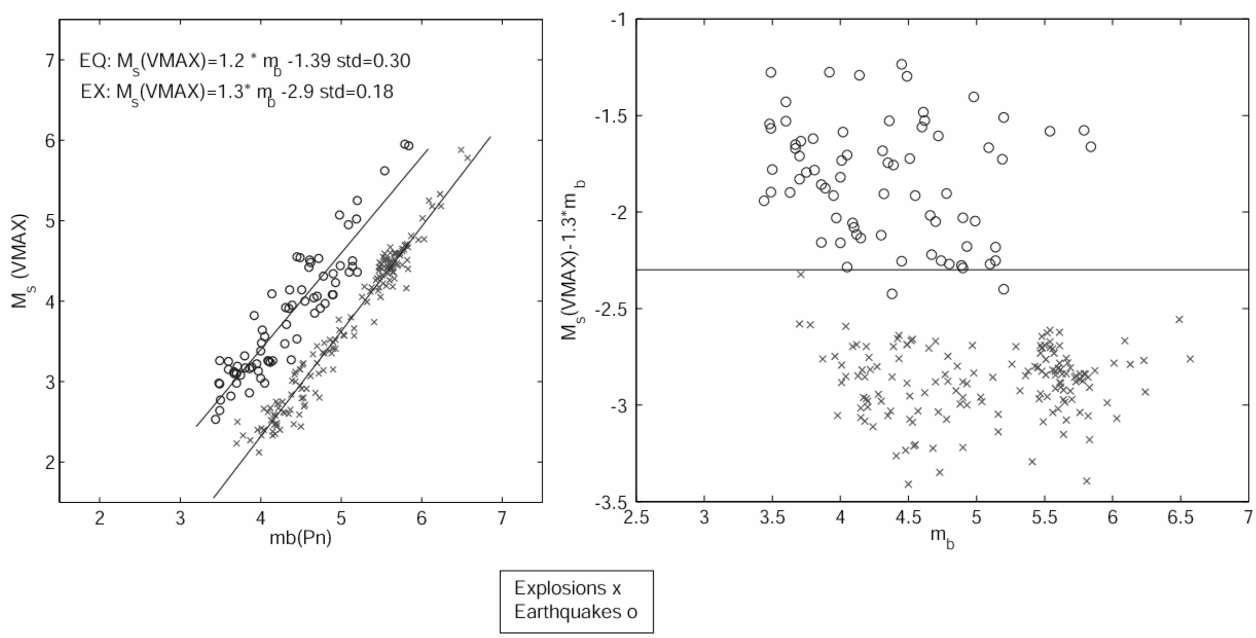

Figure 6. Discrimination results for M_s (VMAX) at the Nevada Test Site. Left: M_s (VMAX) vs. m_b for western United States earthquakes and nuclear explosions. Right: Linear discrimination of the two datasets showing the decision line for classifying an event as a possible nuclear explosion. If d=M_s (VMAX) – 1.3m_b is less than -2.45, the event may be an explosion, and additional analysis will be required to prove the event is not a deep and/or anomalous earthquake.

The slopes for the earthquake and explosion data were 1.0 and 1.2, respectively. Again, there is no evidence suggesting that the populations are converging at smaller magnitudes. We used the slope for the explosions to compute a linear discriminant analysis. As a result, we developed the following classification equation:

$$d = M_s(\text{VMAX}) - 1.2m_b, \quad (4)$$

where d is the decision value. If d < -2.6, the event will reside in the explosion population and requires additional processing prior to being classified as a candidate explosion. If d > -2.6, the event falls into the earthquake classification. We note that no Lop Nor explosions or earthquakes were misclassified using the VMAX magnitude estimation technique with the Russell (2005) surface-wave magnitude scale. However, we have fewer events for this region than we did for the NTS comparison.

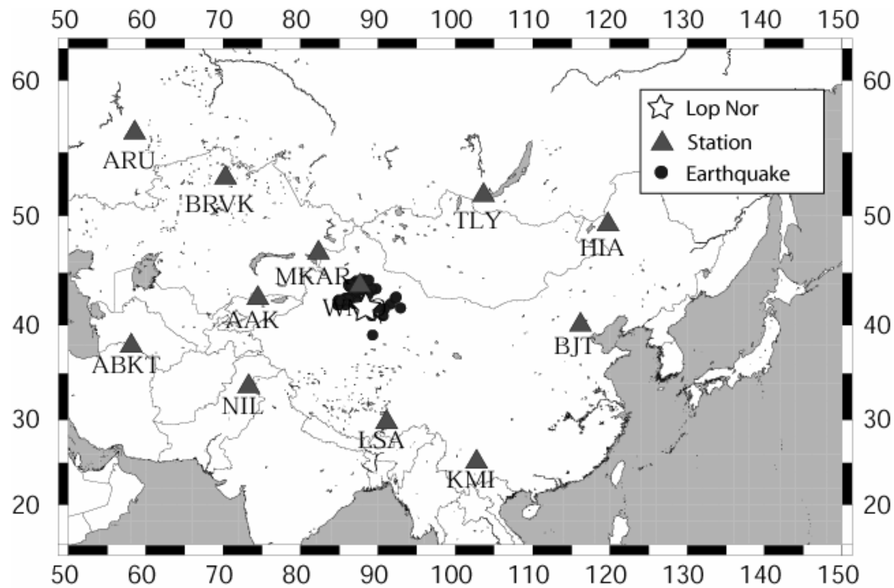

Figure 7. Test dataset consisting of Lop Nor explosions recorded on regional and near-teleseismic stations (triangles) together with western Chinese earthquakes (solid circles).

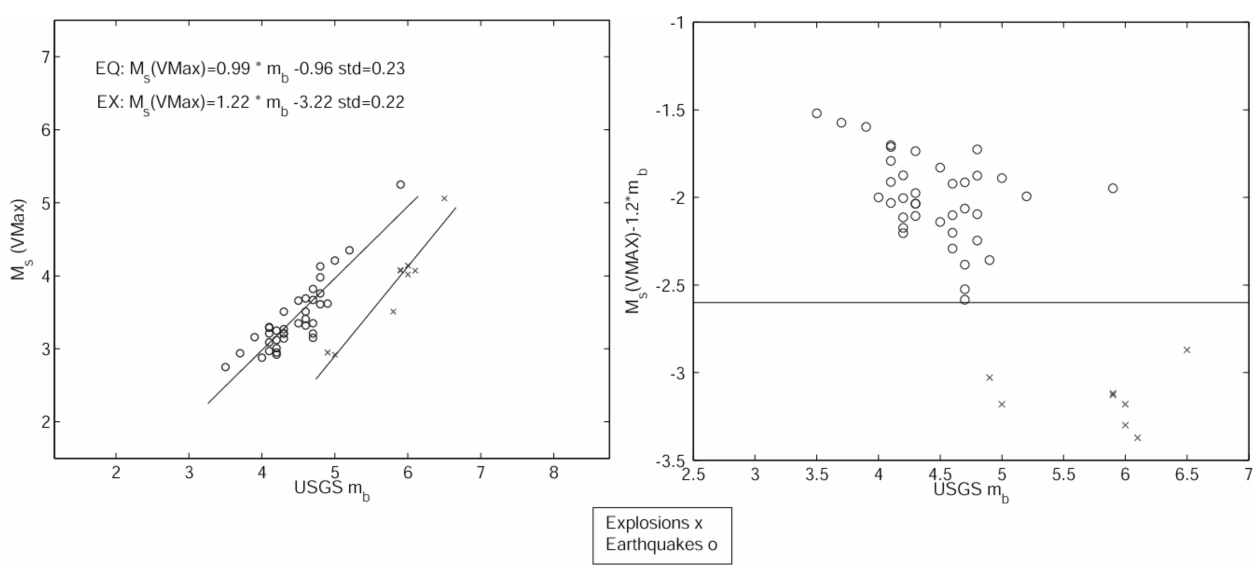

Figure 8. Discrimination results for M_s (VMAX) at the Lop Nor Test Site. Left: M_s (VMAX) vs. m_b for northwestern China earthquakes and nuclear explosions at Lop Nor. Right: Linear discrimination of the two datasets showing the decision line (-2.6) for classifying an event as a possible nuclear explosion.

Eurasian Results

There is a general disagreement among researchers in the nuclear monitoring community as to how well the M_s—m_b discriminant performs at small-to-intermediate body-wave magnitudes. Some researchers believe that the available M_s—m_b datasets suggest that the two populations converge at smaller magnitudes (e.g., Stevens and McLaughlin, 2001). These researchers believe that the population convergence is caused by earthquake and explosion sources that become phenomenologically similar at smaller magnitudes. Lambert and Alexander (1971) determined that the earthquake and explosion populations at the Nevada Test Site are characterized by parallel M_s vs. m_b curves, with slopes of 1 and a difference of 0.82 magnitude units based on linear regression fits. Alexander (2002; personal communication) suggests that any convergence at the smaller magnitudes is related to depth and not the phenomenology behind explosion and earthquake sources.

To determine whether depth or source phenomenology is responsible for converging M_s—m_b behavior at smaller magnitudes, we pooled all of our Eurasian M_s(VMAX) estimates. We also calculated M_s(VMAX) for 11 additional nuclear explosions in Eurasia and combined them with the Lop Nor explosions from Figure 8. Figure 9 shows the M_s(VMAX) estimates from all these data plotted versus USGS m_b.

Because of corner frequency effects for earthquakes and m_b measurement procedures, there should be a change in slope for regressed M_s(VMAX) vs m_b near $m_b = 5$ (Nuttli, 1983). As shown in Figure 9, the slope for the best-fit regressions above $m_b = 5$ is 1.46 with a standard deviation of 0.21 magnitude units. The slope for the regressions below $m_b = 5$ is 0.94, which is similar to the slope determined for the observed explosion data (1.04). With the current dataset, we cannot rule out the possibility that a single line with slope equal to 1.54 can fit all of the earthquake data. In fact, the correlation coefficients for single-line or two-line fits are essentially the same ($R^2 > 0.85$). If the earthquake data were fit with a single line, we would see convergence of the populations near $m_b = 3.5$, which agrees with Stevens and McLaughlin (2001).

However, if we focus on the two-line case, the slopes for our earthquake and explosion populations at m_b values < 5 are similar to the Lambert and Alexander (1971) results. Additionally, we observed 0.90 magnitude units separation between the two populations at m_bs below 5, while Lambert and Alexander (1971) noted a difference of 0.82 magnitude units, based on the fitted regression lines for their NTS earthquakes and explosions. Differences between the theoretical and observed slopes above $m_b > 5$ may be related to the difficulties of measuring body-wave magnitudes for large events. While more data will be required to finalize the two-slope hypothesis, these preliminary results suggest that the discrimination of explosions from earthquakes can be achieved at lower magnitudes using the Russell (2005) formula and the M_s(VMAX) measurement technique.

Murphy et al. (1997) determined an event screening relationship based on M_s—m_b estimates. For USGS estimated m_b, the screening criterion is

$$M_s = 1.25\ m_b - 2.60. \qquad (5)$$

We plotted the Murphy et al. (1997) criterion in Figure 9 as the dashed line and note that two of the earthquakes fall below this line. More importantly, none of our explosions plotted above this line.

CONCLUSIONS AND RECOMMENDATIONS

The Russell surface-wave magnitude formula and the M_s(VMAX) measurement technique provide a new method for estimating surface-wave magnitudes. There are several benefits to the new method. First, the technique allows for time domain measurements of surface-wave amplitudes, giving an analyst the ability to visually confirm that the pick is correct and is an actual surface wave. Also, it allows for surface-wave magnitudes to be measured at local and regional distances where traditional 20-second magnitudes cannot be used. And these magnitudes are not biased with respect to teleseismic estimates using the same M_s(VMAX) measurement technique. Additionally, the application of narrow-band Butterworth-filtering techniques appropriately handles Airy phase phenomena that prior to this study, had to be accounted for using Marshall and Basham's (1972) empirical corrections. Finally, because the method is variable period and not restricted to near 20-seconds period, the analyst is allowed to measure M_s where the signal is largest. The new method has been successfully tested on three research datasets, and the results suggest that the method can be used to screen out a large percentage of small earthquakes at $m_b < 5$. Thus, we are currently implementing the technique for operational testing.

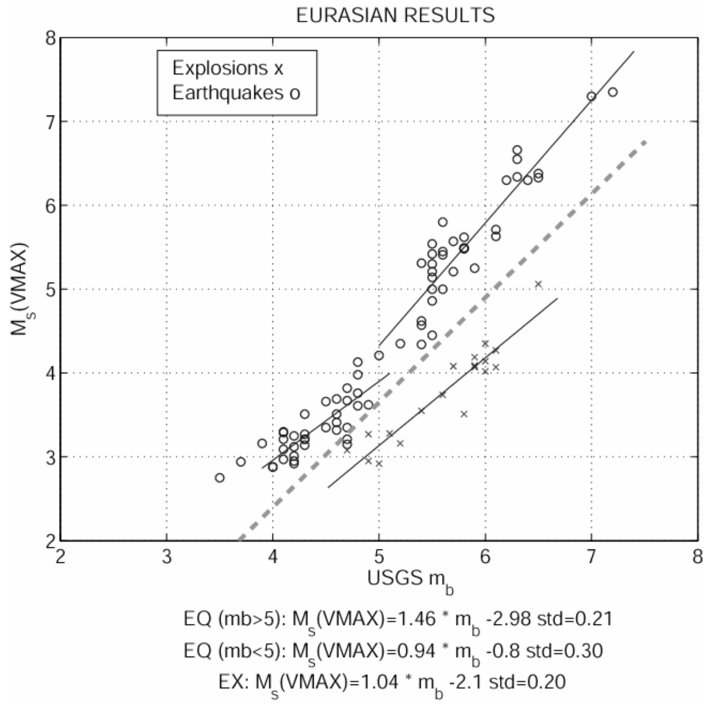

Figure 9. M_s—m_b relationships for all Eurasian earthquake and explosion data for which an M_s (VMAX) was estimated during this study. The body wave magnitudes are all from the United States Geological Survey. We split the earthquake data at $m_b = 5$ based on corner frequency effects for earthquakes and m_b. The earthquake and explosion populations both have slopes that are approximately 1 for $m_b < 5$ and are separated by an average of 0.90 magnitude units. The dashed line is the Murphy et al. (1997) criterion for event screening.

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