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Title: Calibrating the MKAR Array Using Transfer Functions

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CALIBRATING THE MKAR ARRAY USING TRANSFER FUNCTIONS

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ABSTRACT

Developing regional discriminants (RDs) at any given seismic station requires a ground-truth database of waveforms from both earthquakes and explosions. Recently installed stations used for seismic monitoring have no single charge explosions on which to base discriminants. We have developed a procedure to map information from surrogate stations, having a long recording history, to newly installed operational stations. We investigated a method to compute transfer functions using known effective RDs for a database of earthquakes and explosions located near the Lop Nor nuclear test site and recorded at the KNET array in Kyrgyzstan. For specific source-station paths, transfer functions work well. However, preliminary analysis of India and Pakistan nuclear tests indicate strong azimuthal dependence in the construction of reliable transfer functions.

The success of the preliminary work suggests we can apply the same technique to calibrate the recently installed MKAR array using the Global Seismic Network station MAKZ as a surrogate. Both MKAR, an 11-element array operational since 2000, and MAKZ (including its earlier counterpart MAK), operating very broadband instruments since 1994, are located in Eastern Kazakhstan and separated by 25 km. To perform the calibration requires additional considerations not taken into account during the initial investigation: (1) utilizing amplitude spectra, rather than using RDs, to calculate transfer functions; (2) computing transfer functions for a range of azimuths, as we believe the transfer function are azimuthally dependent; and (3) determining whether working with each array element separately or developing a single-input/multiple-output model will provide more stable results and better error estimates.

OBJECTIVE

The area around Lop Nor has a moderate rate of natural seismicity. Many of these events are oblique thrusting earthquakes, which can produce dominantly compressional P waves at teleseismic distances. This highlights the importance of regional distance discrimination and provides an example for testing the transfer function method for discrimination at the Makanchi seismic array (MKAR) in Kazakhstan, which is part of the IMS network.

Since MKAR was installed after nuclear testing at Lop Nor concluded, discriminant behavior for explosions as compared to earthquakes is unknown. The transfer function method provides a means of "predicting" such behavior at MKAR using known explosion discriminant behavior at the nearby seismic station MAKZ. Using a transfer function that is unique to each array element, an amplitude spectrum for a theoretical Lop Nor explosion can be simulated at MKAR, allowing for more confident discrimination between natural seismicity and clandestine events.

Regional distance discrimination has traditionally been done at a single station. Arrays pose a new challenge in that discrimination can be done in several ways: (1) measurements made on each element, and averaged, (2) measurements made on each array, spectral ratios (discriminants) made and averaged, or (3) treating each element as a separate station. The objective of this work is to determine which of the aforementioned ways, with respect to the construction of transfer functions between MKAR and MAKZ, allows for the most optimal discrimination performance at MKAR.

RESEARCH ACCOMPLISHED

The goal of simulating the expected explosion characteristics at a newly installed seismic station requires a transfer function that is composed of three filter functions: (1) a source excitation function that accounts for the explosion spectral effects, (2) a propagation filter that accounts for the effects of crustal and mantle structure on the partitioning of seismic energy as well as focusing and attenuation effects, and (3) a site response. The data available for calibrating a new station using data from a historical station can be written in terms of these three filter functions:

$$A_{QS}(\omega) = S_Q(\omega)E_{QS}(\omega)P_S(\omega)$$
$$A_{QO}(\omega) = S_Q(\omega)E_{QO}(\omega)P_O(\omega) \qquad (1)$$
$$A_{XS}(\omega) = S_X(\omega)E_{XS}(\omega)P_S(\omega)$$

where A is the amplitude spectrum, S is the source-excitation spectrum, E is the earth response, X or Q is earthquake or explosion, and S or O is surrogate (historical) or operational (new) station. We wish to predict the amplitude spectrum for an explosion at an operational station:

$$A_{XO}(\omega) = S_X(\omega)E_{XO}(\omega)P_O(\omega) \qquad (2)$$

Previous work (Renwald et al, 2002) suggests that we can predict $A_{XO}(\omega)$, the explosion spectrum from the operational station, using a transfer function based on common earthquakes recorded at both the operational and surrogate station. This transfer function, defined as T_Q, is computed from:

$$\frac{A_{QO}(\omega)}{A_{QS}(\omega)} = \frac{E_{QO}(\omega)P_O(\omega)}{E_{QS}(\omega)P_S(\omega)} = T_Q(\omega) \qquad (3)$$

and when combined with the known explosion spectrum from the surrogate station, give:

$$A_{XO}(\omega) = T_Q(\omega)A_{XS}(\omega) \qquad (4)$$

For Equation (4) to predict $A_{XO}(\omega)$, we have assumed that:

$$\frac{E_{XO}(\omega)}{E_{XS}(\omega)} \approx \frac{E_{QO}(\omega)}{E_{QS}(\omega)} \qquad\qquad (5)$$

This procedure was initially tested at the KNET seismic network in Kyrgyzstan (Renwald et al, 2002). We predicted various discriminants known to be effective in the region (Hartse et al, 1997) using Equation (4). Working with discriminants, rather than amplitude spectra, allowed us to simply test the effectiveness of the transfer function method. KNET was chosen for several different reasons: first, the network is at a regional distance from the Lop Nor Chinese nuclear test site and has recorded a number of earthquakes and explosions; second, the network spacing of the KNET stations allowed us to determine the role interstation distance played in the success of the transfer functions; third, the variable topography and geology at KNET allowed us to investigate the procedure of predicting a discriminant at one station using the discriminant at a station in a different geologic setting.

We utilized four discriminants to calculate the transfer functions: two phase ratios and two cross-spectral ratios and computed transfer functions for all stations predicting all other stations for nine earthquakes and six explosions. We calculated a single transfer function for each surrogate-operational station pair by taking the mean of all transfer functions computed for each pair of stations. Finally, we used Equation (4) to calculate the predicted discriminants. The results, shown in Figure 1, illustrate that this method works well. The discriminant ratios predicted by Equation (4) show a good correlation to the discriminant ratios actually observed at each station for the six explosions. The only significant scatter is seen with the high frequency (6-8 Hz) Pg/Lg discriminant. We also investigated whether or not the distance between the surrogate and operational station affected the outcome of the transfer function method. Through regression analysis, we found that interstation distance does not affect the success of the transfer function method; therefore, the surrogate and operational stations need not be in close proximity for the method to be useful.
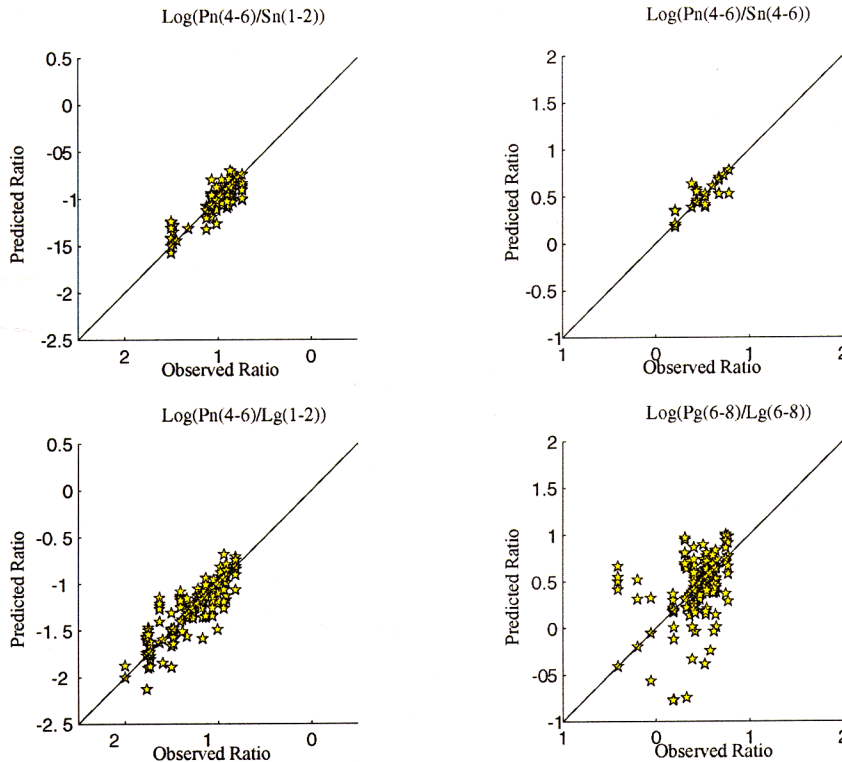

Figure 1. Four different discriminants were predicted using Equation (4) for all stations at KNET and then plotted against the actual observed discriminant values. The solid line indicates a one-to-one relationship.

We used the same methodology to calibrate MKAR using MAKZ as a surrogate. However, instead of working with discriminants selected a priori, we used MDAC2 (revised Magnitude Distance Amplitude Correction) residual amplitudes. The MDAC2 procedure removes magnitude and distance trends in regional phase amplitudes using an earthquake source model and allows for maximum flexibility in the later construction of discriminants (Walter and Taylor, 2002).

Transfer functions were calculated by finding the common earthquakes at or near Lop Nor recorded by MAKZ and individual array elements of MKAR. There were 21 common events which were recorded by at least one array element and MAKZ, spanning the years 2001 through 2003. These events fell within a geographic window of 40° to 45° N and 86° to 94.5° E (Figure 2). Using Equation (3), transfer functions were computed using the MDAC2 residual amplitudes; a unique surrogate-operational station transfer function was found by taking the mean over all transfer functions computed for individual events for each station pair.
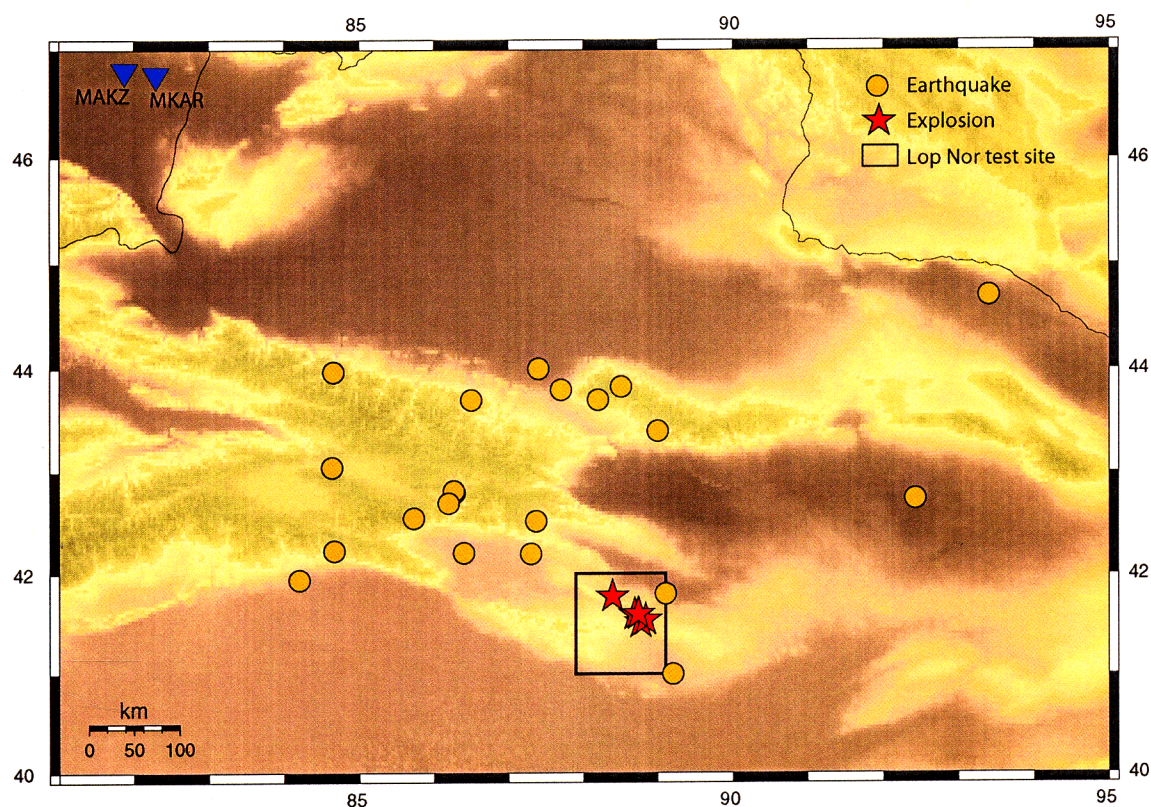

Figure 2. Earthquakes (circles) recorded by at least one element of the Makanchi array and by station MAKZ, spanning from 2001 through 2003. The stars show Lop Nor nuclear explosions recorded by station MAK from 1994 through 1996.

Figure 3 illustrates the transfer function variability for the regional phase Pn across the array, and Figure 4 shows the transfer function variability for MKAR element 04, which lies at the center of the array. Examining the transfer function values across the array show that, while there is a consistent trend with respect to the mean transfer function value for some of the array elements, there is variability across the array. This is an important observation because it suggests that although the array elements are closely spaced (between 0.5 to 3 km), there are site-specific effects that affect the mean transfer function value. In looking at the corrected amplitudes as a function of phase and frequency for element 04, phases Pn and Sn have more high frequency energy at the array element as compared to MAKZ; this is manifested as a higher transfer function value.
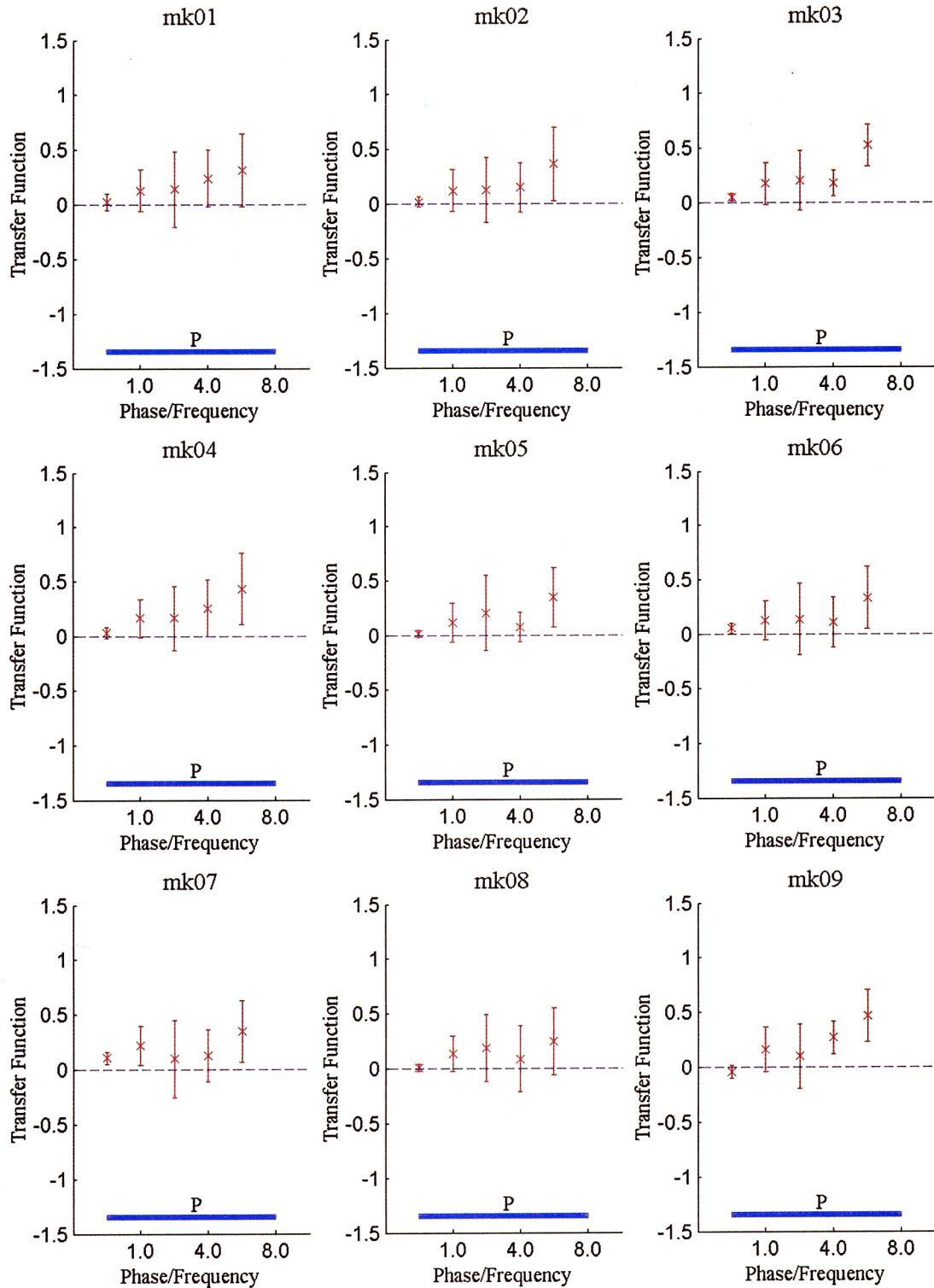
Figure 3. One-sigma error bars show the range of transfer function variability for the regional phase Pn for all nine elements of MKAR. Error bars are shown for the six MDAC2 frequency bands (0.5-1, 1-2, 2-4, 4-6, 6-8, and 8-10 Hz). The "x" in each error bar represents the mean transfer function value which was used in Equation (4) to make MDAC2 residual amplitude predictions using the MAKZ explosions. The dashed line at zero represents a transfer function value of one (in log space).
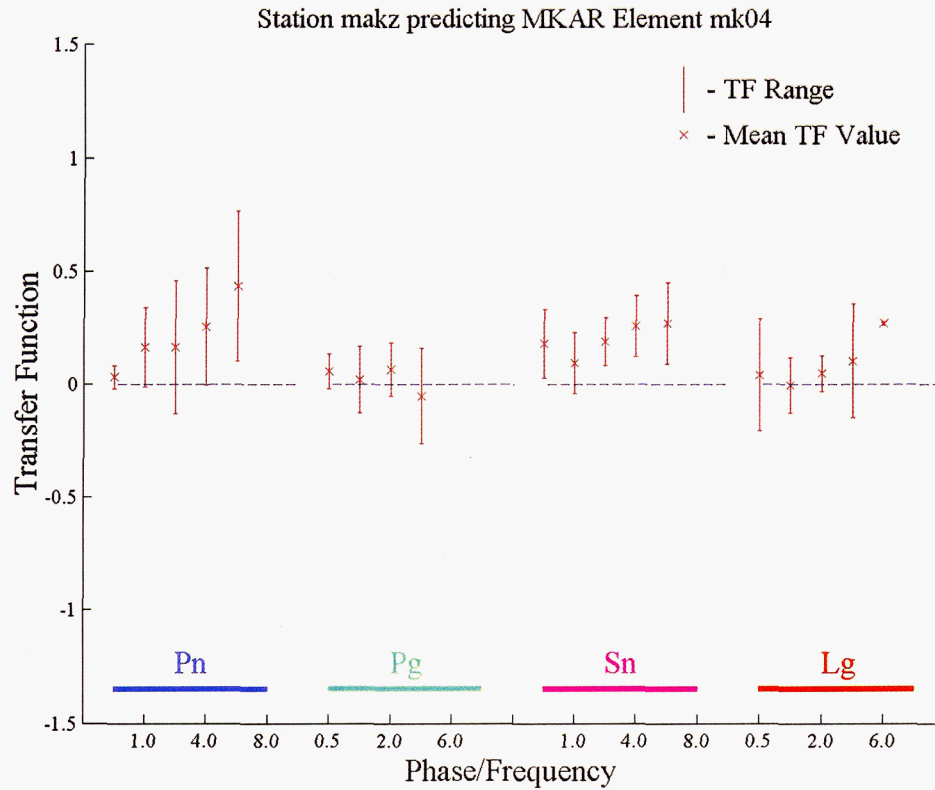
Figure 4. One-sigma error bars show the transfer function variability for MKAR element four, which lies in the center of the array. All four main regional phases are shown, as are the six MDAC2 frequency bands. The dashed line, again, indicates a transfer function value of one (in log space) and the "x" indicates the mean value that was used in the calculation of the predicted explosions.

Using Equation (4), we predicted the MDAC2 residual amplitudes for all nine array elements for the explosions shown in Table 1 recorded at MAKZ. Examining the residual amplitudes versus phase and frequency band for MKAR element 04 (Figure 5) shows typical results – the explosions are enriched in Pn energy and lack strong Sn or Lg energy. This behavior is further quantified by looking at discriminant performance for MKAR element 04. Four strongly-performing discriminants show good population separation between earthquakes and explosions (Figure 6).

Table 1. Explosions recorded at MAKZ

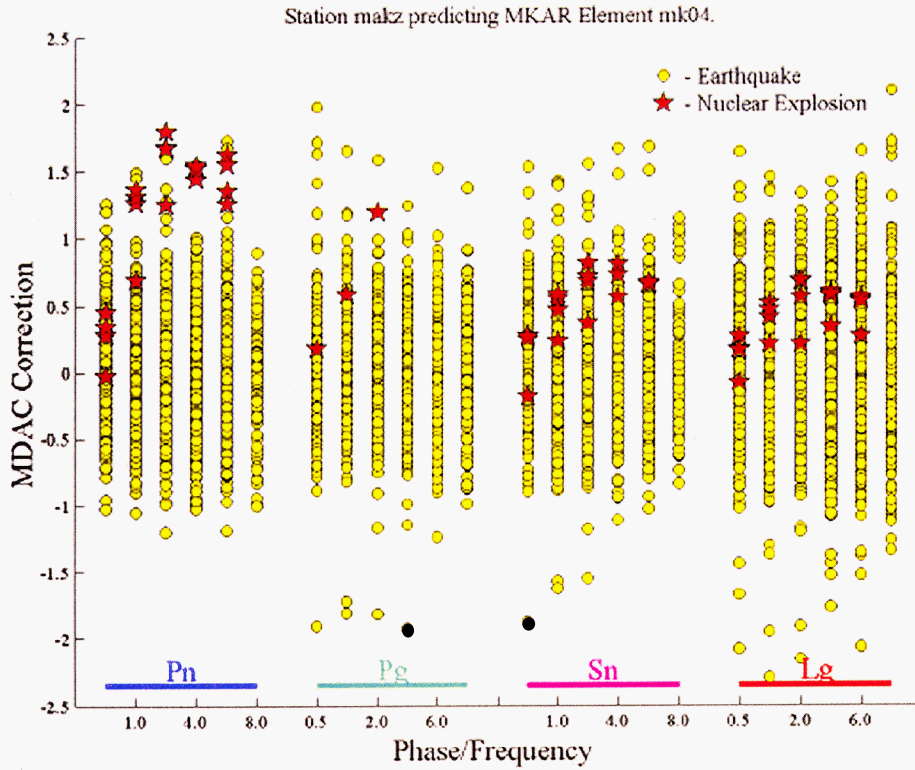| Event date and time	Magnitude (mb)	Latitude (°N)	Longitude (°E)
1994/10/07 03:25:57	6.0	41.57	88.73
1995/05/15 04:05:57	6.1	41.55	88.75
1996/06/08 02:55:57	5.9	41.58	88.69
1996/07/29 01:48:57	4.9	41.72	88.38

Figure 5. MDAC2 residual amplitudes as a function of phase and frequency for MKAR element four. The circles show the range of earthquake values, while the stars show the predicted explosion values.
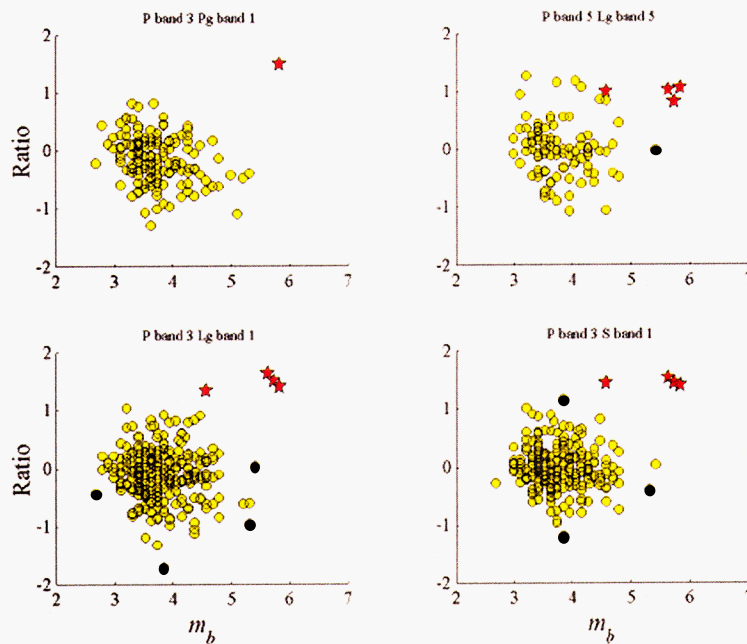

Figure 6. Four discriminants as a function of magnitude (mb) show good population separation between earthquakes (circles) and predicted explosions (stars).

CONCLUSIONS AND RECOMMENDATIONS

Our preliminary work indicates that individual array element transfer functions can be used to simulate explosion spectra at MKAR using explosion spectra at the nearby station MAKZ. Further investigation is needed to determine whether or not using array methods, instead of individual elements, will result in more stable results. Additionally, we need to assess transfer function performance when a maximum likelihood approach (Dempster et al, 1977; Little and Rubin, 1987) is applied to correct for missing data at individual array elements.

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