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

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ABSTRACT

We continue to examine the feasibility of using short-period surface waves for estimating magnitude at regional distances. In previous research studies, we demonstrated that calibrated surface wave magnitudes (e.g., Marshall and Basham, 1972; Rezapour and Pearce, 1998) based on 7-second surface waves provided adequate M_s-m_b discriminant performance at the Nevada Test Site (NTS). However, at the Lop Nor test site we determined that the method worked best by forming magnitudes at the period of maximum amplitude.

We have recently shifted our focus to a new surface wave magnitude scale developed by Russell (2004) that uses Butterworth-filtered seismic signals. Russell (2004) developed a zero-phase 3rd order Butterworth magnitude equation (with amplitude, a_b, measured zero-to-peak in nanometers) of:

$$M_s = \log(a_b) + \frac{1}{2}\log\left(\sin(\Delta)\right) + .0031\left(\frac{T_0}{T}\right)^{2.3}\Delta - \log(f_c) - 0.43 - 0.66\log\left(\frac{20}{T}\right)$$

where T_o is 20 seconds, Δ is distance, and f_c is the Butterworth corner frequency which is defined by

$$f_c \le \frac{G_{\min}}{T\sqrt{\Delta}}\ .$$

Setting $G_{\min}$= 0.6 is appropriate for continental signals between 8 and 40 seconds and oceanic signals between 20 and 40 seconds, including mixed oceanic and continental paths.

We have developed a new processing methodology in order to use the Russell (2004) equation. Our current processing technique begins with a multiple filter analysis on the vertical component seismic data of interest. We use this trial estimate of the dispersion curve to complete phase-matched filtering by following the iterative approach of Herrin and Goforth (1977). Next we apply a filter comb to the data, using center periods at 1-second intervals between 5 and 25 seconds. The envelope function of the filtered signal is constructed, and the maximum zero-to-peak amplitude is measured. An amplitude correction based on the assumption that the event is a shallow explosion is applied to account for the larger shorter period amplitudes generated from shallow earthquakes and explosions. The final processing step is to form a network average of the maximum magnitudes between 8 and 25 seconds, dependent on pre-event noise conditions. M_s (VMAX) is the name that we have given to this combination of the Russell (2004) magnitude scale and the variable-period maximum magnitude averaging.

We have tested this M_s (VMAX) methodology on synthetic data from various earthquake fault mechanisms and depths and found the method to be an improvement over the currently employed methods of surface wave estimations at regional distances. We have also applied the processing methodology to 154 explosions and 69 earthquakes from the NTS region and have found that the new method decreases the variance from single-period estimates by 33%, thus improving the M_s-m_b discriminant performance. Extensive testing of the technique will be completed using a dataset of Eurasian explosions and earthquakes during the next two years as part of a joint project with Lawrence Livermore National Laboratory (LLNL).

OBJECTIVES

Most surface-wave magnitude (M_s) measurements determined for explosion sources consist of events with m_b greater than 4.5; thus, there is uncertainty in the performance of the M_s-m_b discriminant for explosions with yields of less than approximately 5 kilotons fully coupled. At regional distances, an important nuclear monitoring question remains as to whether variable and short-period magnitude scales can be applied successfully to lower M_s thresholds and reduce the variance in the estimates. The objective of this research is to propose and test a new methodology for measuring variable-period surface waves at both regional and teleseismic distances. These new methods take advantage of a recently developed, time-domain surface-wave magnitude formula (Russell, 2004) designed for Butterworth-filtered surface waves. These new methods also make use of a new magnitude measuring procedure that uses the maximum magnitudes at variable periods from multiple stations to form a network-averaged M_s estimate. In this paper, we present the results of applying this new formula and measurement technique to explosions at the NTS and earthquakes in the western United States.

RESEARCH ACCOMPLISHED

A New Surface Wave Magnitude Formula

Russell (2004) has developed a new time-domain surface wave magnitude formula based on a theoretical derivation for surface waves and a zero-phase 3rd order Butterworth filter (with amplitude, a_b, measured zero-to-peak in nanometers). The equation is

$$M_s = \log(a_b) + \frac{1}{2}\log\left(\sin(\Delta)\right) + .0031\left(\frac{T_0}{T}\right)^{2.3}\Delta - \log(f_c) - 0.43 - 0.66\log\left(\frac{20}{T}\right), \quad (1)$$

where T_o is 20 seconds and the filter corner frequency is given by:

$$f_c \le \frac{G_{min}}{T\sqrt{\Delta}} \quad (2)$$

Russell (2004) notes that setting G_{min}= 0.6 should be valid for continental signals between 8 and 40 seconds and oceanic signals between 20 and 40 seconds, including mixed oceanic and continental paths. The formula is equivalent to the von Seggern (1977) magnitude formula at 20 seconds.

Variable-Period, Maximum Magnitude Estimation (VMAX)

The surface-wave magnitude estimation procedure currently employed at most data centers involves measuring the amplitude of surface waves near 20-seconds period. In previous research projects (Bonner et al), we tried to extend this technique to lower periods (e.g., 7 seconds). It was determined that shorter-period surface waves could be used for magnitude estimation for events with smaller m_bs than when only considering 20-second data. Although the 7-second magnitude scale formed a robust discriminant at NTS, it failed to provide adequate explosion/earthquake separation at other test sites, where earthquakes were deeper than the nearby NTS. This failure led to our current design of measuring the maximum magnitude at variable periods between 8 and 25 seconds. We refer to this technique as VMAX. In the following paragraphs, we describe this new magnitude estimation technique.

Phase-Matched Filtering. Our current processing technique begins with a multiple filter analysis on the vertical component of data (in displacement) for our test dataset. We use this trial estimate of the dispersion curve to complete phase-matched filtering following the iterative approach of Herrin and Goforth (1977). The phase-matched filtered and extracted surface waves are then entered into a Matlab-based surface wave magnitude program that calculates the Russell (2004) magnitude. This method is easily automated in a data center setting. We note that for events with $m_b > 4.5$, the phase matched filtering processing step is not needed because the surface waves have significant signal-to-noise ratio (SNR) and are easily identified. This processing step is most advantageous for smaller magnitude events, where the surface wave SNR may be approaching 1.

Butterworth Filtering. We apply a zero-phase 3rd order Butterworth filter to the data with the corner frequency determined from Equation 2. The center periods are at 1-second intervals between 5 and 25 seconds. An example of these filter "combs" applied to a nuclear explosion recorded at Mina, Nevada (MNV), is shown in Figure 1. The envelope function of the filtered signal is then constructed and the maximum zero-to-peak amplitude is measured in a group velocity window between 2.0 and 4.0 km/sec. Equation 1 is used to calculate a variable-period Butterworth surface-wave magnitude. The advantage of the time-domain measurement is evident in Figure 1, as the technique allows the analyst to visually confirm that the correct waveform feature is being measured.

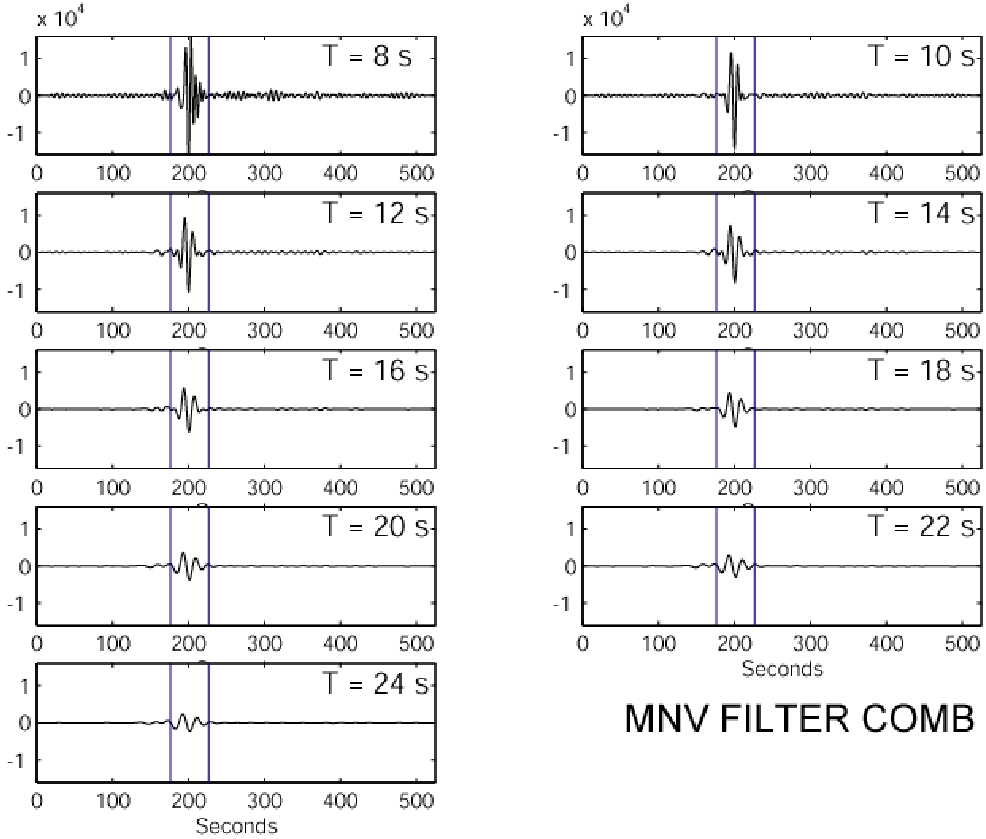


Figure 1. Filter combs through explosion seismograms recorded at station MNV for the m_b=5.26 Serpa explosion. The vertical lines represent group velocity windows of 4.0 and 2.0 km/sec. Amplitudes are in nm. We filter the data between periods of 5 and 25 seconds at 1-second intervals; however, only the periods between 8 and 25 seconds are used for magnitude estimation due to the values used for G_{min} in Equation 2.

Amplitude Corrections. The final step in calculating the M_s(VMAX) magnitude requires the application of an amplitude correction based on the excitation differences for shallow earthquakes and explosions at shorter periods. These corrections are relative to 20-seconds period and will account for the larger, shorter-period amplitudes generated from shallow earthquakes and explosions. This method is similar to the methodology of Stevens and McLaughlin (2001) for path-corrected spectral magnitudes. The correction does not create problems for deeper events (mid- to lower-crust events), because we use the period of maximum magnitude (VMAX) when estimating the final M_s. We calculated these corrections using simple regionalized simulations. For example, we used the Stevens et al., (2001) velocity models for the NTS to MNV, ELK, KNB, and LAC paths and generated fundamental-mode, Rayleigh-wave synthetics (Herrmann, 2002). We did not consider attenuation in the synthesis of these corrections, because variable-period attenuation is considered in Equation 1. We then used the same Butterworth filtering techniques discussed earlier to compare the log amplitude of the variable-period filter combs to the log amplitude of the filter at 20 seconds. At the periods and distances considered in this study, we used the mean of the corrections shown in Figure 2 as our period-dependent amplitude corrections. It is important to note that this correction, based on synthetic signals, replaces the final term in Equation 1 for our analyses because the correction values shown in Figure 2 are approximated by -0.66 log (20/T).

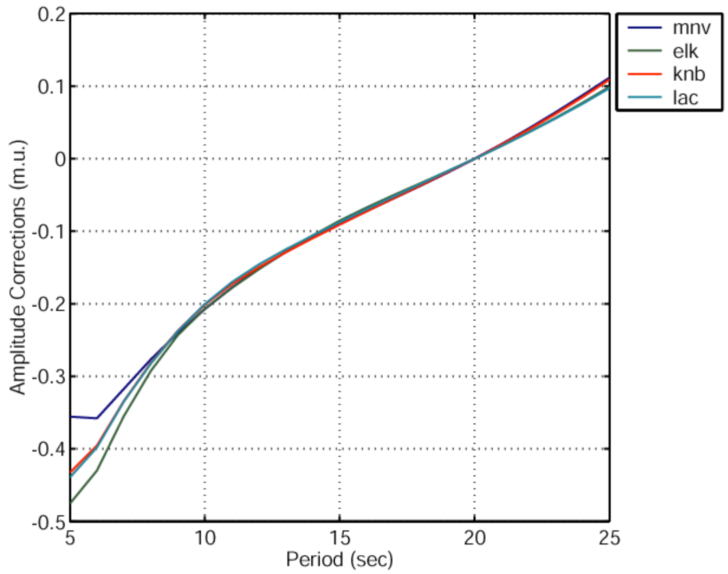


Figure 2. Amplitude corrections for a simulated 1-km deep explosion relative to 20-seconds period. The corrections were estimated using the same Butterworth filters as used on the real data.

VMAX. To obtain a final M_s(VMAX) value for each explosion or earthquake, we average the maximum magnitude at variable periods between 8 and 25 seconds over multiple stations and determine the standard deviation of the observations. Examples of the VMAX methodology applied to four earthquakes and explosions in the western U.S. are shown in Figures 3 and 4. Given in each explosion subplot, the 7-second magnitude estimate (M_s(7)) determined from Bonner et al., (2003) using a regionally-calibrated Marshall and Basham (1972) equation is given. The behavior of the noise (dashed lines in Figure 3) is a motivating factor behind this study. As the events become smaller, the noise and signal-based M_s estimates begin to overlap. For example, for the m_b=4.54 event DEPHINIUM, the noise and signal overlap at periods greater than 15 seconds. Therefore, for small events, we restrict the M_s(VMAX) analysis to periods where the signal is above the background noise levels (e.g., 8-14 seconds for this event). By allowing for the variable-period estimates, we can estimate surface wave magnitudes for smaller events than previous techniques would allow.

Testing the VMAX Methodology in the Western United States

Database. We developed a test dataset consisting of explosions and earthquakes in the western United States. The explosion data are vertical-component, digital broadband seismograms from NTS explosions recorded on two or more stations of the Lawrence Livermore Regional Seismic network (LNN). The LNN network consists of seismic stations at Landers, California (LAC); Mina, Nevada (MNV); Elko, Nevada (ELK); and Kanab, Utah (KNB). The network has been in operation since the 1960s (Figure 1).

M_s (VMAX) for NTS explosions that occurred between December 1968 and September 1992 were estimated. The primary research focus was on the 198 NTS explosions that were detonated after August 1979, for which digital data are available from the LNN stations. Sixty-five (65) of these events have no LNN data available, are plagued by untimely data dropouts and glitches, or are too small for measurable surface wave energy. We also analyzed 21 events prior to July 1979 that were digitized from analog records so that we could compare our new results with previous M_s studies completed by Yacoub (1983), Woods and Harkrider (1995), Marshall et al., (1979), and Stevens and Murphy (2001). We also estimated the M_s and m_b magnitudes for 69 earthquakes whose locations are shown in Figure 5. These events were recorded on various networks in the region; however, we required that at least one LNN station recorded the event so that an unbiased m_b could be measured using the Denny et al., (1987) *Pn* magnitude scale.

***M*$_s$(VMAX) vs *M*$_s$(7).** The M_s (VMAX) measurements for 154 explosions were compared, using the new Russell (2004) time-domain procedure and our variable-period measurement techniques, to the single 7-second period measurements from our previous research (Bonner *et al*., 2003). Figure 6 shows that VMAX explosion magnitudes are approximately 0.25 magnitude units (m.u.) larger than the Marshall and Basham M_s(7) estimates. The slope of the best fit line between the two datasets is approximately equal to 1. The VMAX methodology resulted in a 33%

reduction of the variance for both earthquakes and explosions over the previous single-period techniques based on Marshall and Basham regionally-calibrated $M_s(7)$ estimates. The VMAX techniques offered 47% reduction over the 7-second estimates based on the Rezapour and Pearce (1998) formula.

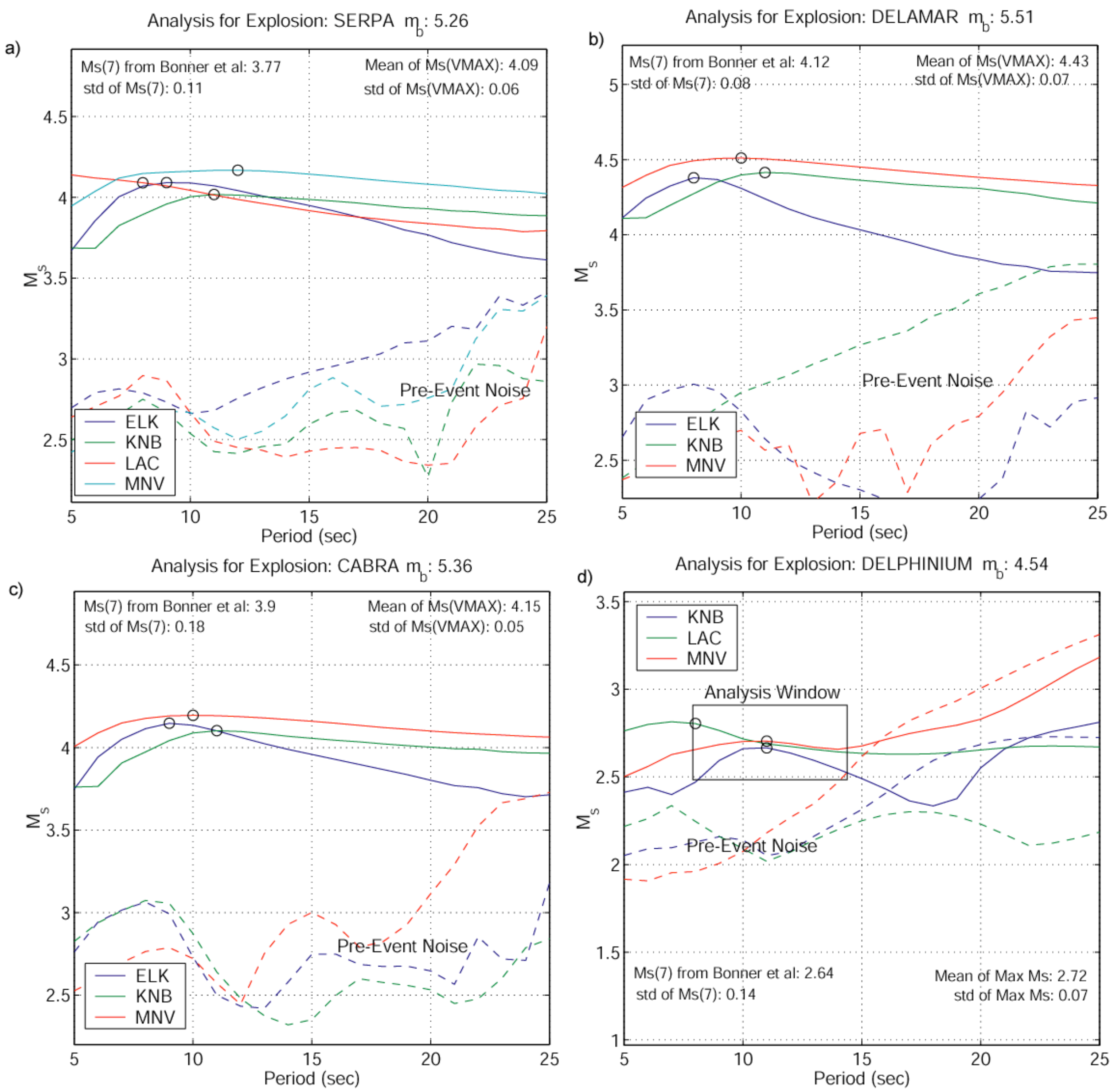


Figure 3. VMAX surface-wave magnitude estimation for NTS explosions (a) SERPA, (b) DELAMAR, (c) CABRA, and (d) DELPHINIUM. Solid lines represent time domain M_s estimates for the surface-wave data plotted as a function of the center period, whereas dashed lines represent similar estimates on pre-event noise data. For the smaller event DELPHINIUM, the noise levels begin to intersect the signal at periods great than 15 seconds, thus we restrict the analysis to 8 to 14 seconds for this event. For comparison, the $M_s(7)$ from Bonner et al. (2003) is listed in each subplot.

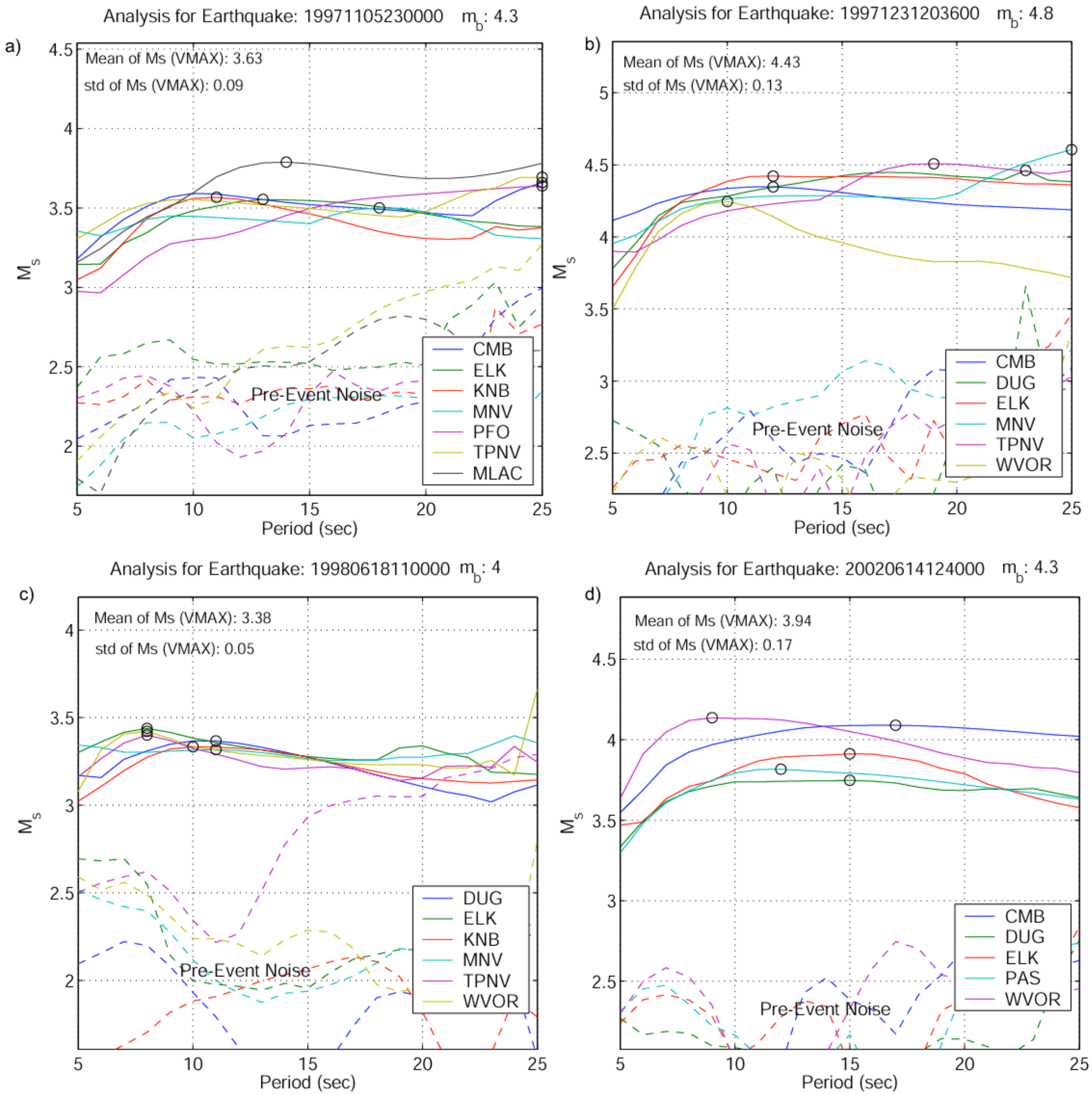


Figure 4. VMAX surface-wave magnitude estimation for four western United States earthquakes. Solid lines represent time domain M_s estimates for the surface-wave data plotted as a function of the center period, whereas dashed lines represent similar estimates on pre-event noise data.

M_s(VMAX) vs. Previous Regional/Teleseismic Studies. Estimating near-regional M_s values for NTS events that can be calibrated to conventional M_s scales is of primary importance to our research. Figure 7 shows the comparison between our M_s(VMAX) estimates taken directly from the regional surface waves with the M_s measurements obtained from a modeling technique derived by Woods and Harkrider (1995), in addition to far-regional/teleseismic data (Yacoub, 1983; Marshall et al., 1979; and Stevens and Murphy, 2001). We note very good agreement to the Woods and Harkrider indirect method of estimating M_s. Woods and Harkrider modeled the surface waves recorded at regional distances, and then propagated the regional synthetics to distances of 40 degrees. At 40 degrees, their synthetics showed significant 20-second surface wave energy, and the authors used a modified von Seggern (1977) formula to measure M_s from the synthetics. We performed a fixed-slope (slope=1) linear regression to compare the M_s(VMAX) values with the Woods and Harkrider (1995) values and found a strong correlation.

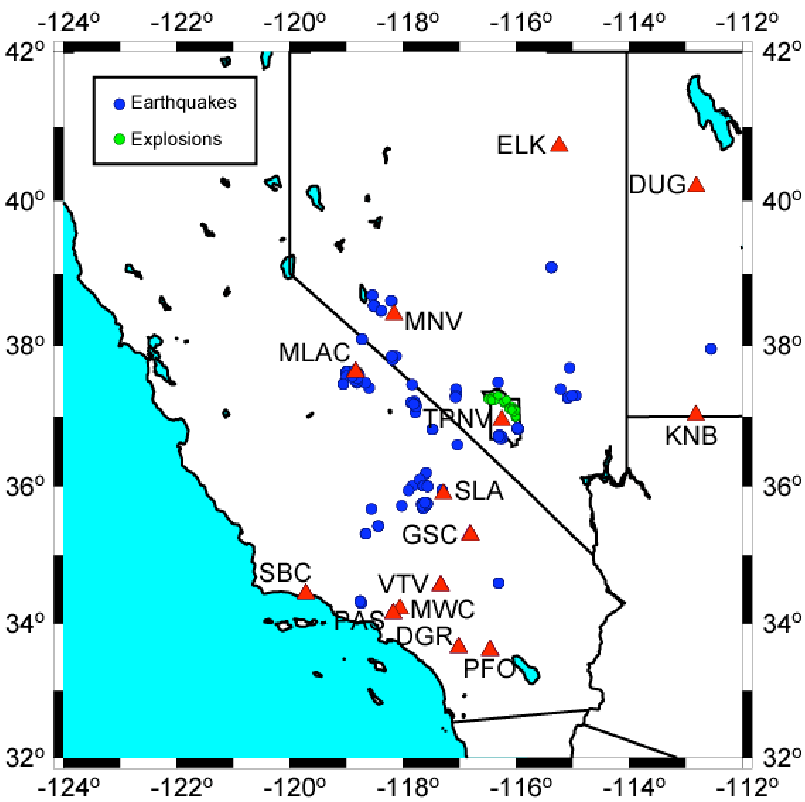
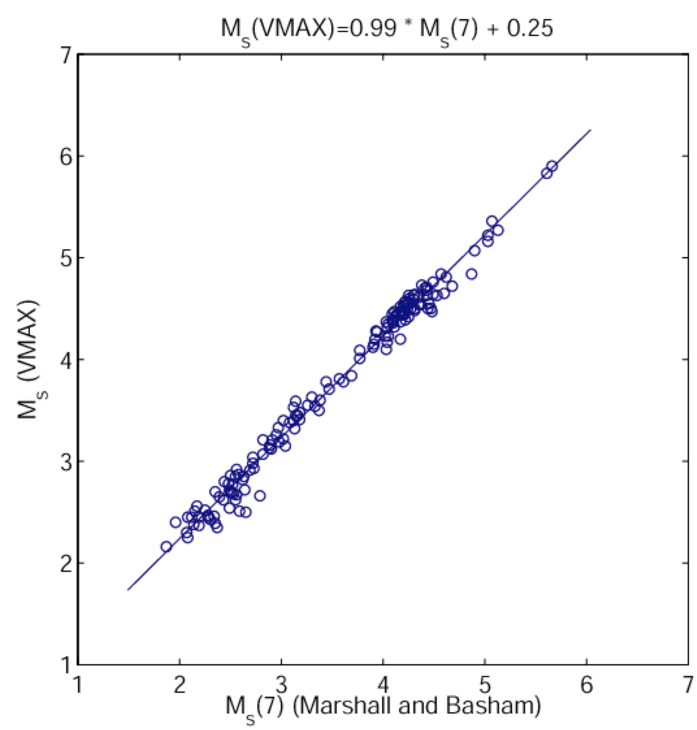


Figure 5. **This test dataset consists of NTS explosions recorded on the LNN dataset together with western United States earthquakes recorded on at least one LNN station and other regional networks.**

Figure 6. ***M_s*(VMAX) magnitude estimates compared to 7-second estimates based on a regionally-calibrated Marshall and Basham formula. The VMAX estimates result in a 33% reduction in variance as compared to the 7-second estimates and are 0.25 m.u. larger.**



The offset shows that the M_s(VMAX) estimates are -0.04 m.u. lower than the Woods and Harkrider (1995) estimates. We also compared the performance of M_s(VMAX) with teleseismic estimates from Yacoub (1983). The results for the comparison with Yacoub (1983) are shown in Figure 7 and indicate similar scaling relationships based on fixed-slope regression analysis. In this case, our M_s(VMAX) is offset from Yacoub's (1983) estimates by approximately +0.1 m.u. M_s(VMAX), which is +0.48 m.u. larger than teleseismic estimates from Marshall et al. (1979; based on the Marshall and Basham formula) and +0.4 m.u. larger than teleseismic/far-regional estimates from Stevens and Murphy (2001; based on the Rezapour and Pearce formula). Differences in these absolute estimates result from the use of different M_s definitions, especially in the attenuation factors. However, these comparisons do show that our estimates scale similarly to other measurements of NTS surface wave magnitudes. For a future study, we hope to further determine the differences in the absolute values of these scales by measuring M_s(VMAX) on the same datasets as used in the previous studies.

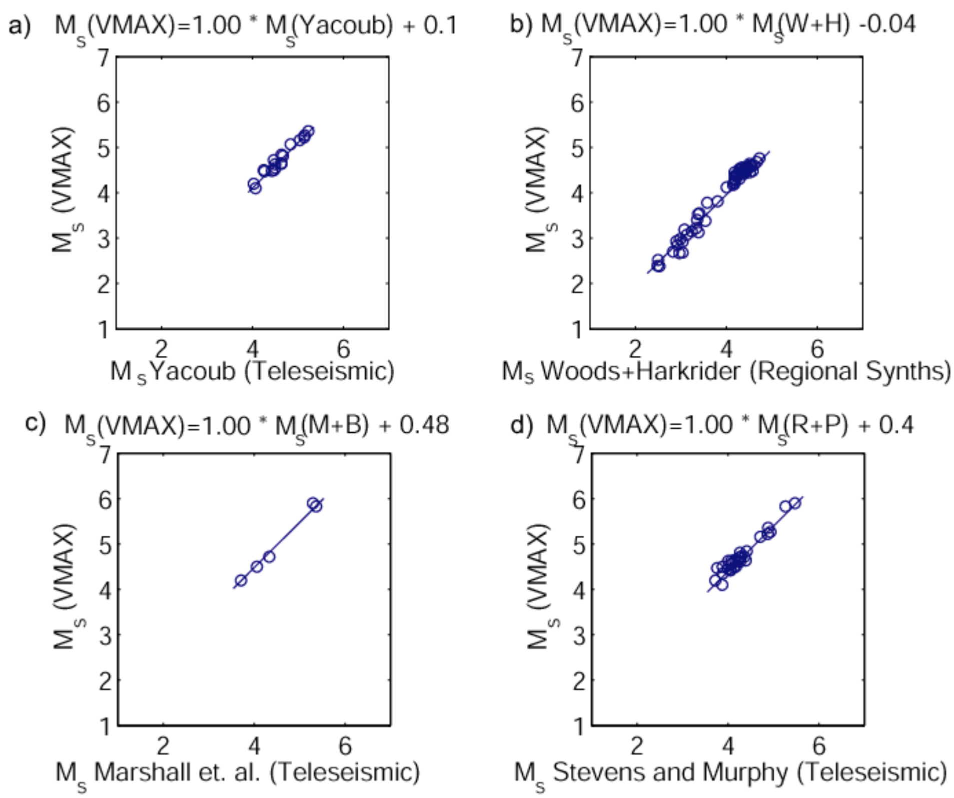


Figure 7. Fixed slope=1 regressions of M_s (VMAX) versus a) Yacoub (1983), b) Woods and Harkrider (1995), c) Marshall *et al.*, (1979), and d) Stevens and Murphy (2001). The best-fitting regression line, with a fixed slope = 1.0, is given by the solid line running through the data points. The offset is referenced in the equation above each plot.

M_s(VMAX) vs m_b. In Figure 8a, we regressed the M_s (VMAX) versus the Denny et al. (1988) m_b for both populations in our test dataset. The best-fitting regression lines are plotted and labeled in the figure and ± 1 standard deviation (σ) is plotted around the average M_s (VMAX). The final objective of this paper is to examine the performance of the M_s(VMAX)-m_b discriminants for earthquakes and explosions. The populations plotted in Figure 8a 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. Although, we did observe slightly different slopes in the regression analyses for the two populations, we believe that this is caused by 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. If d < -2.45, the event will reside in the explosion population. This does not require the event to be a nuclear explosion, as noted, and additional testing is needed to ensure the event is shallow enough to be a candidate explosion. If d > 2.45, the event falls into the earthquake classification. We note that no explosions were misclassified as earthquakes using the VMAX magnitude estimation technique with the Russell (2004) surface-wave magnitude scale. One earthquake was misclassified in the explosion population. In our previous studies based on 7-second data, four earthquakes were misclassified as explosions and two explosions as earthquakes.

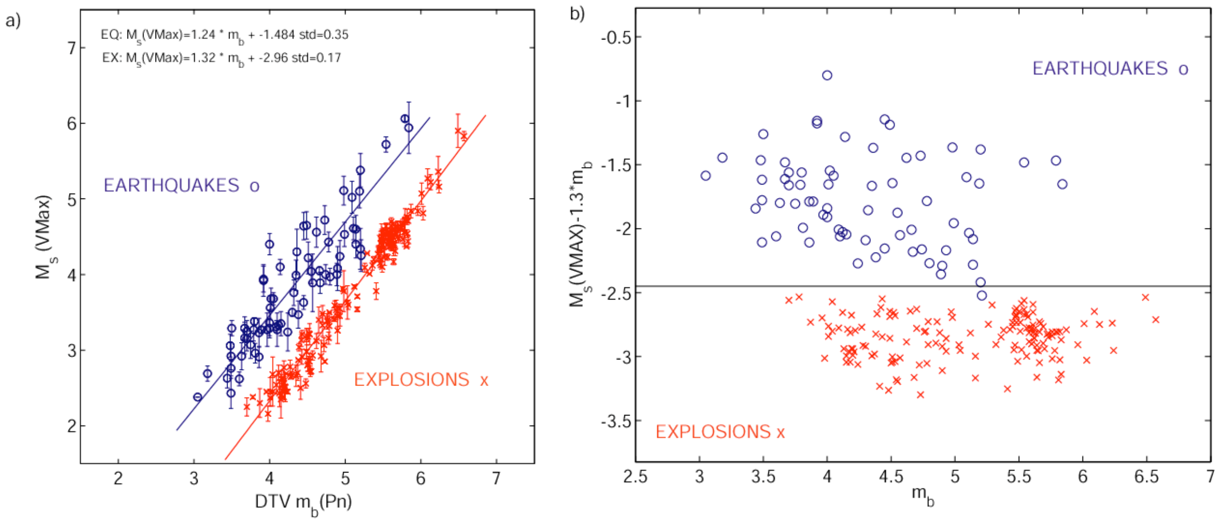


Figure 8. Discrimination results for M_s (VMAX). a) M_s (VMAX) vs. m_b for western United States earthquakes and nuclear explosions. b) Linear discrimination of the two datasets showing the decision line for classifying an event as a possible nuclear explosion. If d=M_s (VMAX) – 1.3m_b is less than -2.45, the event may be an explosion, and as a result may require additional analysis to prove the event is not a deep and/or anomalous earthquake.

Regional vs. Teleseismic. In future work, we will analyze whether there are biases in the M_s(VMAX) measurement technique when regional and teleseismic data are combined. Equation 1 should theoretically have no regional to telseseismic biases, unless there are changes to the attenuation models at greater distances. In these cases, a variant of Equation 1 has been defined by Russell (2004) so that a known frequency-dependent attenuation model can be applied. In the current study, we are using Equation 1 to determine if regional and teleseismic magnitudes estimated using the VMAX technique are equivalent. An example of the analysis to be completed is shown in Figure 9. In this example the regional and near-teleseismic magnitudes agree to within 0.1 m.u. However, we note that the period of the maximum magnitudes may be distance dependent. Additional analyses, including data at epicentral distances of 60 degrees and less, will be completed to quantify possible biases and better understand the behavior of our method.

CONCLUSIONS AND RECOMMENDATIONS

The results presented in this paper suggest that the 33% decrease in variance offered by the new Russell surface-wave magnitude formula, combined with the VMAX estimation technique, offers improved discriminant performance at the NTS over our previous 7-second magnitude estimation techniques. Additionally, using the Russell equations and the variable-period VMAX technique will allow flexibility when we examine the transportability of this method at other test sites, particularly in regions where the events may be deeper than the earthquakes near NTS. During the next two years, we will continue extensive testing of these techniques using a dataset of Eurasian explosions and earthquakes as part of a joint project with LLNL.

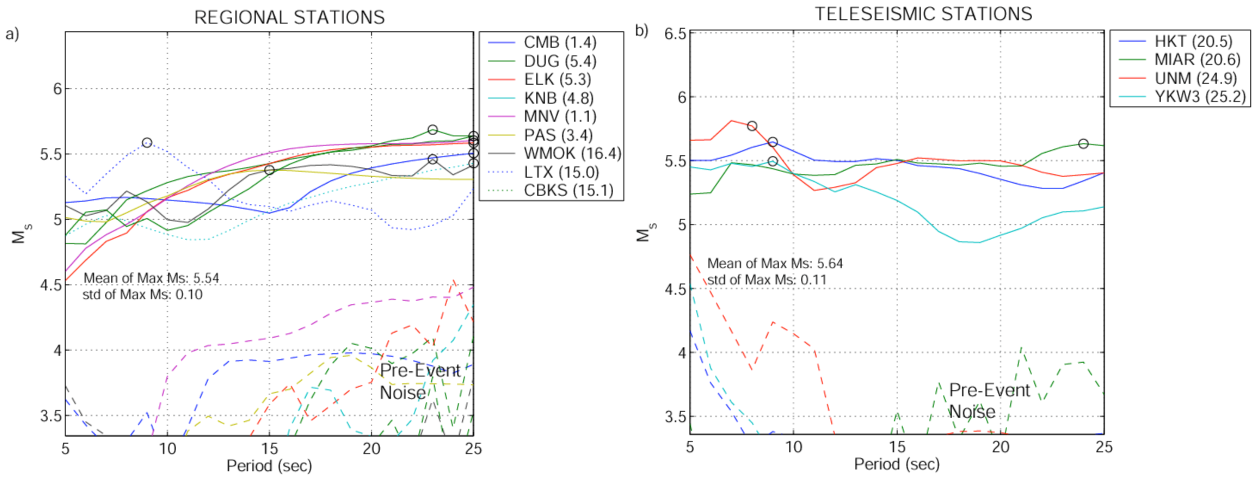


Figure 9. M_s(VMAX) comparison for regional and near-teleseismic data. a) M_s(VMAX)=5.54 (σ=0.1) for a nine-station regional network recording of an m_b=5.1 western United States earthquake. b) M_s (VMAX)=5.64 (σ=0.11) determined from four near-teleseismic records of the same event. Epicentral distance (in degrees) is provided next to each station name in the legend.

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