IMPROVING ESTIMATES OF DEPTH, MAGNITUDE, AND FAULTING PARAMETERS OF EARTHQUAKES IN CENTRAL ASIA

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ABSTRACT

Accurate and stable seismic source parameters for small-to-moderate size events are essential for many aspects of regional nuclear-explosion monitoring. For example, magnitude and distance amplitude corrections (MDAC) have been developed for regional discrimination, but they rely on stable moment estimates. We develop a catalog of regional earthquakes in eastern Asia with estimated seismic moments, source mechanisms, and depths using regional seismic data. A significant challenge of modeling small-to-moderate-size seismic sources is the necessity of relying on short-period signals with long travel paths that have substantial sensitivity to earth structure along the path. When the path effects are unknown or difficult to account for, we must rely on components of seismic signals that are minimally dependent on the structure. Although regional surface-wave phases are strongly influenced by structure, surface-wave amplitude spectra can be modeled adequately with relatively simple earth models, and these spectra carry valuable information on source character. Our efforts build on existing seismic source analysis techniques. We directly model regional seismograms where possible but combine those with surface-wave amplitude spectra observed at more distant regional stations. The inversion is performed using a grid search for strike, dip, rake, moment, and depth. Choosing suitable weights for the different data sets remains a challenge that will only be overcome with experience. Initially, all data are weighted equally by normalizing seismograms and spectra by their uncertainty and the number of observations in each data set. For larger events (MW > 5) we can also include long-period (approximately 40-s period) body-wave trains, which can be modeled reliably using simple stratified earth models. The use of spectra and long-period signals is ideal for estimating the moment and faulting geometry of signals but simple least-squares norms based on these signals do not often provide satisfactory resolution of source depth (when the source is shallow). However, in cases where the long-period mechanism is relatively stable as a function of depth, we can overcome this limitation by exploiting signals more diagnostic of source depth such as teleseismic body-waveforms, broadband Pn waveforms, or select short-period Rayleigh wave spectra. Our recent focus has been on the inclusion of signal-to-noise estimates into the inversion norms, tracking separate norms for time and frequency-domain signals, separate norms for P-SV-Rayleigh and SH-Love wave signals, and the use of more statistically robust amplitude spectral measures. Our preliminary results suggest that Harvard CMT moments may be biased slightly high for events near the low end of their threshold. We have not modeled enough events to explore potential regional variations in the bias. Moments from the inversion can be used to help calibrate coda-based magnitude scales for the region.

coverage of radiation patterns is improved and second, Rayleigh wave amplitude spectra contain valuable information on the source depth. For shallow events, improved resolution of the depth requires short-period information because the information on shallow depths is contained in the short-period signals. Herrmann (1979) exploited information in intermediate-period surface waves to estimate the faulting geometry and depth of earthquakes in east and central North America from old analog records. He observed signals out to distances of thousands of kilometers and extracted spectral amplitudes suitable for constraining the earthquake parameters. Our experience suggests that observations from such large distances in central Asia are not as simple or robust as those in the stable part of North America (*e.g.* Levshin *et al.*,1990). The signal amplitudes are complicated due to scattering and intrinsic attenuation, but generally well observed for larger events (Mw ~ 5). However, signals from small events may be isolated from background noise and extracted using phase-match filtering exploiting dispersion observations from larger events.

OBJECTIVE

Estimating the source type or faulting geometry of small seismic events located hundreds of kilometers from the nearest seismometer can be difficult. Typically one of two classes of modeling approaches is adopted: spectral or time-domain. Spectral techniques use the observed variation in surface-wave spectra as a function of azimuth to match the radiation pattern of the source (*e.g.* Patton, 1976, 1980, 1998; Herrmann, 1976, 1979; Romanowicz, 1982; Patton and Zandt, 1992; Herrmann and Ammon, 1997, and many others). Time-domain methods are straightforward matches to the observed seismograms and include both amplitude and phase information (*e.g.* Langston, 1981; Dreger and Helmberger, 1991, 1992, 1993; Lay *et al.*, 1994; Randall *et al*., 1995; Ghose *et al*, 1998; Ammon *et al*., 1998, and others). Spectral methods can be designed to include amplitude only, or amplitude and phase information, while time-domain methods include both. Phase information provides valuable constraints on the source mechanism and depth, but the observed phase is often sensitive to details in Earth structure along the propagation path. Time-domain source inversion methods are usually applied to large events with good long-period signals or short-period signals of small events that have minimal distortion from Earth structure (such as teleseismic P and SH waves) or local and close-regional (less than a few hundred *km*) signals. To use phase in surface-wave spectral analyses, a good estimate of the surface-wave phase velocity variations between the source and receiver is needed.

In the case of nuclear-explosion monitoring, the best signals from a shallow small event are most likely to be short-period surface waves. But directly fitting the phase of short-period Rayleigh waves (probably the best regionally observed, deterministic signal from a small, shallow event) is challenging because these waves are sensitive to shallow, variable structure along the propagation path. Rayleigh-wave spectral amplitudes are less sensitive to structure variations than the corresponding signal phase, and contain valuable information on the source depth. Thus, it is desirable to combine the part of distant signals that is less sensitive to structure with the amplitude and phase information from the closer stations.

Simultaneous spectral and time-domain seismic source modeling

To achieve this, we combine surface-wave spectral amplitude modeling and time-domain waveform fitting in a grid-search algorithm to estimate the source mechanism (systematically check strike, dip, rake, and depth, and include an isotropic source for comparison). The procedure includes surface-wave amplitude information for stations distant from the source and includes both amplitude and phase information from the closer observations and teleseismic body waves if the event is large enough for these to be observed (Figure 1). Incorporating observations from more distant stations makes a significant contribution to seismic source studies in two important ways: First, the azimuthal coverage of radiation patterns is improved and second, Rayleigh wave amplitude spectra contain valuable information on the source depth. For shallow events, improved resolution of the depth requires short-period information because the information on shallow depths is contained in the short-period signals. Herrmann (1979) exploited information in intermediate-period surface waves to estimate the faulting geometry and depth of earthquakes in east and central North America from old analog records. He observed signals out to distances of thousands of kilometers and extracted spectral amplitudes suitable for constraining the earthquake parameters. Our experience suggests that observations from such large distances in central Asia are not as simple or robust as those in the stable part of North America (*e.g.* Levshin *et al.*,1990). The signal amplitudes are complicated due to scattering and intrinsic attenuation, but generally well observed for larger events (Mw ~ 5). However, signals from small events may be isolated from background noise and extracted using phase-match filtering exploiting dispersion observations from larger events.

RESEARCH ACCOMPLISHED

The goal of estimating source depth with some precision requires a combination of observations. Particularly valuable in constraining earthquake depth are short-period Rayleigh waves, which may contain a spectral notch indicative of source depth (e.g. Herrmann, 1979) but often show systematic amplitude variations that vary with depth. Short-period surface waves can be tricky and when analyzing the signals some form of mode isolation can help simplify their interpretation. For now we have used group velocity windows with spectral smoothing to simplify the seismic signals, but our spot checking the impact of mode isolation indicates that it is often not necessary for larger events - or

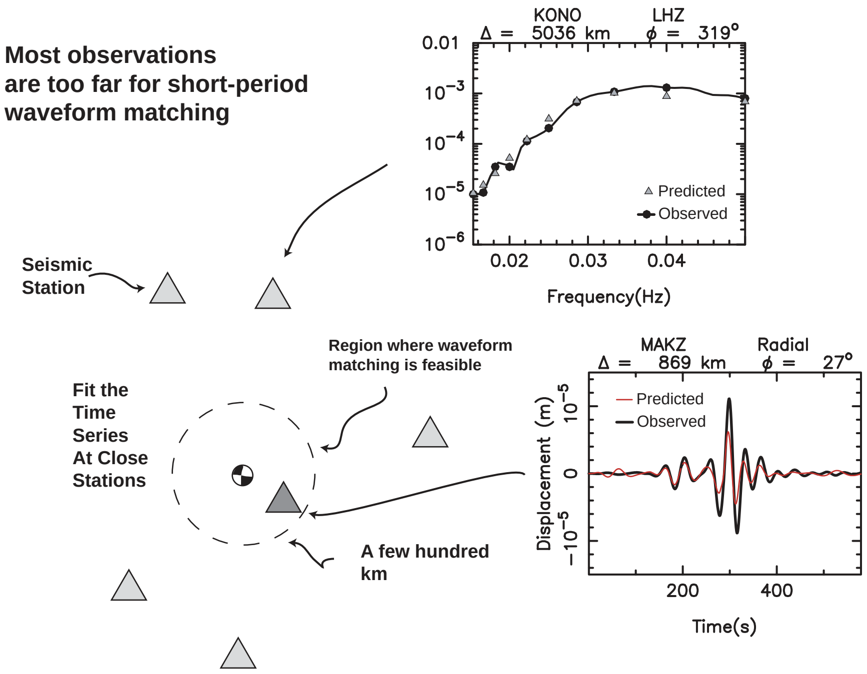

Figure 1. Schematic illustration of the joint source parameter inversion scheme. The triangles represent seismic stations, the focal mechanism represents the source location. The basic idea is to combine observations with a minimal sensitivity to earth structure to produce more accurate estimates of the event mechanism and depth. Since most observations are too far for direct short-period waveform modeling, we sacrifice the phase information and use only the more robust spectral amplitudes at those sites. Phase information is included from seismograms recorded at nearby stations, teleseismic P-waves, or regional *Pnl* arrivals. Sample observations and predictions are shown to the right of the cartoon.

at best it adds little improvement. Such may not be the case for small events with low signal-to-noise where some form of signal enhancement is needed.

Our primary control on the source mechanism arises from the azimuthal variation of Rayleigh and Love wave spectra. Nearby time-domain signals provide the required phase information as well as additional information on the mechanism and often the most sensitivity to depth. All spectra are estimated using a windowed auto-correlation function which produces smoother and statistically more reliable spectral amplitudes. This procedure requires substantially more time than simply using the FFT amplitude spectrum since the smoothing requires that we incorporate periods adjacent to those used in the misfit norm. However, the smooth, statistically better measures will undoubtedly be more valuable for analyses of path effects and systematic variations in signals at particular stations. The seismic moment for each mechanism tested in the grid search is estimated using an L1 fit to the logarithm of spectral amplitudes of all the signals. Green's functions are computed using a generic model of a slightly thicker than average (46 km) continent resting on and earth-flattening transformed version of the isotropic PREM model.

Our early inversions revealed that many of the data available from the global seismic networks are noisy or contain other problems that render them unsuitable for use in an inversion. To identify such problems we visually inspect all the data in the bandwidth from 100 to 20 seconds period to identify signals with grossly inadequate signal-to-noise ratios. To insure that we rely more heavily on the best observations, we weight each spectral observation by the inverse of the ambient seismic noise at the same period. The ambient noise is estimated using the pre-P-wave signal. Each signal's spectrum is also weighted relative to all other spectra using the mean of spectral amplitude of the noise in the period range of interest. Distant stations are down-weighted using a simple one-over-distance measure - this is strictly a pragmatic approach designed to include our *a priori* assumption that the model we are using is probably best suited for short paths. Interestingly, we have found little correlation of misfits with distance, suggesting that we are able to fit the most distant observations with the same fidelity with which we can fit the intermediate distance obser-

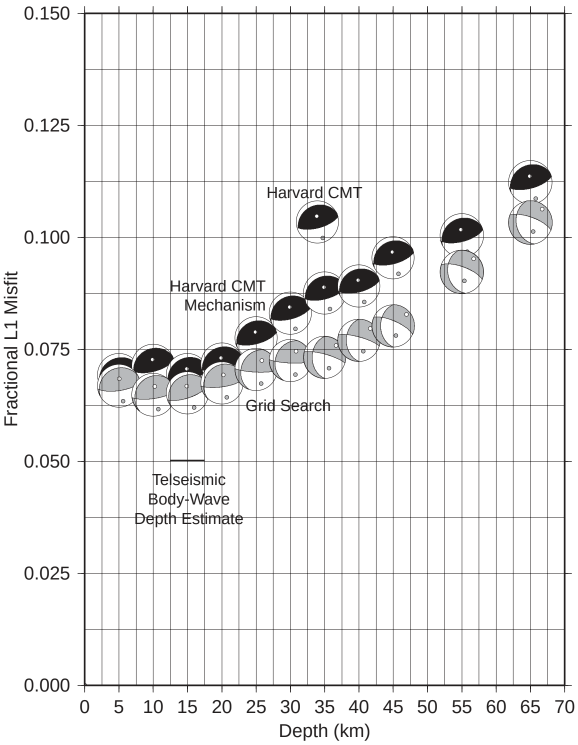

Figure 2. Misfit versus depth variation (along with mechanism variations) for a fixed mechanism (moment, depth) and full grid searches (mechanism, moment, depth).

vations. Azimuthal bias in station coverage is moderated by weighting observations by the number of other signals within 15° azimuthal range of the particular observation. In other words, a signal separated from all others by a gap of more than 15° has an azimuthal weight of 1.0, a signal with four other signals within 15° has an azimuthal weight of 0.2 (1/5, including the observation). Automating the weights reduces substantially the time needed to adjust the parameters during an inversion. Observation weights reflect our attempts to cope with the problems of driving an inversion with a single-number norm.

Although each event is different, the combination of these observations can produce good depth, mechanism, and seismic moment constraints. An example depth-misfit curve is shown in Figure 2. The shallow nature of this reverse faulting event is very nicely constrained by the short-period surface waves, as well as nearby time-domain signals. The mechanism near the top-center of the plot (33 km, 0.1 misfit) identifies the misfit of the Harvard CMT solution to our observations using the Harvard best double couple, the Harvard seismic moment, and the assumed source depth of 33 km. The other dark shaded mechanisms identify grid-search results assuming the Harvard CMT best double-couple mechanism with a seismic moment optimized to fit our data using Green's functions for our model. The optimal moment for the assumed Harvard mechanism is about 20% lower than that reported in the CMT catalog. The lightly shaded mechanisms are the results of a full grid search with a free mechanism and seismic moment. The best fitting solutions from both the constrained and unconstrained grid searches agree well in both mechanism and depth (near 10 km). The unconstrained mechanism is slightly rotated relative to the Harvard solution, but the agreement is certainly within uncertainties of either technique. The abrupt change in focal mechanism in the full grid search results near 25 km does not correspond to a change in the velocity model but is a depth at which the fit to the time domain signals degrades quickly. The variation in the complete norm shown in Figure 2 does not necessarily reflect the variation in fit to just the time-domain signals. To identify such instances we track five norms, 1. vertical-radial time-domain and 2. spectral misfits, 3. transverse time-domain and 4. spectral misfit, and the 5. combination of all misfits (which we used in Figure 2).

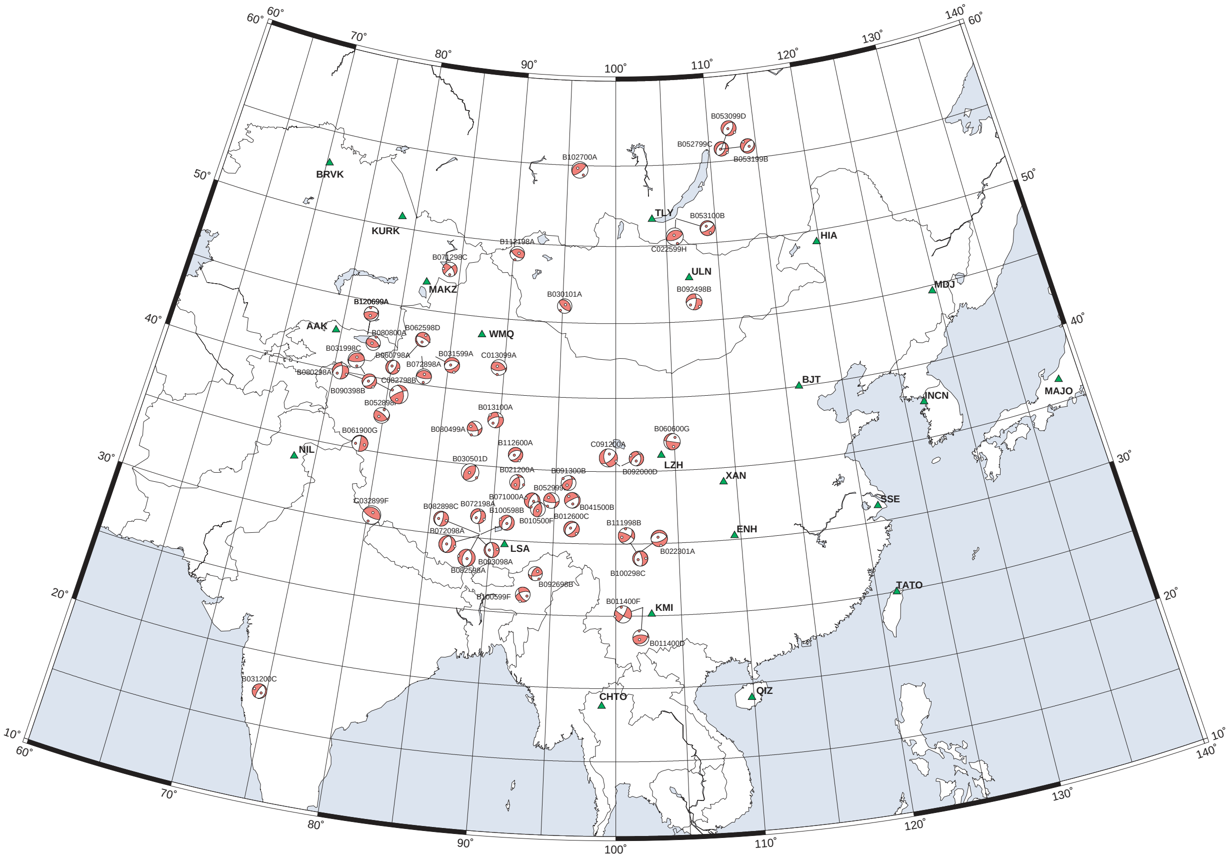

Figure 3. The map above shows the results of inversions using the waveforms and spectra for 30 events in the Harvard CMT Catalog. The results are generally consistent although some of our mechanisms have significant rotations relative to the CMT solutions (and what you might expect from tectonics). We believe that part of the problem with our preliminary results lies in the use of small-amplitude signals. Our seismic moments (or Mw) are less sensitive to variations in structure and noisy traces (for these inversions we used the L1 norm and the median values to compute an optimal moment in the period range from 65 to 20 s). For some events, no nearby waveforms are available and the results are ambiguous (but constrained) - for example, the rake can be changed by $-\pi$.

Joint Amplitude-Spectra/Seismogram Grid-Search Inversion Results

Preliminary grid-search results are shown in Figure 3. In general our results agree with the Harvard mechanisms, although often some rotation of the mechanisms is required by our data and occasionally we appear to have less control on the mechanism. Perhaps the most interesting difference is the dependence of the seismic moment difference between Harvard and our analyses on seismic moment. For moderate-size events (Mw > 5.5) our moments agree well with Harvard's, for events near the threshold of the CMT method, more often than not the Harvard CMT moment is larger than the moments derived by us (Figure 4). No doubt some of the difference arises from the different models used in each method and our moment is really a fit of the spectrum from 80 to 20 seconds, for the smaller events, Harvard's moment is generally more appropriate near 40 seconds period (when only body waves are used). Most interesting is the character of the discrepancy, which suggests a systematic difference as a function of moment. For the smaller magnitude events, the misfit is substantial when inspecting the time-domain signals. All events with a grid-search moment magnitude less than 5.0 produce positive residual magnitudes (which indicates overestimation by Harvard or underestimation by us). Such differences may reflect the excitation functions for the different velocity structures assumed in each method, and while they cannot be resolved completely (moment depends on the assumed structure), the differences can be important and are worth noting.

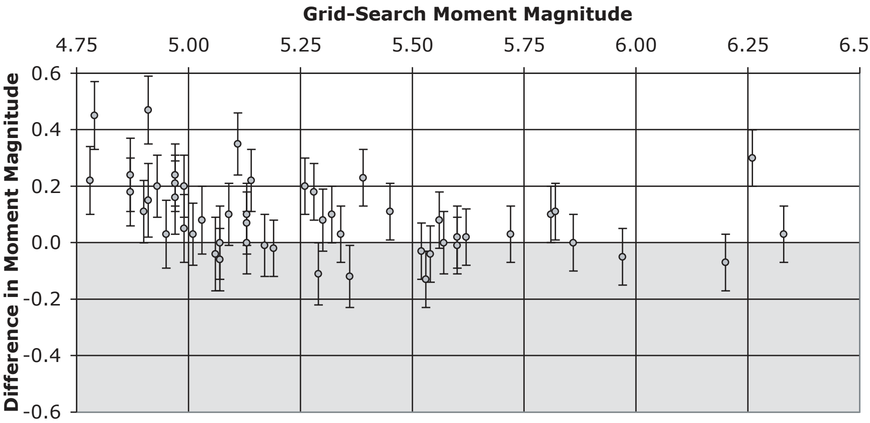

Figure 4. Comparison of the moment from grid searches and the Harvard CMT moment. Vertical axis shows the (Harvard Mw) — (Grid-Search Mw). Since the two approaches use different velocity structures and fit the data over different, finite bandwidths, the agreement should not be perfect. The CMT method tends to over-predict (or our method under-predicts) the moment for small events. Uncertainties were computed for the Harvard CMT using a Monte-Carlo method. The outlier at Mw 6.25 is a result of our failure to incorporate a time function for this larger event (Mw > 6.5).

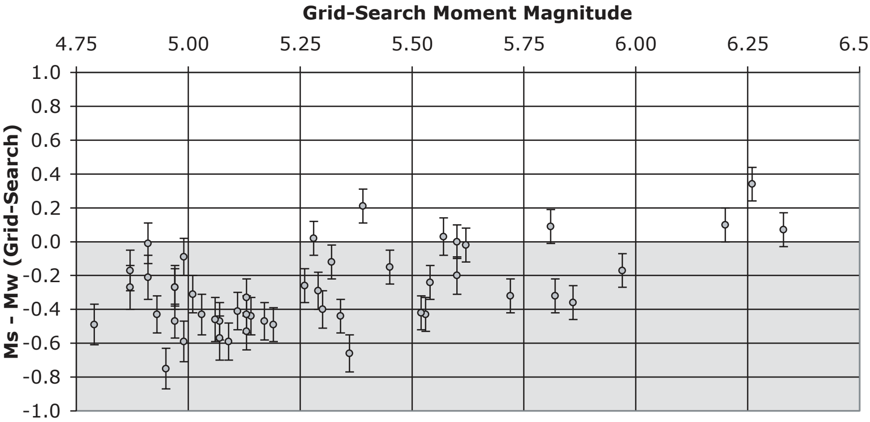

Figure 5. Comparison of the moment magnitude from grid searches and the USGS Ms estimate. Vertical axis shows the (Ms) — (Grid-Search Mw). Uncertainties were computed for the grid-search were computed using a Monte-Carlo method on the CMT moments (an approximation).

The moment-magnitudes obtained from the two waveform modeling techniques agree better than either does with Ms. A comparison of the grid-search M_W and the USGS Ms is shown in Figure 5. For simplicity, we've assumed the same uncertainty in grid search M_W as exists in the Harvard CMT solution. Here the trend is the opposite with M_S for smaller events under-predicting their size. The trend is unchanged if you use the Harvard CMT moments - the differences are larger.

CONCLUSIONS AND RECOMMENDATIONS

The addition of teleseismic body waves directly into the inversion will also help refine the depths of the larger events for which the body-wave signals are adequate. It may be possible to simply use the teleseismic body waves to estimate depth, fixing the moment and mechanism from the spectra and regional seismograms. Then a relatively easy-to-implement cross-correlation misfit norm, which requires little effort on aligning the signals, could be used to estimate

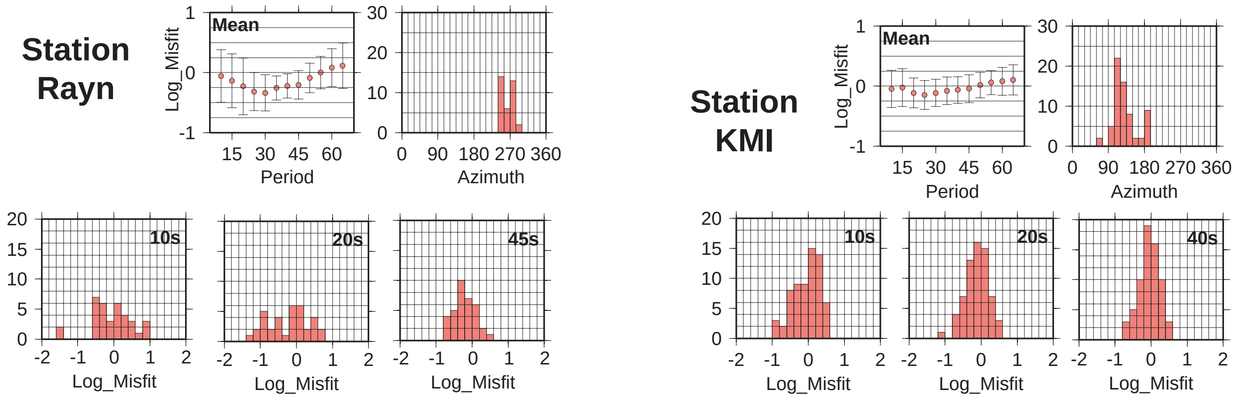

Figure 6. Comparison of path complexity issues in modeling. The panel on the left shows the performance of station RAYN (Saudi Arabia) in the inversion of events in Asia compared with station KMI located in south-central Asia. As expected KMI performs much better. We recommend that information based on the actual fits of the data of large events signals can be used to construct a table of station weights for events in different locations (eventually). Note the variation in performance with period. These weights should perform better than simple distance-dependent weights.

the depth. For the shallowest events, inspection of short-period surface waves from nearby stations may help confirm source depth and add important confidence to the grid-search results. Such additional information is subjective but there may be no likely way to avoid classifying solution quality without some fuzziness. Seismic signals are complex, and their sensitivity to different aspects of the source are difficult to quantify with easily computed misfit norms.

The key to producing a reliable system for inverting spectra and seismograms is the assignment of appropriate weights to the observations. Weighting by signal-to-noise is a straightforward decision. Other weights require more expertise and experience to assign. In particular, we have computed misfits for a set of events throughout central Asia. We recommend that any system designed to invert for moment, mechanism, and depth be adaptable and updated to include new information on station performance (e.g. Figure 6). These station experience-based weights are not so much a statement on station quality, but on path complexity. This information could, for example, be used to replace our simple distance-dependent weight using information on path complexity and length, which is reflected in the station misfits. These weights would also naturally be period-dependent, and we expect that the longer periods may be less corrupted by geologic complexity.

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