IMPROVING M_s:m_b DISCRIMINATION USING MAXIMUM LIKELIHOOD ESTIMATION: APPLICATION TO MIDDLE EAST EARTHQUAKE DATA

Anastasia Stroujkova and Jessie L. Bonner

Weston Geophysical Corporation

Sponsored by the National Nuclear Security Administration

Contract No. DE-AC52-04NA25547
Proposal No. BAA04-63

ABSTRACT

During this project, we have combined the Russell (2006) surface wave magnitude (M_s) formula and the M_s(VMAX) measurement technique (Bonner et al., 2006) for improved event discrimination at regional and teleseismic distances. The MATLAB-based processing program is called EVALSURF and includes Rayleigh-wave detection algorithms and phase match filtering using the Pasyanos (2005) group-velocity models. The program has been applied to earthquakes and explosions in Eurasia and offered improved earthquake screening performance compared to other well known formulas. We used EVALSURF to evaluate the anomalous M_s from the 2006 North Korean nuclear explosion (Bonner et al., 2008) and have applied it to the larger 2009 event. For the final year of our project, we are researching new methods for improving M_s-m_b discrimination for earthquakes and explosions.

The Maximum Likelihood Estimate (MLE) was proposed by Ringdal (1976) to reduce the network bias due to non-detection. We estimated the M_s *(VMAX)* magnitudes for approximately 100 seismic events located in the Middle East using MLE approach and compared the results with conventional-averaged estimates. To evaluate the performance of the method, we tested it using a set of simulated events recorded by the network with an assigned magnitude close to a threshold value. In our simulation experiments, we chose the same number of the events and the same station distribution as in our Middle East dataset. We found that the bias introduced by the averaging depends on the standard deviation of the inter-station M_s*(VMAX)* measurements. The bias is increasing as M_s *(VMAX)* decreases below 4 m.u., which represents the upper bound for the station magnitude thresholds.

An important part of the MLE application is evaluation of the detection thresholds for the stations used for the magnitude estimation. The threshold values for each station could be estimated using a “noise magnitude” for each event-station pair using the broadband ambient noise estimates for the Global Seismographic Network (GSN) e.g., Berger et al., (2004). A different way to assign the threshold values is to find the smallest magnitude actually detected by each station. In this article we estimated the detection threshold using both techniques and obtained similar results with both methods.

Finally, we applied the MLE estimate to the Middle East event dataset. We found significant differences between the conventional averaging and the MLE estimates for the magnitudes near the detection threshold for most of the stations (< 4 m.u.). The MLE estimates above M_s *(VMAX)* > 4 m.u. are identical to the results of the averaging.

OBJECTIVES

Developing a methodology for calculating surface wave magnitudes that is valid at both regional and teleseismic distances, applicable to events of variable sizes and signal-to-noise ratios, calibrated for variable structure and propagation, and easy to automate in an operational setting, is an important monitoring goal. Our objectives are to create such a methodology, and to use it to lower M_s estimates and detection thresholds. We hope that the method will provide a seamless tie between M_s estimates at regional and teleseismic distances.

To accomplish our objectives, we developed the Matlab program EVALSURF (Bonner et al*.,* 2006) , which estimates variable-period (8 < T < 25 sec; recently updated to 40 sec) Rayleigh-wave magnitudes using the Russell (2006) and M_s(VMAX) measurement technique (Bonner et al*.*, 2006) for comparison to the historical formulas of Marshall and Basham (1972) and Rezapour and Pearce (1998). The program uses the updated Lawrence Livermore National Laboratory group velocity models for Eurasia (Pasyanos, 2005) to identify, phase match filter, and extract the fundamental-mode Rayleigh waves for analysis. During the past year, we have determined a methodology to estimate the M_s detection thresholds for European and Asian GSN stations as well as estimating Maximum Likelihood Estimates of magnitudes.

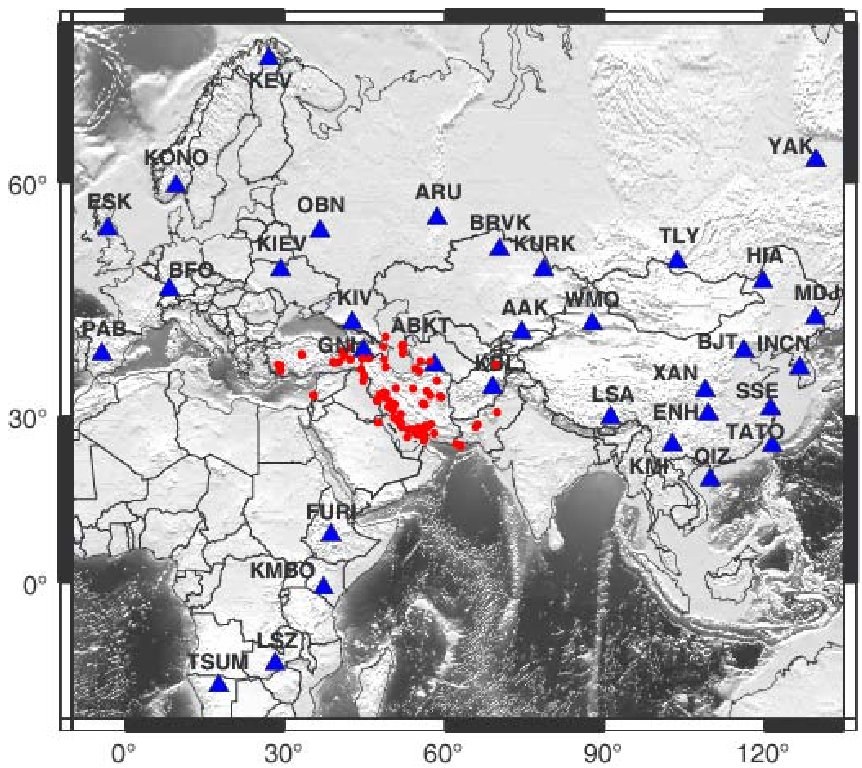

Figure 1. Map of the seismic events (red circles) and stations (blue triangles) used for M_s *(VMAX)* study.

RESEARCH ACCOMPLISHED

M_s (VMAX) or Variable-period, MAXimum amplitude magnitude estimates is a time-domain technique for determining surface wave magnitudes at variable periods between 8 and 25 s using both regional and teleseismic waves (e.g., Russell, 2006; Bonner et al., 2006):

$$M_s = \log(a_b) + \frac{1}{2}\log(\sin(\Delta)) + .0031\left(\frac{T_0}{T}\right)^{1.8}\Delta - \log(f_c) - 0.43 - 0.66\log\left(\frac{20}{T}\right) \qquad (1)$$

where a_b is the amplitude of the Butterworth-filtered surface waves (zero-to-peak in nanometers), f_c is the filter frequency of a zero-phase Butterworth band-pass filter with corner frequencies ($1/T- f_c$, $1/T+ f_c$), T=20 sec is the reference period. For variable periods 8 sec < T < 25 sec, the equation is corrected to T=20 sec, accounting for source effects, attenuation, and dispersion.

Previously we computed M_s (VMAX) for over 100 seismic events located in the Middle East region (Figure 1) with reported body wave magnitudes (m_b) between 3.8 and 5.6 (NEIC). We extended the period range to 40 s to improve magnitude estimation for larger or deeper events. During this reporting period we compared the magnitude estimation using conventional averaging between the individual station magnitude measurements and the Maximum Likelihood Estimation (e.g. Ringdal, 1976).

Maximum Likelihood Magnitude Estimate

Using the Maximum Likelihood Estimate (MLE) to reduce the network bias due to non-detection was proposed by Ringdal (1976). Generalization of this procedure to include data clipping was proposed by von Seggern and Rivers (1978). The network magnitude bias is caused by the loss of information from non-reporting stations. For small and intermediate size events this means that the stations with the magnitude measurements below a certain threshold may not report the signal and therefore get ignored. This effect is called “censoring”. A number of studies have shown that the magnitude bias could be significant, particularly for the events close to the detection threshold (Ringdal, 1976; Evernden and Kohler, 1976).

The MLE method is based on the assumption that for a given event the magnitude estimates follow a Gaussian distribution with unknown mean and variance $M_s \sim N(\mu, \sigma)$. We assume that an event is detected by a station if the station magnitude exceeds a certain threshold magnitude a_i ($i = 1,\ldots, n$), where n is a number of the stations in the network. Ringdal (1976) provided an expression for the maximum likelihood estimate of an event magnitude with a true magnitude μ:

$$L(m_1 ... m_n / \mu, \sigma) = \prod_{i, m_i > a_i} \frac{1}{\sigma} \phi\left(\frac{m_i - \mu}{\sigma}\right) \prod_{j, m_j < a_j} \Phi\left(\frac{a_j - \mu}{\sigma}\right), \tag{2}$$

where ϕ and Φ are the Gaussian PDF and CDF respectively. This expression is maximized numerically in order to obtain a maximum likelihood estimate of the magnitude μ.

The threshold values for each station a_i could be estimated using “noise magnitude” for each event-station pair. We converted the broadband ambient noise estimates for the Global Seismographic Network (GSN, e.g., Berger et al., 2004) from decibels to nanometers (nm) and input them into the M_s (VMAX) formula (1) for variable-period surface waves. We propagated these noise estimates at periods (T) between 8 and 40 s to distances Δ corresponding to each earthquake-station pair. Table 1 (columns 3-6) shows the estimates of the magnitude threshold for a representative event in the region (2006.06.03).

A different way to assign the threshold values is to find the smallest magnitude actually detected by each station. In this article, we follow the work of Ringdal (1976), who found the thresholds by averaging over the three smallest detected magnitudes. The second column in Table 1 (in Appendix A) shows the values estimated using this approach. Figure 2 shows the correspondence between the estimates made with different methods for different periods for the stations with both estimates available. The magnitude thresholds show the best agreement for the period T=20 sec (blue circles). Notice that a different set of stations was used for the thresholding application. The threshold values using the minimum M_s (VMAX) approach are missing for the stations with not enough M_s (VMAX) measurements to obtain a reliable threshold. Some of the noise floors were not reported, which resulted in missing values in columns 3-6 of Table 1.

An important issue to consider is which stations should be added to MLE estimates as censored values. In practice selection of the stations for threshold Ringdal (1986) divided all stations into: a) detecting stations, b) non-detecting stations due to noise; and c) non-detecting stations due to maintenance issues. For the third group of stations, Ringdal suggests computing the probabilities of each station of being off-line and adding them randomly. We, however, only used the reporting stations to use as either measured or a censored (threshold) value.

Another issue, mentioned in Ringdal (1986) is the increase of noise due to special circumstances, such as time intervals coinciding with large events and their aftershocks overlapping with the event in question. In this case we did not estimate the magnitudes even though they were significantly above the detection threshold. These events require special attention, for instance using the information about the noise amplitude just before the event to establish the detection threshold.

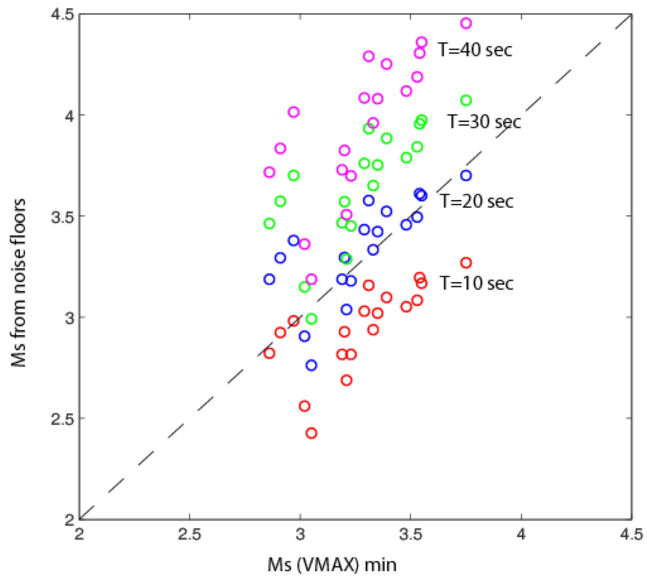

Figure 2. Comparison of the magnitude thresholds computed with different methods with each circle corresponding to one station having both threshold values defined in Table 1. Horizontal axis: detection threshold computed by averaging 3 lowest magnitudes actually detected by the station (Ringdal, 1976); vertical axis: detection threshold computed using the noise floors for different periods for a representative event (2006.06.03). The best agreement (dashed line) is for T=20 sec.

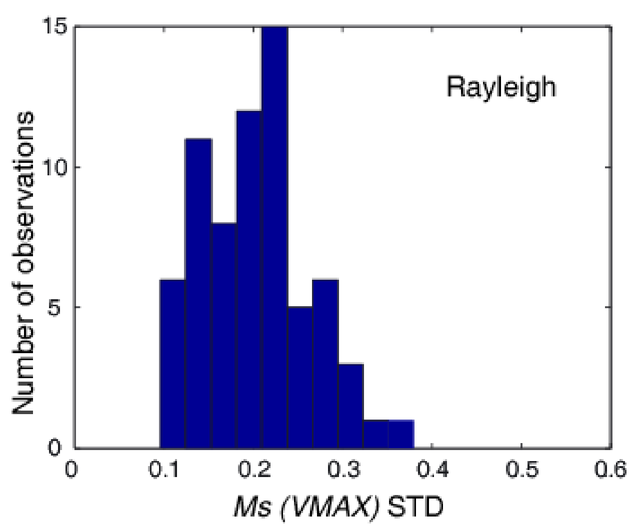

Figure 3. Histogram of M_s (VMAX) RMS residuals for nearly 100 events located in the Middle East.

It was noted by Ringdal (1976) that the estimate of the true magnitude μ depends on the inter-station magnitude variance σ. Figure 2 shows the histogram of M_s (VMAX) RMS residuals for the Middle East dataset with the mean values of approximately 0.2. To evaluate the performance of the method for our dataset, we created a set of simulated events recorded by the network with an assigned magnitude close to a threshold value. In our simulation experiments, we chose the same number of the events and the same station distribution as in our Middle East dataset. The individual station magnitudes for each event were normally distributed with the variance of $\sigma = 0.2$. We used the threshold magnitudes estimated using both methods shown in Table 1.

The synthetic testing of the MLE algorithm was implemented as follows. For a fixed magnitude value μ we generated a set of station measurements with normal distribution of the measurement errors $N(\mu, \sigma)$. For the measurement standard deviation we used the value $\sigma = 0.2$ obtained for our dataset. In addition we performed the simulations with $\sigma = 0.4$, which was used in the earlier simulations by Ringdal (1976) based on the work by Veith and Clawson (1972). For each of the n stations of each hypothetical event we determined detection/no detection, by comparing m_i and a_i. All the stations with $m_i < a_i$ were designated as non-detections and removed from the averaging magnitude estimate. Then we estimated network event magnitude using the conventional averaging over all stations detected the event, and by maximizing the likelihood function using both detecting and non-detecting stations.

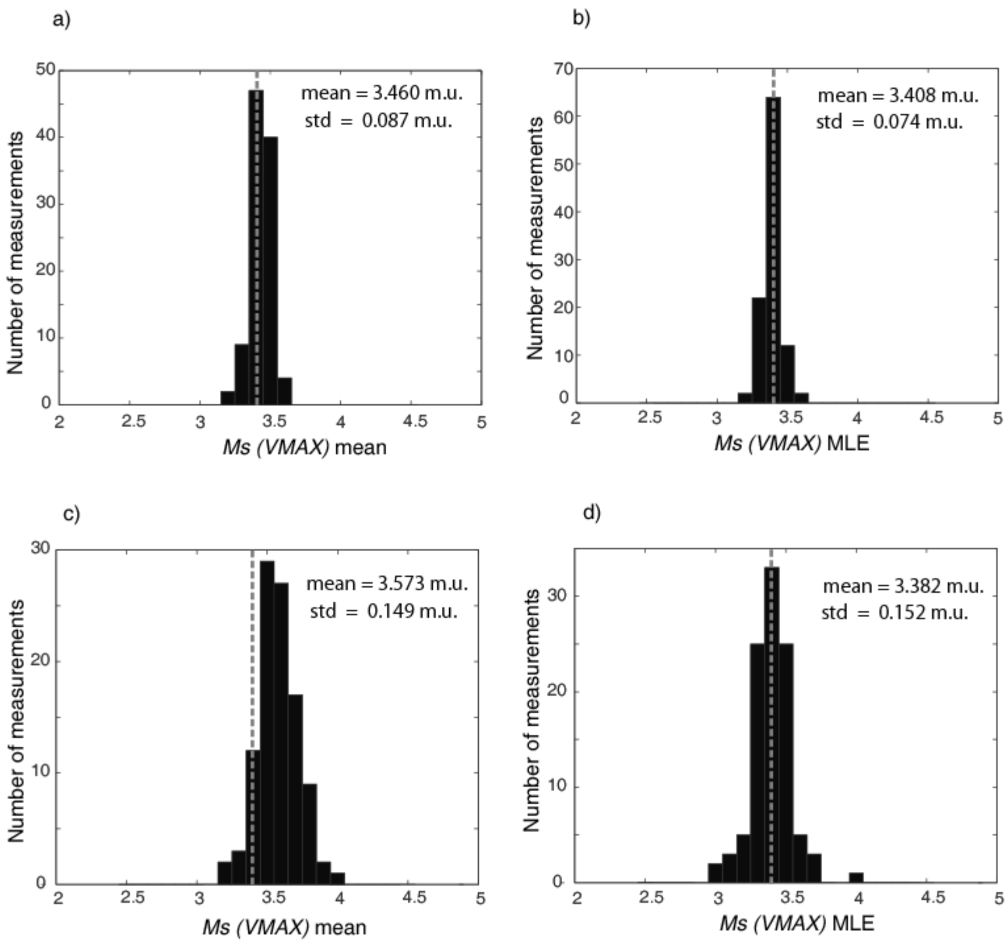

Figure 4. Histograms of M_s (VMAX) estimates for 100 synthetic events with M_s *(VMAX)* =3.4 and the same reporting station distribution as in the Middle East dataset. a) M_s *(VMAX)* estimated as a mean value of the station measurements with σ=0.2; b) M_s *(VMAX)* estimated using MLE approach with station measurement σ=0.2; c) M_s *(VMAX)* estimated as a mean value of the station measurements with σ=0.4; b) M_s *(VMAX)* estimated using MLE approach with station measurement σ=0.4.

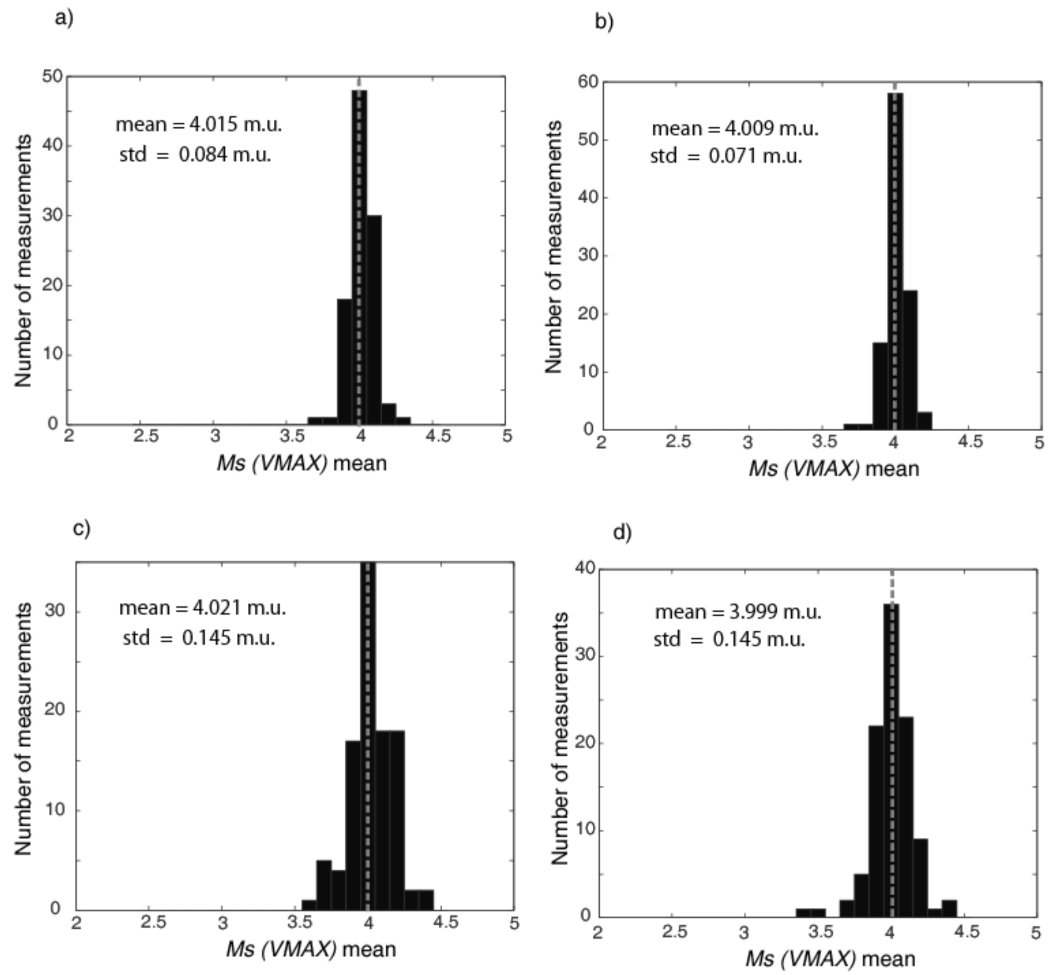

Figure 5. Histograms of M_s (VMAX) estimates for 100 synthetic events with M_s *(VMAX)* =4.0 and the same reporting station distribution as in the Middle East dataset. a) M_s *(VMAX)* estimated as a mean value of the station measurements with σ=0.2; b) M_s *(VMAX)* estimated using MLE approach with station measurement σ=0.2; c) M_s *(VMAX)* estimated as a mean value of the station measurements with σ=0.4; b) M_s *(VMAX)* estimated using MLE approach with station measurement σ=0.4.

The results of both estimates are shown in Figures 4 and 5. Figure 4 shows the histogram of the estimates for the true magnitude $\mu = 3.4$. This value is below or close to the detection threshold for several stations (Table 1); therefore we expect the conventional averaging estimates to have relatively large network bias. For example, Figures 4a and 4c show the histograms of the M_s (VMAX) estimates using the conventional average (Figure 4a) and the MLE technique (Figure 4b) for the measurement $\sigma = 0.2$. The mean value of the recovered magnitude values is 3.460 (compare with $\mu = 3.4$) using the averaging, and 3.408 using the MLE approach. Thus the bias is 0.06 in the former case and 0.008 in the latter case. The bias is more pronounced if the larger value of the measurement error is used (e.g. $\sigma = 0.4$, Figure 4c and 4d). In this case the magnitude estimate bias is 0.173 for the conventional averaging and -0.018 for the MLE approach. However the bias is not as significant as obtained by Ringdal (1976), probably because in this study we used larger station network. Only 13 stations were used in the Ringdal (1976) study.

Figure 5 shows the distribution of the estimated magnitudes for $\mu = 4.0$. This value is higher than the detection threshold for all stations, so there is not a significant difference between the average and the MLE estimation. Even in case of larger inter-station variance the bias of the conventional averaging estimate is relatively small (0.015-0.021 m.u.).

Application of MLE Technique to the Middle East Dataset

We estimated M_s (VMAX) using a standard approach (station average) and an MLE approach for the Middle East dataset discussed earlier. For the earthquake dataset we used a slightly different thresholding approach than was used for the synthetic dataset. For the synthetic data, all the measured values below the threshold values a_i were replaced with the threshold values and marked as "censored". For the real dataset, some of the measured values were below threshold, in which cases we used the measured values. For the events with the magnitudes significantly larger than the threshold magnitude with missing stations due to unusually high noise, we didn't use the threshold values if the average magnitude exceeded the threshold value by more than 0.6 m.u., which corresponds to a standard error multiplied by 3.

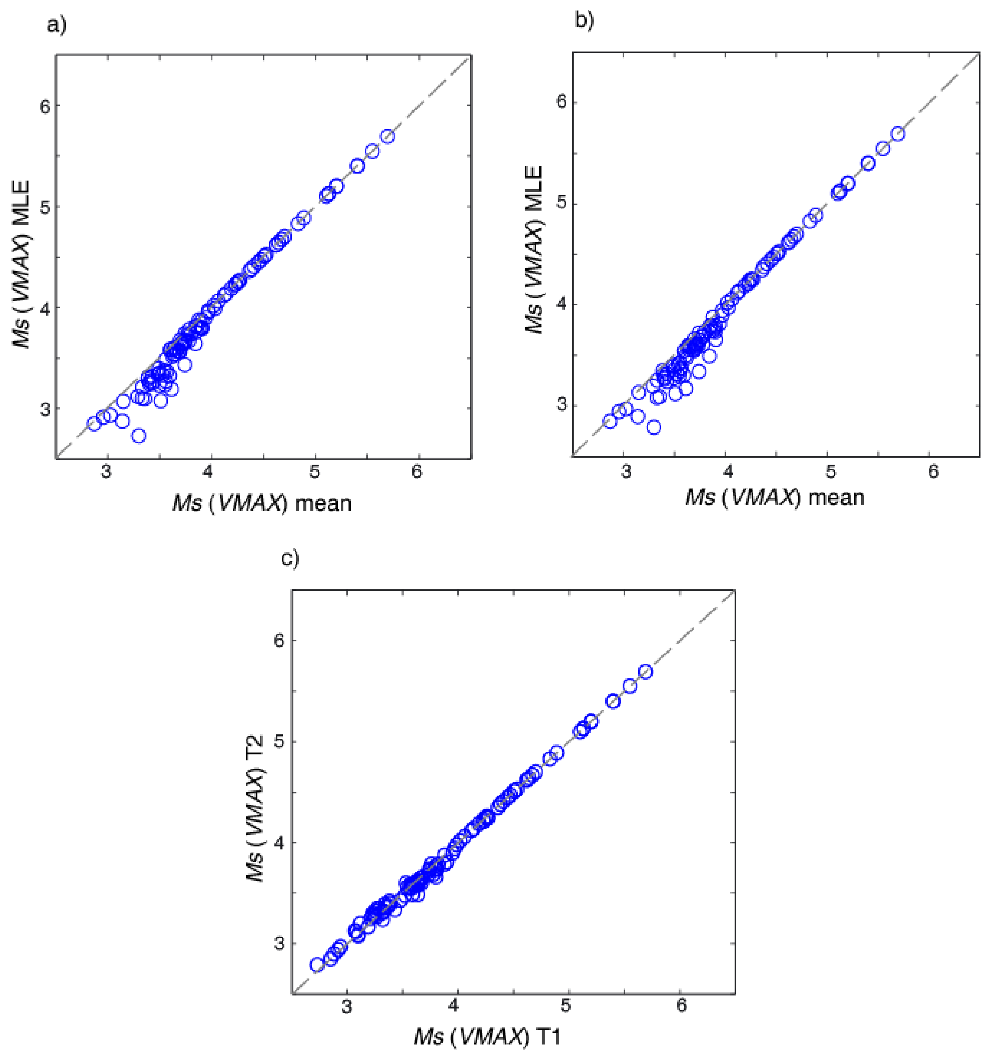

Figure 6. Comparison between the mean and the MLE estimates of the M_s *(VMAX)* applied to the Middle East event dataset: a) using minimum detected magnitude threshold; b) using noise magnitude approach; c) cross-plot between the two MLE estimates with different threshold definitions (T1 as in (a) and T2 as in (b)).

Figure 6 shows the cross-plot between the mean and the MLE estimate of M_s *(VMAX)*. We repeated both estimates using the two types of the station threshold estimates, shown in Table 1. Figure 6a shows the results using the minimum magnitude approach, while Figure 6b shows the MLE estimate using the station noise floor approach. Both thresholding approaches produce similar results as shown in Figure 6c; however, there are some differences between the individual events. As mentioned earlier, different sets of stations were used to generate the censored values due to data availability. Above the magnitude of approximately 4.1 both MLE and conventional estimates are essentially equal. Below this point there is a significant positive bias for the conventional network average estimate. In addition, the events occurring during high-noise time intervals, such as large earthquakes and their aftershock sequences require special consideration and should be processed with caution.

CONCLUSIONS AND RECOMMENDATIONS

MLE technique was developed to reduce the network magnitude estimation bias for magnitudes near the detection threshold. We evaluated the detection thresholds for the series of stations used for the magnitude estimation in the Middle East. Most of the stations used in this study are located in the Eurasia, and several stations are located in Africa. We evaluated performance of the MLE estimate using a simulated dataset with magnitudes close to a network detection threshold magnitude. The bias due to non-detections is somewhat smaller than the bias estimated in Ringdal (1976). We attribute it to a larger number of stations used in this study.

We estimated the M_s *(VMAX)* magnitudes using MLE approach and compared it with conventional averaged estimates for the dataset consisting of approximately 100 events located in the Middle East. The major differences between the two estimates are observed for the magnitudes smaller than 4.

Future work will include application of the MLE approach to Love waves. We are also going to continue research on the different ways to find and apply station magnitude thresholds, and to evaluate network detection capabilities.

ACKNOWLEDGEMENTS

We wish to thank Drs. Robert Shumway and David Russell for insightful discussions concerning this project. We also thank Peter Davis for providing us with the GSN noise curves used in this study. We are grateful to Jim Lewkowicz for his continued support.

REFERENCES

Berger, J., P. Davis, and G. Ekstrom (2004). Ambient earth noise: a survey of the Global Seismographic Network, *J. Geophys. Res.* 109: B11307.

Bonner, J. L., D. Russell, D. Harkrider, D. Reiter, and R. Herrmann, (2006). Development of a Time-Domain, Variable-Period Surface Wave Magnitude Measurement Procedure for Application at Regional and Teleseismic Distances, Part II: Application and M_s—m_b Performance. *Bull. Seism. Soc. Am.* 96*:* 678–696.

Bonner, J., R. B. Herrmann, and H. Benz (2008). Rapid estimates of seismic moment using variable-period surface-wave magnitudes. *Seism. Res. Letts.* 79: 349.

Engdahl, E. R., J. Jackson, S. Myers, E. Bergman, and K. Priestley (2006). Relocation and assessment of seismicity in Iran region, *Geophys. J. Int.* 167: 761–778.

Evernden, J. F., and W. M. Kohler (1976). Bias in Estimates of mb at small magnitudes, *Bull. Seism. Soc. Am.* 66: 3, 1887–1904.

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

Pasyanos, M. E. (2005). A variable-resolution surface wave dispersion study of Eurasia, North Africa, and surrounding regions, *J. Geophys. Res.* 110: No. B12, B12301 10.1029/2005JB003749.

Rezapour, M., and R.G. Pearce, (1998). Bias in surface-wave magnitude M_s due to inadequate distance correction. *Bull. Seism. Soc. Am.* 88: 43–61.

Ringdal, F. (1976). Maximum-Likelihood Estimation of Seismic Magnitude, *Bull. Seism. Soc. Am.* 66: 3, 789–802.

Ringdal, F. (1986). Study of magnitudes, seismicity, and earthquake detectability using a global network, *Bull. Seism. Soc. Am.* 76: 6, 1641–1659.

Russell, D. R. (2006). Development of a time-domain, variable-period surface wave magnitude measurement procedure for application at regional and teleseismic distances, part I: theory, *Bull. Seism. Soc. Am*. 96: 2, 665–677.

Veith, K. F. and G. E. Clawson (1972). Magnitude from short-period *P*-wave data, *Bull. Seism. Soc. Am.* 62: 435–452.

von Seggern, D. and D. W. Rivers (1978). Comments on the use of truncated distribution theory for improved magnitude estimation, *Bull. Seism. Soc. Am.* 6: 1543–1546.

Table 1. Comparison of the magnitude threshold values computed using the two approaches described in the article. The omitted threshold values in the column 2 mean that there was not enough M_s (VMAX) measurements to obtain a reliable threshold. The values in the columns 3-6 were skipped for the stations for which the noise floors were not reported.

Station	Minimum M_s (VMAX)	Magnitude thresholds computed for the event 2006.06.03			
		T=10 sec	T=20 sec	T=30 sec	T=40 sec
AAK	3.21	2.69	3.04	3.29	3.51
ABKT	-	2.40	2.73	2.94	3.12
ANTO	2.94	-	-	-	-
ARU	3.20	2.93	3.30	3.57	3.83
BFO	3.33	2.94	3.33	3.65	3.96
BJT	3.54	3.20	3.61	3.96	4.31
BRVK	3.23	2.82	3.18	3.45	3.70
ENH	3.48	3.05	3.46	3.79	4.12
ERM	-	3.24	3.70	4.11	4.55
ESK	3.53	3.08	3.50	3.84	4.19
FURI	-	2.78	3.14	3.39	3.62
GNI	3.05	2.43	2.76	2.99	3.19
GRFO	3.19	-	-	-	-
GUMO	-	3.07	3.55	4.01	4.50
HIA	3.31	3.16	3.58	3.93	4.29
INCN	3.55	3.17	3.60	3.97	4.36
KBL	2.78				
KBS	3.39	3.10	3.52	3.88	4.25
KEV	3.35	3.02	3.42	3.75	4.08
KIEV	3.19	2.82	3.19	3.47	3.73
KIV	3.02	2.56	2.91	3.15	3.36
KMBO	3.51	-	-	-	-
KMI	-	3.03	3.42	3.74	4.05
KONO	3.29	3.03	3.43	3.76	4.08
KURK	2.86	2.82	3.19	3.46	3.72
LSA	2.91	2.92	3.29	3.57	3.83
LSZ	-	3.26	3.67	4.01	4.35
MDJ	-	3.13	3.57	3.95	4.33
OBN	-	2.83	3.21	3.49	3.75
PAB	-	3.07	3.48	3.83	4.18
PMG	-	3.48	3.99	4.49	5.03
QIZ	-	3.14	3.56	3.90	4.24
SSE	-	3.09	3.51	3.88	4.25
SUR	-	3.33	3.78	4.19	4.61
TATO	-	3.20	3.63	4.00	4.38
TLY	2.97	2.98	3.38	3.70	4.02
TSUM	3.75	3.27	3.70	4.07	4.45
WMQ	-	2.85	3.22	3.49	3.75
XAN	-	3.07	3.48	3.81	4.13