TRANSFER FUNCTIONS AND SESIMIC DISCRIMINATION

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ABSTRACT

Nuclear explosion monitoring requires both the detection and the identification of underground explosions. Although fundamental source physics can predict the basic character of a seismic recording from an explosion, experience indicates that discrimination between explosions and earthquakes is highly station centric. This is particularly true for recordings at regional distances where propagation and station site effects associated with a complex crustal waveguide can overprint source signature. As new stations are installed in official monitoring networks, the lack of recording history can dramatically affect confidence in discrimination. Though some monitoring stations have established recording histories, a significant portion has never recorded a nuclear explosion. To address this problem, we are investigating procedures to “map” the recording history of a station that has had a long period of operation onto a newly installed station. Our goal is to develop a transfer function to predict the recording at a given seismic station from the actual recording at a nearby station.

To accomplish this, we have used a data set consisting of waveforms from nuclear explosions detonated at the Lop Nor test site in western China as well as earthquakes within a 100-km radius of that site. The waveforms were recorded at the ten-station Kyrgyz [KNET] array located in Kyrgyzstan approximately 1100 km from Lop Nor. The data span from 1992 through 1999 and contain six known explosions and nine earthquakes. The KNET stations are all very broadband (STS-2 seismometers), and have station separations ranging from 30 km to 250 km. The KNET stations are located in a variety of geologic environments, making the assembled data set a good test bed for investigating both the variability of spectral measurements as well as the scale lengths for predicting station-to-station correlations.

OBJECTIVE

Seismic discrimination requires calibration. This is especially true at regional distances where the seismic wavefield has very strong signatures of the travel path, and empirical evidence suggests that even small variation in source-to-station paths can cause unexpected changes in energy partitioning between Pn, Pg, Sn, S and Lg. Although the general characteristics of seismic discriminants, such as high-frequency P-to-S amplitude ratios, can be used to qualitatively identify explosions, only a database with ground truth explosions will allow quantitative and statistical assessment of identification capabilities. However, many of the IMS and other monitoring stations have never recorded a nuclear event at regional distances. For this reason we are using *historical* recordings of nuclear explosions at stations near the locations of present monitoring seismic stations to devise a methodology to predict discrimination.

The basic problem of discrimination is to clearly determine whether an unknown seismic waveform was generated by an explosion or an earthquake. Various discriminants, such as the Pn/Lg show variability from event to event: in other words, the discriminants do not define a point but rather a population. Discrimination then becomes a problem of separating populations of measurements associated with explosions and earthquakes. For regional spectral discriminants there is no single measurement that separates populations for all regions, even after corrections for propagation and size (for example MDAC, or magnitude-distance amplitude corrections); thus, regional discrimination is largely an empirical technique in which spectral ratios from ground truth events are used to statistically assess the source character of an unknown event. If no ground truth events exist for nuclear explosions, then some technique must be used to simulate the expected seismic waveforms. This requires at least three transfer or 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. There are several ways to develop these transfer functions or filters. Our objective in this research project is to develop techniques for transfer functions, and to develop understanding of transportability of regional discriminants.

RESEARCH ACCOMPLISHED

We have explored the possibility of generating transfer functions using ratios for various spectral bands for known events. The basic problem can be analyzed using the frequency-domain model for seismic-wave generation and propagation. Consider the observed amplitude spectrum between a given source, *i*, and receiver, *j*, to be given by:

$$A_{ij}(\omega) = S_i(\omega)E_{ij}(\omega)P_j(\omega) \qquad (1)$$

where S is the source-excitation spectrum, E is the Earth response, and P is the site response. Letting $i = X,Q$ for explosion, earthquake, respectively and $j = S,O$ for surrogate and operational station, respectively, we can write three equations representing the data that will be available for calibrating a new station

$$\begin{aligned} A_{QS}(\omega) &= S_Q(\omega)E_{QS}(\omega)P_S(\omega) \\ A_{QO}(\omega) &= S_Q(\omega)E_{QO}(\omega)P_O(\omega) \\ A_{XS}(\omega) &= S_X(\omega)E_{XS}(\omega)P_S(\omega) \end{aligned} \qquad (2)$$

and we wish to predict what the explosion spectra will look like at the operational station

$$A_{XO}(\omega) = S_X(\omega)E_{XO}(\omega)P_O(\omega) \qquad (3)$$

For a common source (assume a well-recorded earthquake for this example) recorded at both S and O, we wish to predict the explosion characteristics at O. We note that it is necessary for the calibration earthquake to be in the vicinity of the region being monitored (*how close* is one of the questions we will consider in this study). Computing a spectral ratio for the calibration earthquake recorded at S and O (using equation 2)

$$\frac{A_{QO}(\omega)}{A_{QS}(\omega)} = \frac{E_{QO}(\omega)P_O(\omega)}{E_{QS}(\omega)P_S(\omega)} = T_Q(\omega) \tag{4}$$

so

$$A_{QO}(\omega) = T_Q(\omega)A_{QS}(\omega) \tag{5}$$

Similarly,

$$\frac{A_{XO}(\omega)}{A_{XS}(\omega)} = \frac{E_{XO}(\omega)P_O(\omega)}{E_{XS}(\omega)P_S(\omega)} = T_X(\omega) \tag{6}$$

and

$$A_{XO}(\omega) = T_X(\omega)A_{XS}(\omega) \tag{7}$$

Noting that we do not actually have $A_{XO}(\omega)$, we wish to study if we can predict it from

$$A_{XO}(\omega) = T_Q(\omega)A_{XS}(\omega) \tag{8}$$

The fundamental question that we wish to answer in this study is whether equation (8) is applicable to the problem of predicting explosion characteristics at a newly operational seismic station and, if so, what are the associated limitations and errors. This is equivalent to asking "is $T_X(\omega) = T_Q(\omega)$?". From equations (4) and (6) we have

$$\frac{E_{XO}(\omega)P_O(\omega)}{E_{XS}(\omega)P_S(\omega)} = \frac{E_{QO}(\omega)P_O(\omega)}{E_{QS}(\omega)P_S(\omega)} \tag{9}$$

Thus, we are assuming

$$\frac{E_{XO}(\omega)}{E_{XS}(\omega)} \approx \frac{E_{QO}(\omega)}{E_{QS}(\omega)} \tag{10}$$

Obviously, there are potentially many limitations to this assumption. Examples include depth effects (i.e. depth $Q >$ depth X), source-mechanism effects, and differences in location. Keeping in mind that discriminants are typically computed by taking logarithms of spectral ratios, some of these effects may be reduced by analyzing a number of calibration events.

We have developed a test bed to examine the nature of the transfer functions. The test data consist of waveforms from nuclear explosions detonated at the Lop Nor test site in western China as well as earthquakes within a 100-km radius. The waveforms were recorded at the ten-station Kyrgyz [KNET] array located in Kyrgyzstan approximately 1100 km from Lop Nor. The data span from 1992 through 1999 and contains six known explosions and nine earthquakes. The KNET stations are all very broadband (STS-2 seismometers), and have station separations ranging from 30 km to 250 km. The KNET stations are located in a variety of geologic environments, making the assembled data set a good test bed for investigating both the variability of spectral measurements as well as the scale lengths for predicting station-to-station correlations. The data are presented in Table 1.

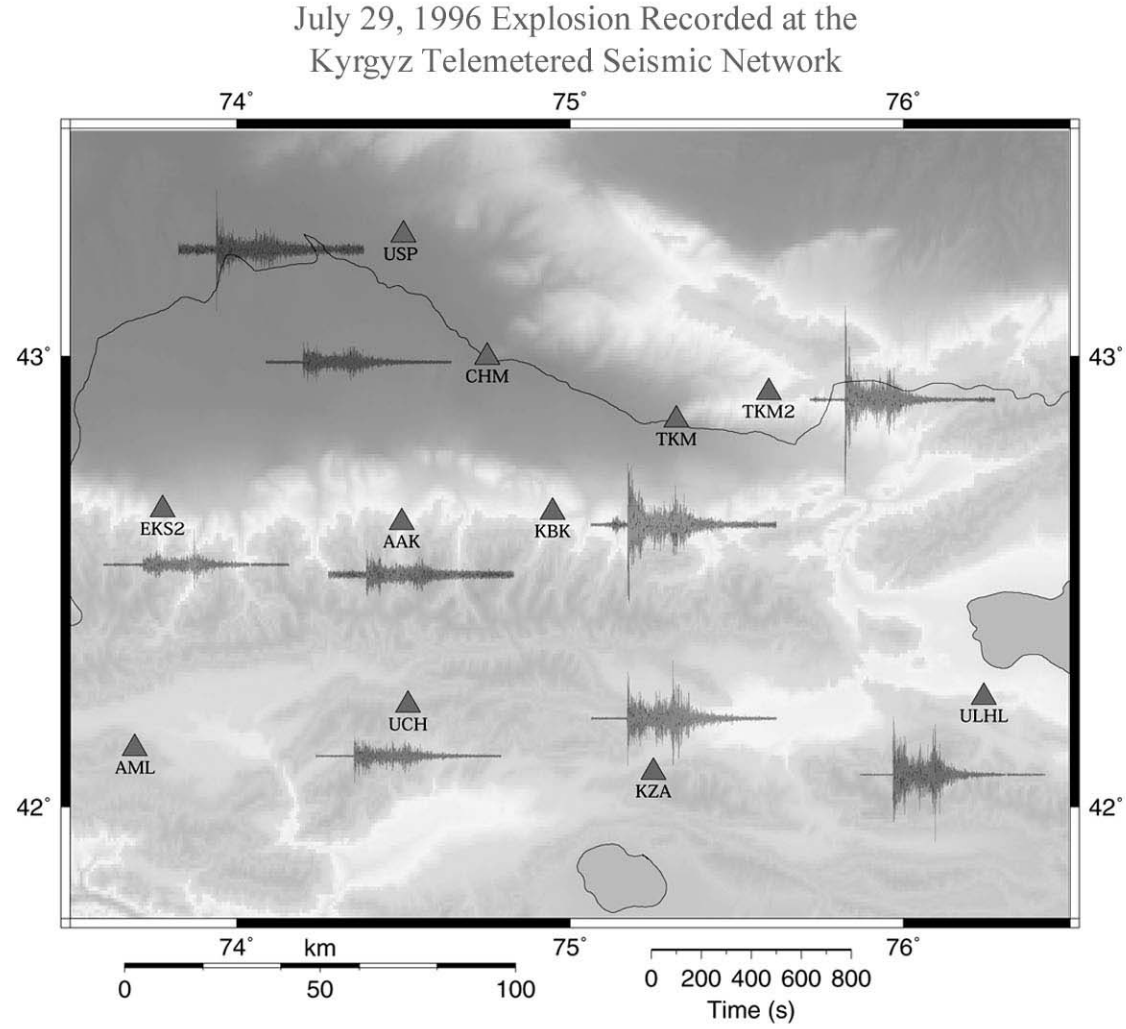


Figure 1: Waveform variability across KNET for the Lop Nor explosion of July 29,1996. Waveforms are on the same amplitude scale, and approximately 800 seconds of record are shown.

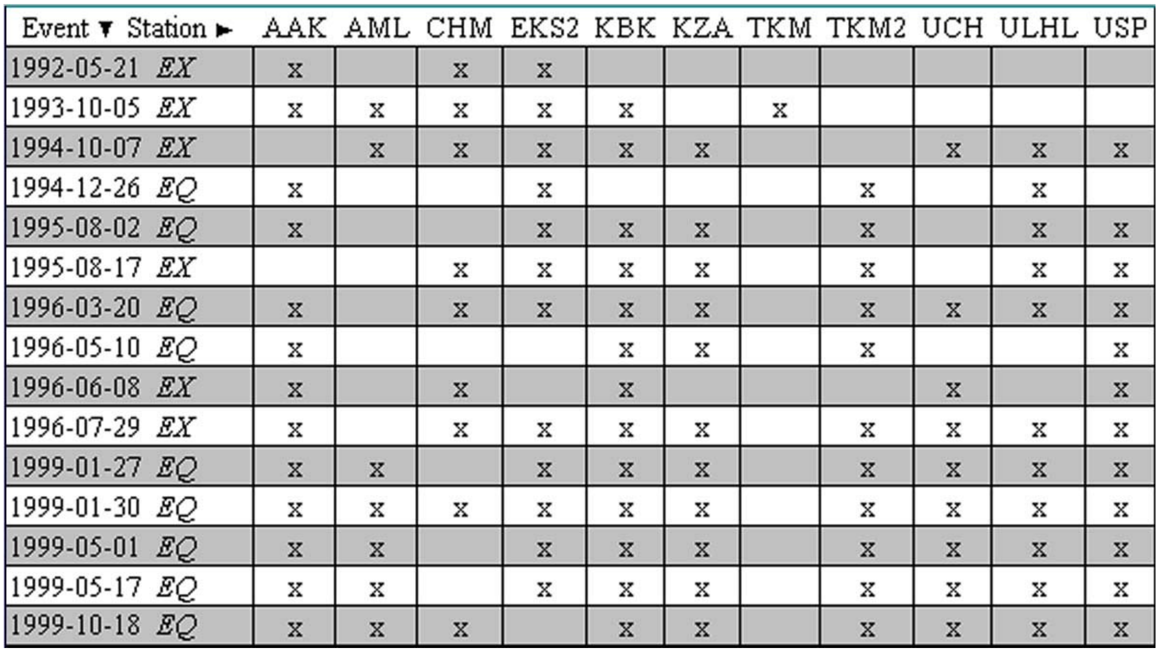
Figure 1 shows the waveforms from the former People's Republic of China (PRC) underground test on July 29, 1996; there is a remarkable change in waveform character across KNET. Stations east of KBK (and including KBK) have very large relative P wave amplitudes, whereas those to the west have smaller absolute amplitudes, and the P to S (or Lg) energy dramatically decreases. There is no surface geology that might explain this variation, although the trend is repeated for all Lop Nor explosions.

The challenge posed by what is shown in Figure 1 is basic to developing transfer functions.

- How does the transfer function developed for earthquakes distort the spectral signatures for explosions?
- Over what range of distances can sources be distributed and still yield reliable transfer spectra? A complementary question is
- Over what scale lengths can transfer functions be applied?

As a first test of a transfer function procedure, we have used measurements of various spectral discriminates made at KBK to “predict” the behavior of the discriminants at other stations. A value of the ratio pair for KBK – Station (where station is any of the KNET stations) for a calibration explosion is used to calculate an expected value of the spectral discriminant for all other explosions recorded. Figure 2 shows the results for four different spectral discriminants.

Table 1: Data used in the transfer function analysis. *EX* =explosion, *EQ*=earthquake. The x denotes whether the event was recorded by a given station.



Event ▼ Station ►	AAK	AML	CHM	EKS2	KBK	KZA	TKM	TKM2	UCH	ULHL	USP
1992-05-21 *EX*	x		x	x							
1993-10-05 *EX*	x	x	x	x	x		x				
1994-10-07 *EX*		x	x	x	x	x			x	x	x
1994-12-26 *EQ*	x			x				x		x	
1995-08-02 *EQ*	x			x	x	x		x		x	x
1995-08-17 *EX*			x	x	x	x		x		x	x
1996-03-20 *EQ*	x		x	x	x	x		x	x	x	x
1996-05-10 *EQ*	x				x	x		x			x
1996-06-08 *EX*	x		x		x				x		x
1996-07-29 *EX*	x		x	x	x	x		x	x	x	x
1999-01-27 *EQ*	x	x		x	x	x		x	x	x	x
1999-01-30 *EQ*	x	x	x	x	x	x		x	x	x	x
1999-05-01 *EQ*	x	x		x	x	x		x	x	x	x
1999-05-17 *EQ*	x	x		x	x	x		x	x	x	x
1999-10-18 *EQ*	x	x	x		x	x		x	x	x	x

CONCLUSIONS AND RECOMMENDATIONS

Preliminary tests on transporting spectral discriminants from a station being used for calibration to nearby stations show that simple procedures work even when stations are separated by more than 100 km. Further, although the signature of receiver geology and topography on the individual waveforms appears to be significant, the repeatability of the spectral ratios is robust. At present we have only tested explosion-to-explosion transfer functions, and the next step is to develop the statistical population of earthquake-to-earthquake transfer functions. Finally, we will explore the cross-source transfer functions (explosion-to-earthquakes).

ACKNOWLEDGEMENTS

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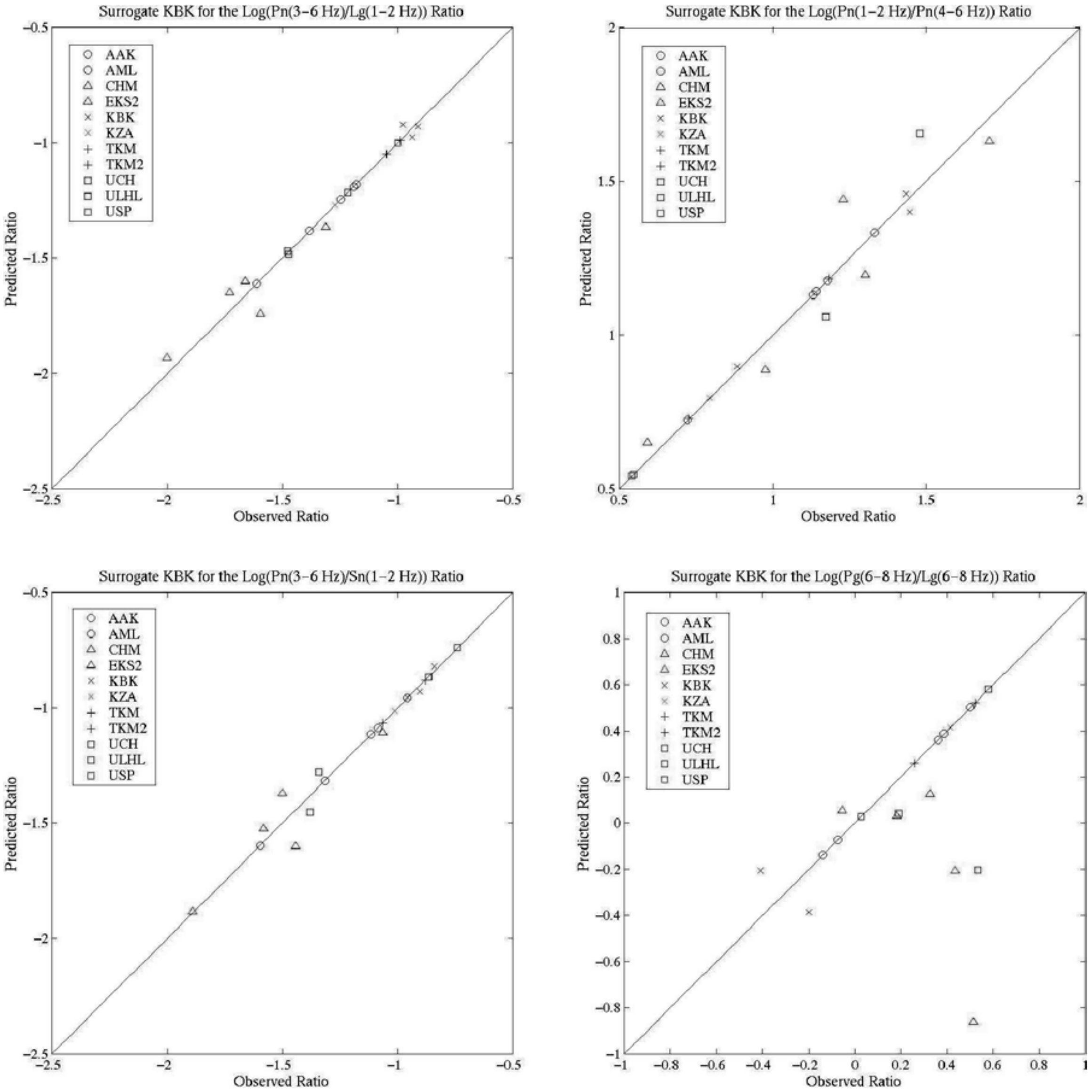

Figure 2: Performance of transfer functions for various spectral discriminates. KBK is the calibration station, and the "known" explosion is the average of the transfer function for five Lop Nor explosions. The predicted value gives the result from the transfer function.