A COMPARISON OF DIFFERENT SURFACE WAVE MAGNITUDE FORMULAS ON A EURASIAN DATASET

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Sponsored by National Nuclear Security Administration
Office of Nonproliferation Research and Development
Office of Defense Nuclear Nonproliferation

Contract Nos. DE-AC52-04NA25547[1] and W-7405-ENG-48[2]

ABSTRACT

One of the most robust methods for discriminating between explosions and earthquakes is the relative difference between the body wave (m_b) and surface wave (M_s) magnitudes for a seismic event. Most M_s formulas have been developed for teleseismic distances and for Rayleigh waves in the period range of 17–23 s. For earthquakes of small-to-intermediate magnitude and explosions recorded at regional distances, the amplitudes of Rayleigh waves in this period range may be below background noise levels; however, shorter period surface waves (< 15 s) may still be extracted and processed using phase-match filtering. Thus, calibrated and transportable formulas, which allow for estimation of M_s at regional distances at the period of maximum amplitude (between 5 and 25 s), can be used to lower the M_s thresholds for small earthquakes and explosions in Europe and Asia. Additionally, these calibrated formulas may be able to significantly reduce the variance in M_s estimates for larger events in the region.

During the past year, we have continued our research into improving M_s measurements. We have developed *evalsurf*, a Matlab program that estimates variable-period magnitudes using the Russell (2006) and M_s Variable-Period, Maximum Magnitude Estimation (VMAX) measurement technique (Bonner et al. 2006) and compares these magnitudes to the popular formulas of Marshall and Basham (1972) and Rezapour and Pearce (1998*). Evalsurf* uses the updated Lawrence Livermore National Laboratory (LLNL) group velocity models (Pasyanos, 2005) to phase-match filter the fundamental mode Rayleigh waves. The models are also used to ensure that the signal passes a dispersion test prior to processing the event for a magnitude. A backazimuth test must also be passed before estimating the M_s (VMAX), Marshall and Basham (1972), and Rezapour and Pearce (1998) magnitudes.

We have applied the program to 240 Eurasian earthquakes recorded on 1 to 21 stations at distances of up to 7,000 km. The M_s(VMAX) and Marshall and Basham surface wave magnitudes were measured at periods between 8 and 25 s and 10 and 40 s, respectively. The Rezapour and Pearce magnitudes were estimated at periods between 18 and 22 s in order to closely mimic processing routines at the International Data Center. We used the Murphy et al. (1997) screening criterion for M_s—m_b to determine the percentage of single-station estimates that screened as earthquakes by each technique. Out of 2,484 station-source pairs, we screened 95.7%, 93.8%, and 89.3% using M_s(VMAX), Marshall and Basham, and Rezapour and Pearce, respectively. We note that for our smaller explosion population (102 estimates), each technique had the same number of single-station estimates that screened as earthquakes: three. For network-averaged magnitudes, there were no misclassified nuclear explosions for any of the three techniques. The M_s(VMAX) technique showed the smallest average interstation standard deviation (0.22 m.u.) followed by the Marshall and Basham (0.26 m.u.) and Rezapour and Pearce (0.27 m.u.) methods.

These results suggest that the M_s(VMAX) technique provides optimal earthquake screening in our Eurasian study region. During the final year of this project, we will develop M_s threshold maps for regions of monitoring concern using the variable-period M_s(VMAX) formula and improved signal processing techniques.

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 estimation and detection thresholds. We hope that the method will provide a seamless tie between M_s estimation at regional and teleseismic distances.

Our methodology includes the following:

1. Extending the geographic coverage of existing group velocity tomography maps to our entire study area, as well as extending the maps to periods of 10 s or less,
2. Using a semi-automated Rayleigh wave detector to verify that the waveforms contain fundamental-mode Rayleigh waves,
3. Using the updated group velocity maps and automated phase-match filtering to extract the surface waves from the waveforms,
4. Using a variable-period maximum amplitude M_s formula based on Russell (2006) to calculate M_s,
5. Comparing the broadband formula and others for regional distance applications at a number of stations in the study area, and
6. Developing empirical and theoretical M_s threshold maps of the study area.

We have made progress in all aspects of our research with the exception of the final task (Task 6), and the results are included in the following sections of this review paper. During the final year of the research project, we will develop empirical and theoretical threshold maps based on our current research findings.

RESEARCH ACCOMPLISHED

Updates to Group Velocity Models

We have updated the LLNL group velocity models in southern Asia (Figure 1). The results highlight the Indian shield region as relatively fast compared with the slower regions associated with the Himalayas and Bay of Bengal. We continue to update the group velocity models for southern Asia at periods greater than 10 s as data become available.

Processing Improvements

We provide an example of our processing using the program *evalsurf*. The data are examined to ensure that they pass dispersion and backazimuth tests before being narrow-band filtered. Then the amplitude is recorded and the magnitude is calculated. Figure 2 shows an example of waveform data for an event in Iran recorded at station AAK at a distance of 2,010 km. The rotated traces in Figure 2 show the Love wave coming in at approximately 570 s on the transverse component and the Rayleigh wave coming in at about 650 s on the radial and vertical components. The red line on the vertical trace shows the phase-match filtered trace, which looks very similar to the original trace, since this event had a good signal-to-noise-ratio. The great circle path for the event is shown in Figure 3, superposed on the LLNL group velocity maps for the region.

Figure 4 shows the dispersion test, in which the dispersion of the trace (illustrated by the colored contours) is compared to that predicted from the surface wave model (white squares with uncertainty bars connected by the dashed white line). For this event the comparison is favorable, indicating that the energy from the event is coming in at the expected arrival time for most periods. Figure 5 shows the backazimuth test. The horizontal traces are rotated to maximize the cross-correlation of the Hilbert-transformed vertical component and the radial component for a number of backazimuths (Chael, 1997; Selby, 2001). In this example, the estimated backazimuth is 246°, while the true backazimuth is 240°, indicating that the event is arriving from the expected direction

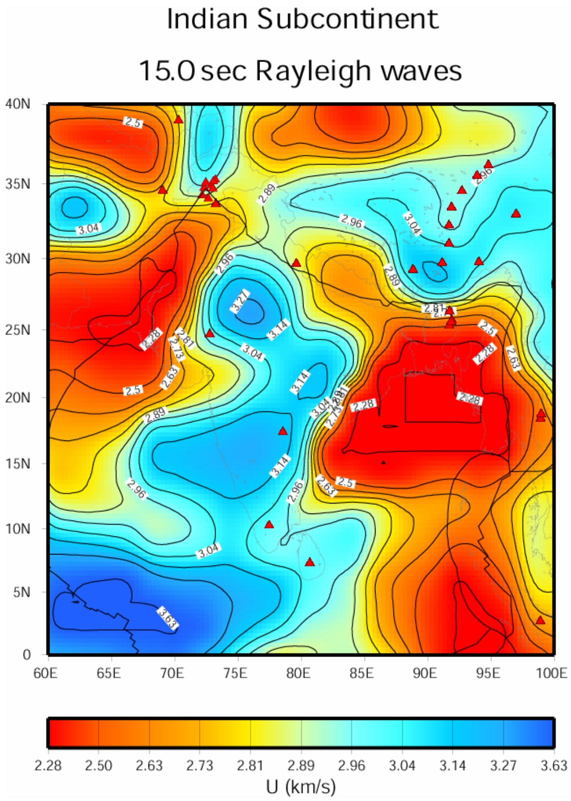

Figure 1. Tomographic inversion of Rayleigh wave dispersion curves at 15-s period for southern Asia.

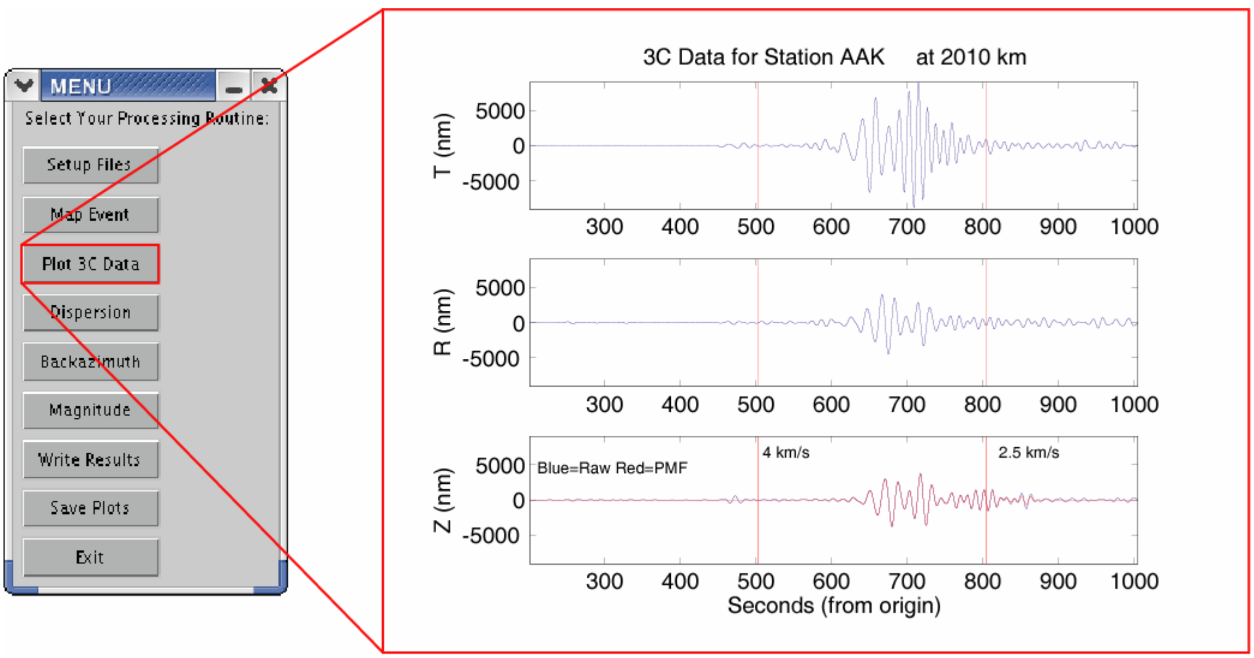

Figure 2. Waveform data and phase-match filtering for an event in Iran recorded at station AAK.

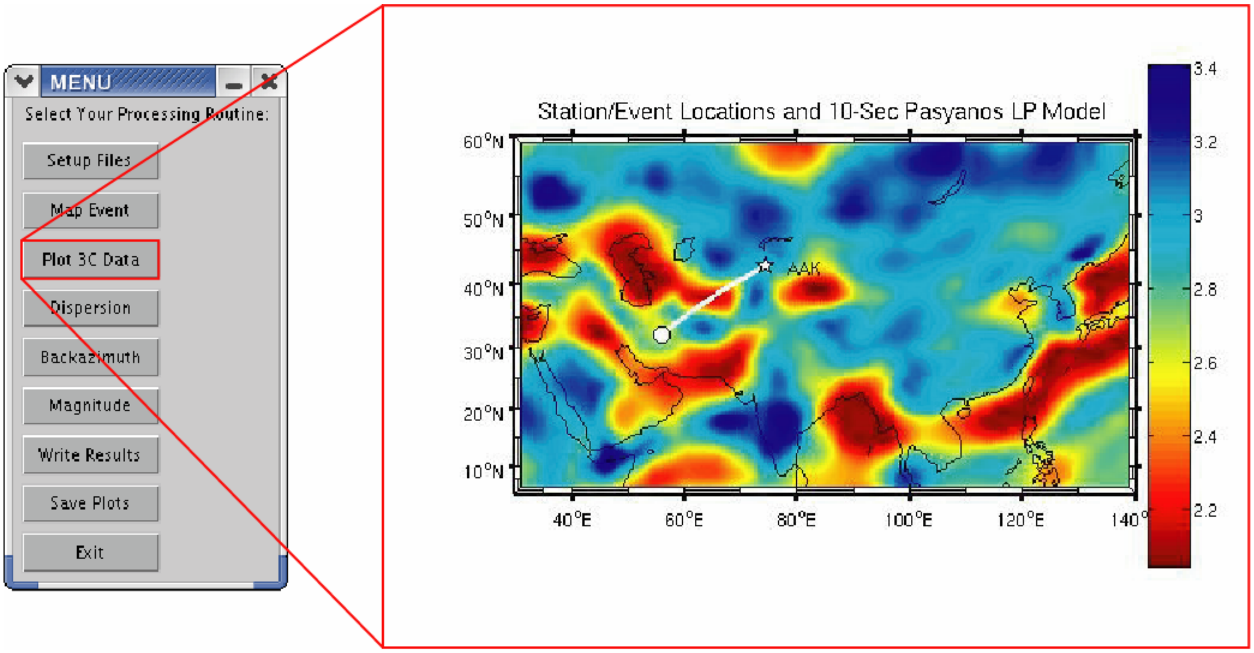

Figure 3. LLNL 10-s group velocity map, event and station locations, and great circle path for the data shown in Figure 2.

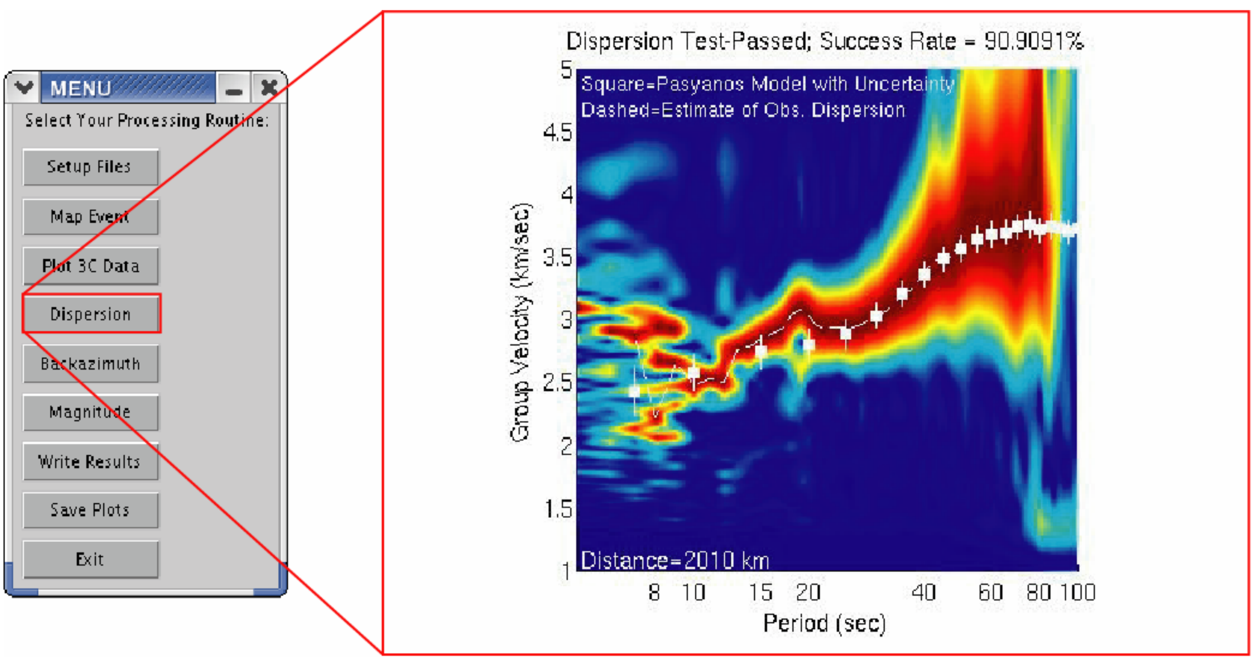

Figure 4. Dispersion test for the data shown in Figure 2.

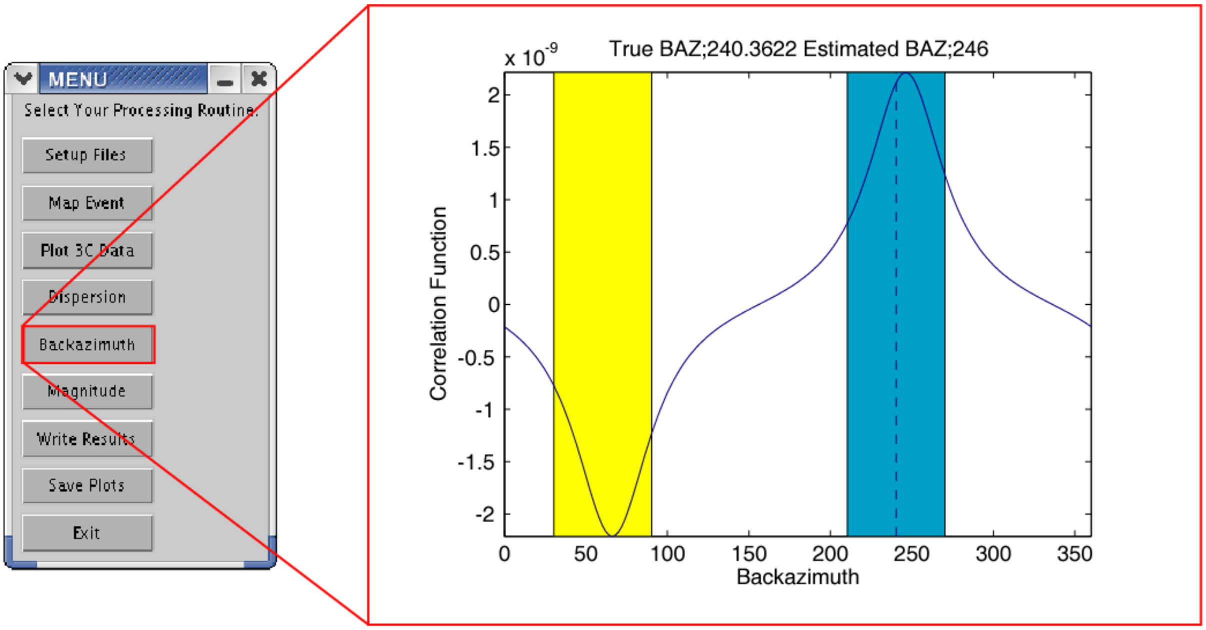

Figure 5. Backazimuth test for the data shown in Figure 2.

Once we are satisfied that we have identified Rayleigh waves with the correct velocity and backazimuth for the event of interest, we calculate surface wave magnitudes using the Rezapour and Pearce (1998), Marshall and Basham (1971), and VMAX (Russell, 2006; Bonner et al. 2006) methods. For this analysis, Rezapour and Pearce (1998) magnitudes are only calculated at periods between 18 and 22 s in order to closely mimic processing routines at the International Data Center. We consider surface waves with periods between 8 and 25 s for the VMAX magnitudes, and surface waves with periods between 10 and 40 s for the Marshall and Basham (1971) magnitudes. The results for this event (Figure 6) and most events analyzed in this study show that the magnitudes from all 3 techniques are within 0.2 m.u. of each other.

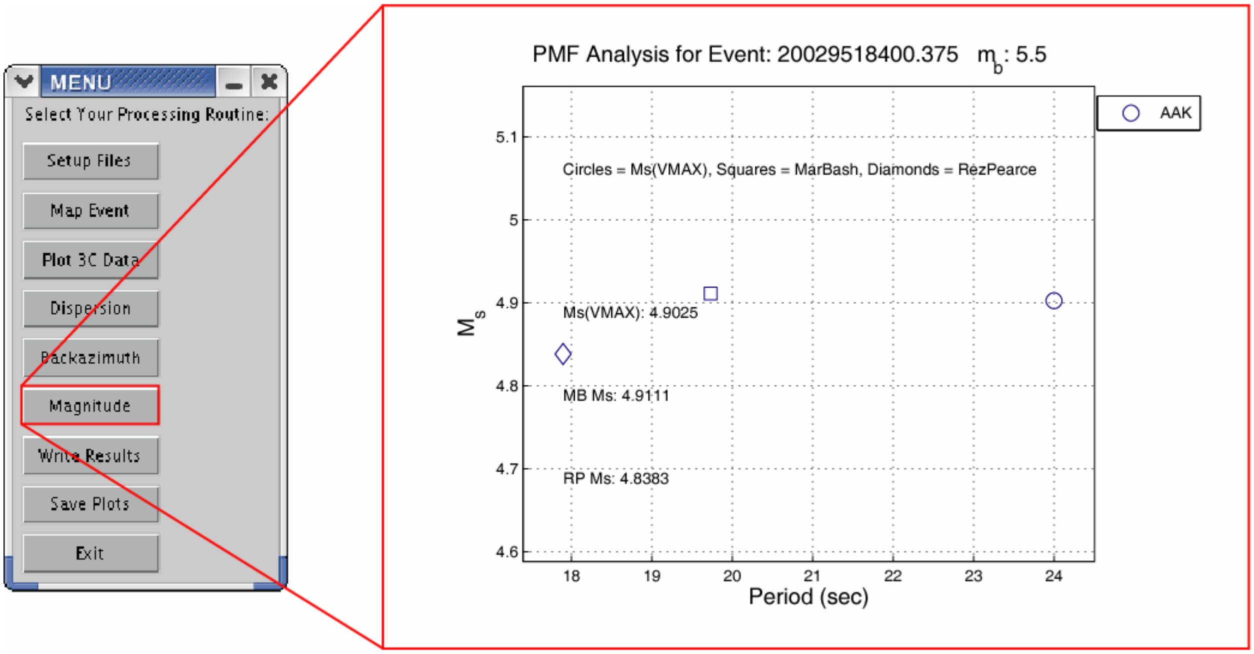

Figure 6. Surface-wave magnitudes for the data shown in Figure 2.

Why Variable Periods?

In Figure 7, we demonstrate one of the reasons why we use variable-period surface waves**.** We have plotted M_s vs. backazimuth for a different earthquake in Iran using the VMAX technique (top panel), Marshall and Basham's variable-period formula (middle panel), and Rezapour and Pearce's formula (which is for periods of 18–22 s only) (lower panel). For this particular event, the slightly sinusoidal nature of the M_s measurements for the Rezapour and Pearce formula (lower panel) demonstrates the effects of a spectral hole at approximately 20 s at some backazimuths, which is a result of the earthquake focal mechanism. Note that the VMAX and Marshall and Basham techniques do not show this pattern, since these techniques ignore the hole. This results in lowered network variance (the variance of M_s calculated using VMAX is usually lower than Marshall and Basham as shown here, even though both are variable period) and a larger M_s estimate. Lowered network variance and larger M_s estimates both improve discrimination.

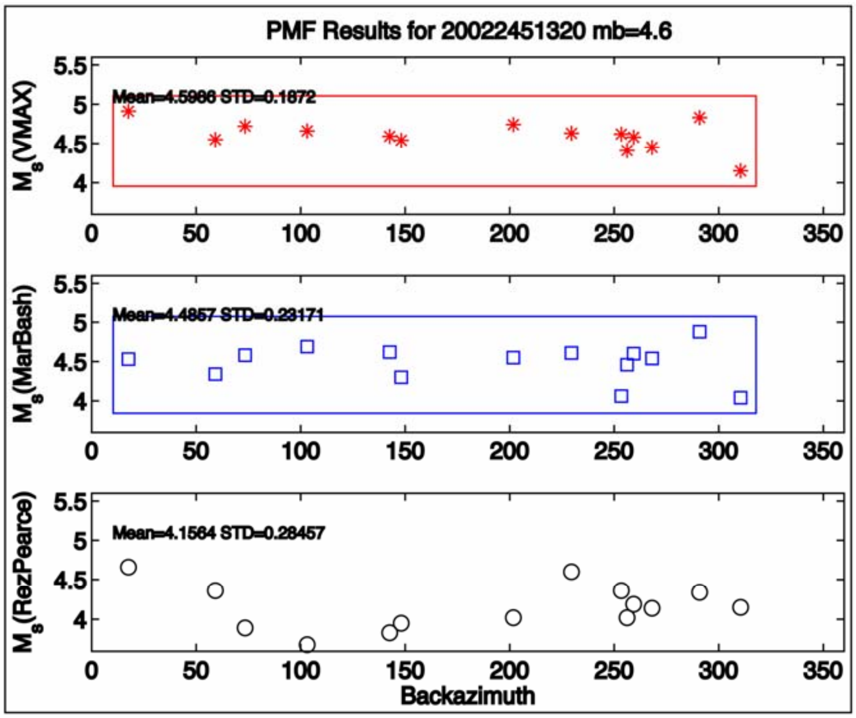

Figure 7. M_s as a function of backazimuth for the three M_s formulas.

Application in Central Asia

We have applied a number of surface wave magnitude formulas to events in Central Asia (Figure 8) at regional distances. We have made M_s estimates for 261 events (240 earthquakes, 3 mine events, and 18 nuclear explosions). Results are shown in Figure 9. The top panels show m_b: M_s, where the surface wave magnitude has been calculated using the Rezapour and Pearce (1998) formula. In the middle panels, we use the formula of Marshall and Basham (1972). We have used the path correction P(T) for continental Eurasia. The bottom panels show M_s calculated using the VMAX formula. For each set, the figure to the right uses the same formula on waveforms that have been phase-match filtered. In each figure, earthquakes are shown as green circles, chemical explosions as yellow diamonds, and nuclear explosions as red triangles. While m_b: M_s easily discriminates the nuclear explosions, the chemical shots generally fall along the earthquake trend. The average interstation deviations of the magnitudes (without phase-match filtering) are 0.24, 0.24, and 0.21 m.u. for each of the formulas, respectively. In this dataset, using phase-match filtering reduces the magnitude variance slightly for earthquakes, but much more significantly for explosions.

We have also examined these techniques for single-station magnitude estimation. We used the Murphy et al. (1997) screening criterion for M_s—m_b to determine the percentage of single-station estimates that screened as earthquakes using each technique. Out of 2,484 station-source pairs, we screened 95.7%, 93.8%, and 89.3% using VMAX, Marshall and Basham, and Rezapour and Pearce, respectively (Figure 10). We note that for our smaller explosion population (102 single-station estimates), each technique had the same number of single-station estimates that screened as earthquakes: three. For network-averaged magnitudes, there were no misclassified nuclear explosions for any of the three techniques.

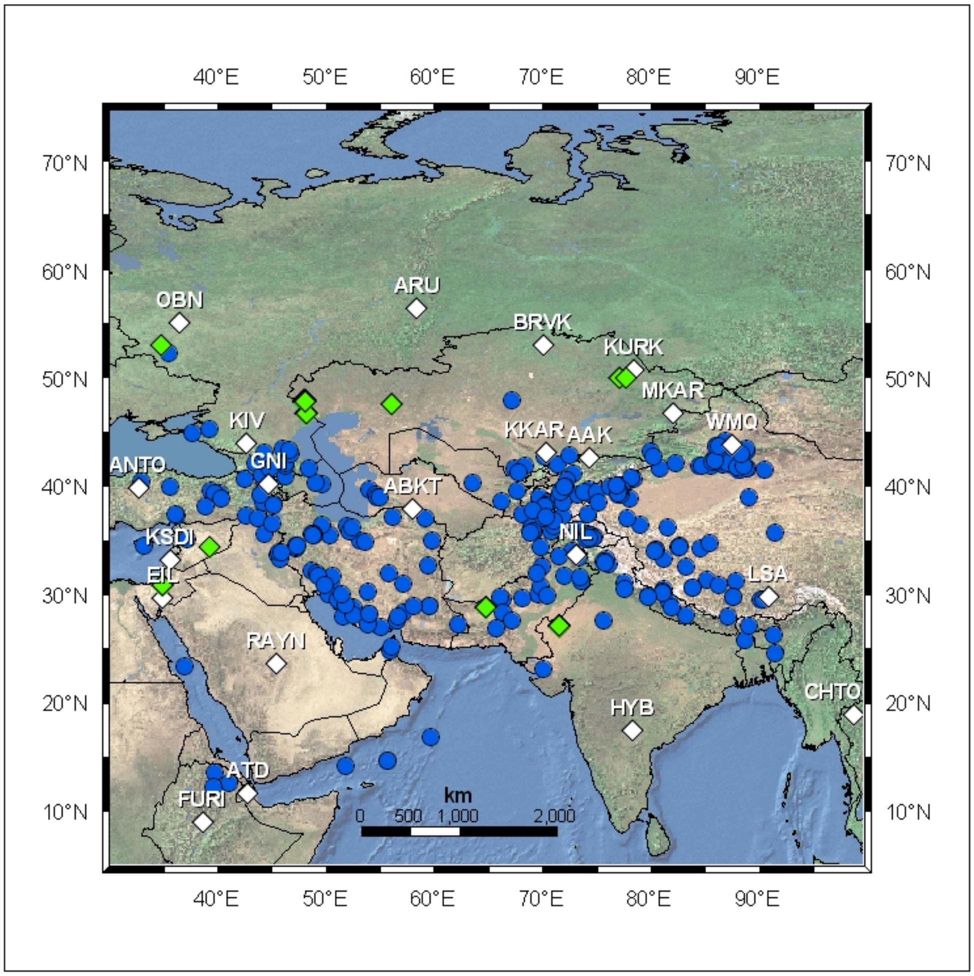

Figure 8. Locations of events and stations in Central Asia used for our study.

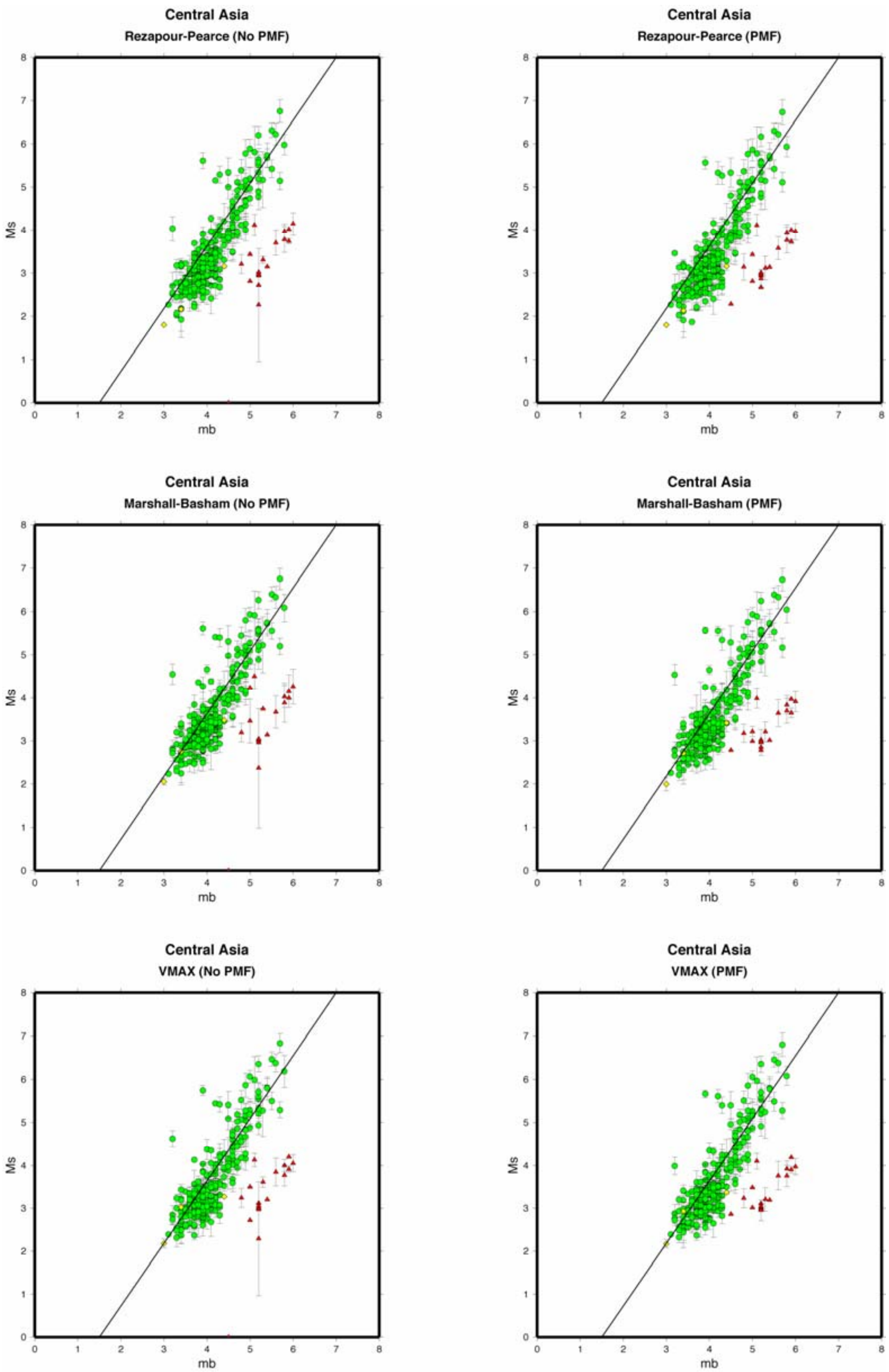

Figure 9. m_b: M_s for Central Asia using the Rezapour and Pearce (top), Marshall and Basham (middle), and VMAX (bottom) formulas without (left) and with (right) phase-match filtering. Red triangles represent nuclear explosions, green circles are earthquakes, and yellow circles are mining explosions.

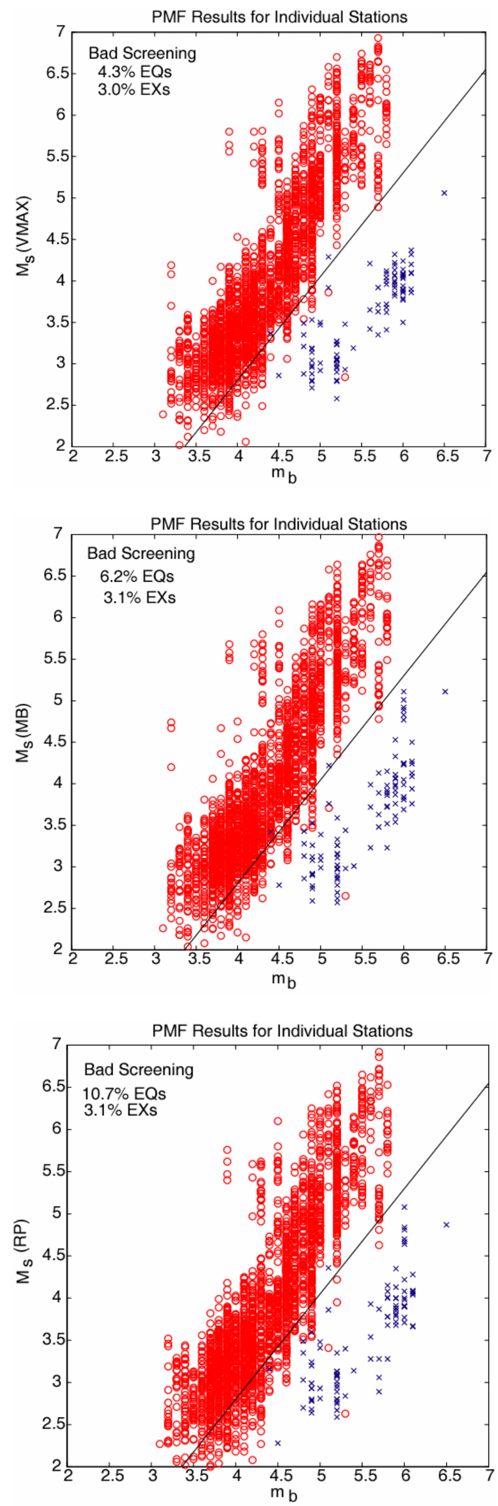

Figure 10. Single-station surface wave magnitude estimates for earthquakes (circles) and explosions (x) in Central Asia. The line is the event screening criterion from Murphy et al. (1997). VMAX (top), Marshall and Basham (middle), and Rezapour and Pearce (bottom).

CONCLUSIONS AND RECOMMENDATIONS

The VMAX appears to provide a better and more consistent estimate of source size, particularly for smaller events and at shorter distances, and especially when combined with phase-match filtering. This combination of methods not only results in the most robust M_s estimate, but also produces the best m_b:M_s discriminant.

REFERENCES

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 Ms-mb performance, *Bull. Seism. Soc. Amer.* 96: 678–696.

Chael, E. P. (1997). An automated Rayleigh-wave detection algorithm, *Bull. Seism. Soc. Am.* 87: 157–163.

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.

Murphy, J. R., B. W. Barker, and M. E. Marshall (1997). Event screening at the IDC using the Ms/mb discriminant. Maxwell Technologies final report, 23 pp.

Pasyanos, M. E. (2005). A variable-resolution surface wave dispersion study of Eurasia, North Africa, and surrounding regions, *J. Geophys. Res.* 110: B12301.

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

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. Amer.* 96: 665–677.

Selby, N. (2001). Association of Rayleigh waves using backazimuth measurements: Application to test ban verification, *Bull. Seism. Soc. Am*. 91: 580–593.