SEISMIC SOURCE LOCATIONS AND PARAMETERS FOR SPARSE NETWORKS BY MATCHING OBSERVED SEISMOGRAMS TO SEMI-EMPIRICAL SYNTHETIC SEISMOGRAMS: APPLICATIONS TO LOP NOR AND NORTH KOREA

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ABSTRACT

The purpose of this study is to demonstrate the feasibility of a full-waveform earthquake location using semi-empirical synthetic waveforms and received data from as few as two regional stations. We previously demonstrated the ability to locate both natural and man made events using events from Central California (natural events) and the Nevada Test Site (NTS) (natural and man-made events). We were able to locate most events to within GT 5 (based on a comparison with the reference (GT, ground truth) catalog and our estimates of the precision of the error ellipses. This precision includes events with varying depths, mechanisms, location, and size. Of particular interest is the ability to simulate and locate an earthquake waveform (Little Skull Mountain, LSM) using an explosion reference event (NTS explosion JUNCTION). Reciprocity suggests that the earthquake could be used to simulate the waveforms from explosions.

In this presentation, the focus is two-fold: first, we present the results of the location study as applied to a Lop Nor, China data set; second, we present parameter extract (yield) of a nuclear explosion (North Korea) based on a distant reference event using records from one station. The Lop Nor example demonstrates (1) the portability of the approach, and (2) the ability to apply it to regions of interest for nuclear monitoring. Unlike the US datasets, general high quality ground truth is only available for a few events: the explosions at Lop Nor (GT from Fisk, 2002). Locations of the nearby earthquakes are not known with enough precision to assess our ability to obtain GT 5 or better location; indeed, it is possible that our locations are the best.

In comparison, the North Korea Nuclear explosion of October 9, 2006, occurred in a seismically isolated region (no nearby earthquakes). However, an active source experiment for wide-angle reflection and refraction near the border in China (Wu, personal communications) provides some sort of calibration. While the yield from the China experiment was small (1.2–1.5 tons, according to Wu), a good signal was recorded at the station MDJ for one particular explosion. This event, roughly ½ way between the North Korean Nuclear Explosion and MDJ, provides our reference event for our yield estimate of the North Korean Nuclear Explosion, which is about 450 tons.

OBJECTIVES

The objective of the research is to provide a method that gives accurate locations (GT5) and source mechanisms using a sparse regional network when two or more seismic stations record the event. Tests using synthetic waveforms indicate that location accuracy on the order of 300–500 km^2 and depth uncertainty of less than 5 km can be obtained with recordings from only two stations low pass-filtered at 0.5 Hz using hold waveforms or 0.1 Hz when using just the Rayleigh waves.

The objective of this paper is two-fold:

- Demonstrate the applicability of our semi-empirical approach outside of the United States by applying it to events in the region around the Lop Nor Test Site.
- Apply the semi-empirical methodology to determine the Yield and characteristics of the October 9, 2006, North Korean Nuclear Test.

RESEARCH ACCOMPLISHED

Portability of the Semi-Empirical Method

We previously derived our semi-empirical methodology from the following equation:

$$u_e(\omega,r) = \frac{s(\omega)}{u(\omega,r_o)} \cdot e^{i\Delta k(r-r_o)} \cdot u(\omega,r) \quad , \qquad (1)$$

where u is the synthetic seismogram, s is the observed seismogram, r_o is the range to the reference event, r is the range to the new event, and Δk is the wave number corresponding the phase mismatch reference data and synthetic (Salzberg et al., 2005, 2006).

This approach has been demonstrated by applying it to regional waveforms from both Central California earthquakes and NTS explosions; the results are shown in Figures 1 and 2. We have begun analysis of events around the Chinese Lop Nor test site, particularly those assigned GT1 by Fisk (2002). Preliminary results based on one station show that we are able to resolve the correct range (Figure 3), even with a nearest station at about 1150 km.

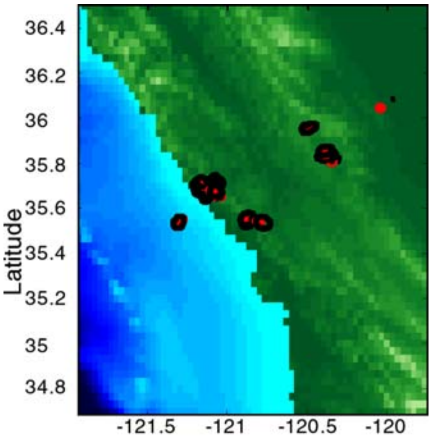

Figure 1. The error ellipses for our relocated earthquakes relative to an aftershock of the Parkfield earthquake. The lines represent the error in our location compared with GT (red circles).

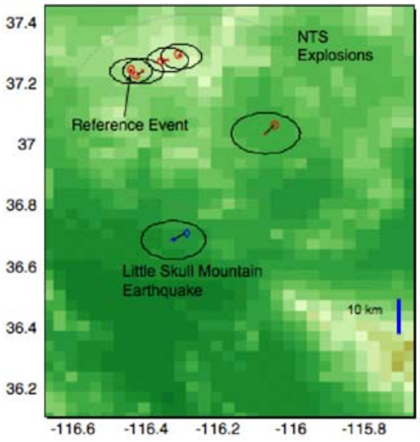

Figure 2. The error ellipses for our relocated explosions and the LSM earthquake. The lines represent the error in our location compared with GT (red circles). The blue vertical line on the right is 10 km long. In all cases, the mislocation is less than 5 km, though for the LSM earthquake, the mean axis of the error ellipse approaches 5 km.

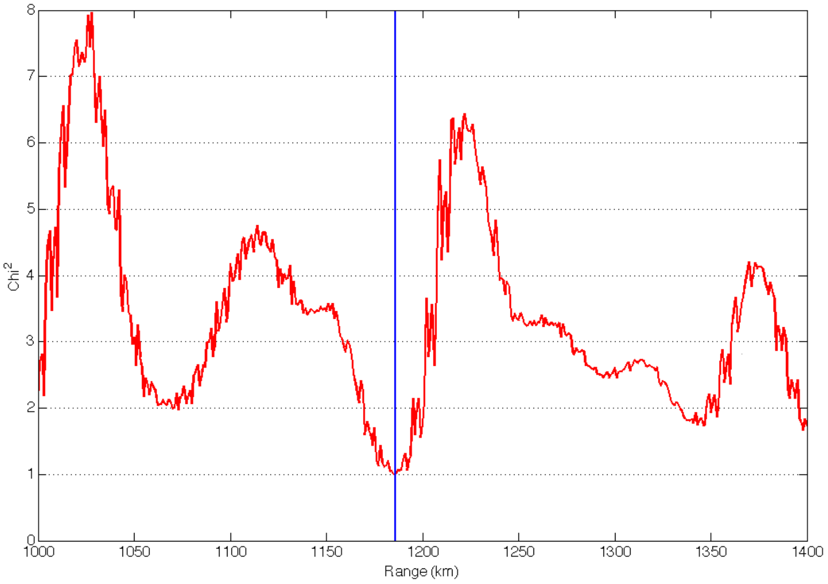

Figure 3. χ^2 vs. range for the May 1992 nuclear explosion recorded at station AAK. The minimum in χ^2 is at the correct GT range, indicating that the range was successfully estimated.

Analysis of the North Korean Nuclear Test

Introduction

We have used a slight modification of our semi-empirical synthetic seismogram method of Salzberg (2005, 2006) to estimate the yield of the North Korea Nuclear test of October 09, 2006. The data used for the processing is from the seismic station,MDJ, which is located in northeastern China, as shown in Figure 4. The reference data, used for calibration, was from a wide-angle refraction experiment. The 1.2- to 1.5-t shot was set off 190 km south of MDJ, or about ½ way between the North Korean test and MDJ. While the data for the Chinese reference event is noisy (Figure 5), at higher frequency bands, (> 1 Hz), the signal is clear. The signal for the North Korea Nuclear test has significant signal at all frequencies (Figure 6).

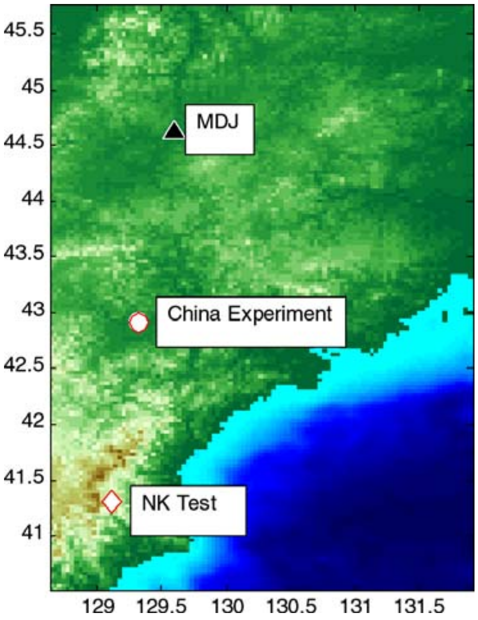

Figure 4. A map showing the relative locations of the North Korean test, the China experiment, and the seismic station MDJ.

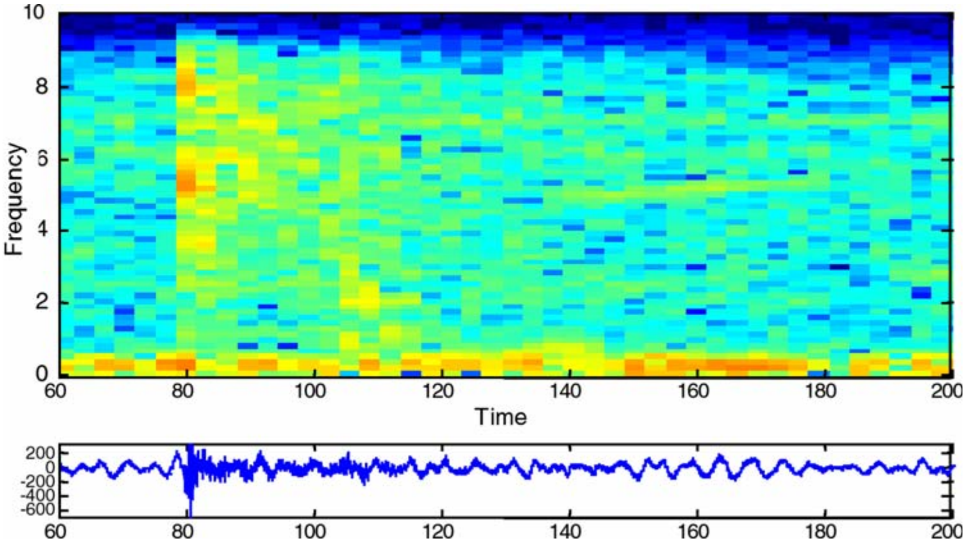

Figure 5. Unprocessed waveform and spectrogram for the waveform from a wide-angle refraction/reflection experiment in northeastern China (1.2–1.5 t). This event is used as a reference event.

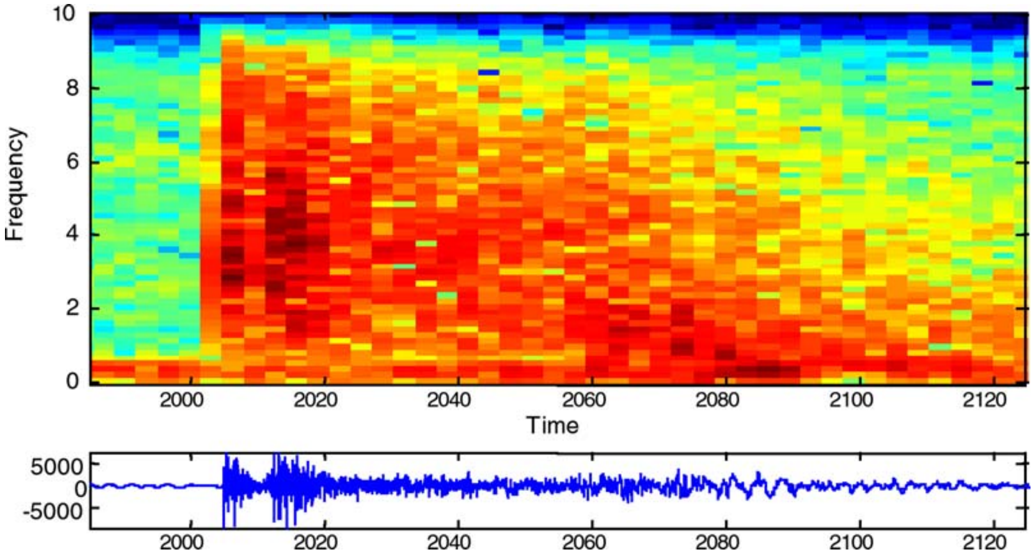

Figure 6. Unprocessed waveform and spectrogram for the North Korean nuclear test.

Method

The approach is to compute a semi-empirical synthetic, which is expressed as

$$new(\omega)=\frac{reference(\omega)}{synthetic_{reference}(\omega)}\cdot synthetic_{new}(\omega),$$

where *reference* and *new* refer to the observed waveforms, and *synthetic* refers to the synthetic waveform computed for a specific event range, depth, and mechanism. Thus, as we know the location of the nuclear and chemical explosions, the mechanism (assumed to be isotropic explosion), and the yield for the chemical shot, formulation can be rewritten to

$$new(\omega)=\frac{reference(\omega)}{synthetic_{reference}(\omega)\cdot yield_{reference}}\cdot synthetic_{new}(\omega)\cdot yield_{new},$$

where the synthetics are computed for the same yield.

Application

As the separation between the reference event (Chinese experiment) and the North Korean explosion was significant (190 km, or ½ of the propagation distance, shown in Figure 4), and the frequency content of the data required high-frequency (>5 Hz) analysis, a coherent comparison was not feasible. Instead, the yield will be estimated by integrating (or summing) the energy envelopes. The data (high-pass filtered at 2 Hz) for the two events are shown in Figure 7. Conceptually, this approach can be viewed as comparing the integrated energy envelopes of the data (Figure 8) and synthetics (Figure 9). This is represented as

$$Yield_{NK} = Yeild_{CN} \cdot \frac{\sum O_{NK}}{\sum O_{CN}} \cdot \frac{\sum S_{CN}}{\sum S_{NK}} ,$$

where *O* is the energy envelope for the observations of the two events, *S* is the energy envelope of the synthetics for the two events, the subscript *NK* refers to the North Korean test, and *CN* refers to the China experiment. The yield results are shown in Table 1 are obtained by multiplying the synthetic fact (3.7) by the observation difference (50) by the yield (1.2–1.5 t), which gives 222 to 277 t.

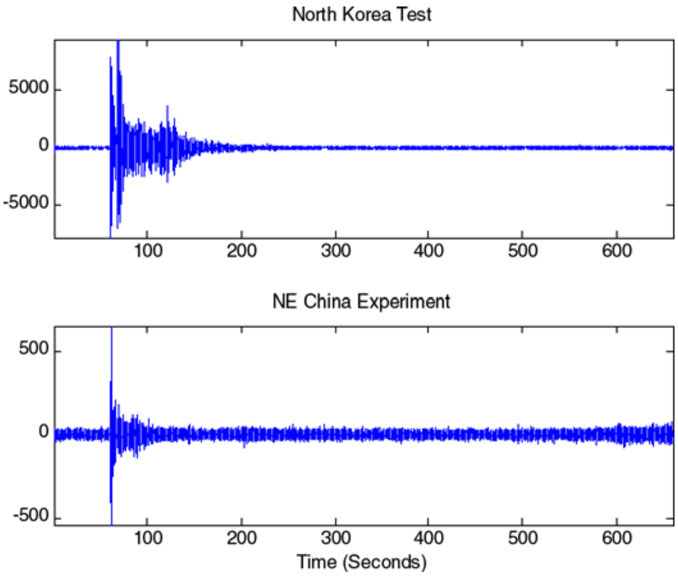

Figure 7. High-pass filtered waveforms at 2 Hz for the North Korean test and the Chinese experiment. The high-pass filtering significantly enhances the signal-to-noise ratio.

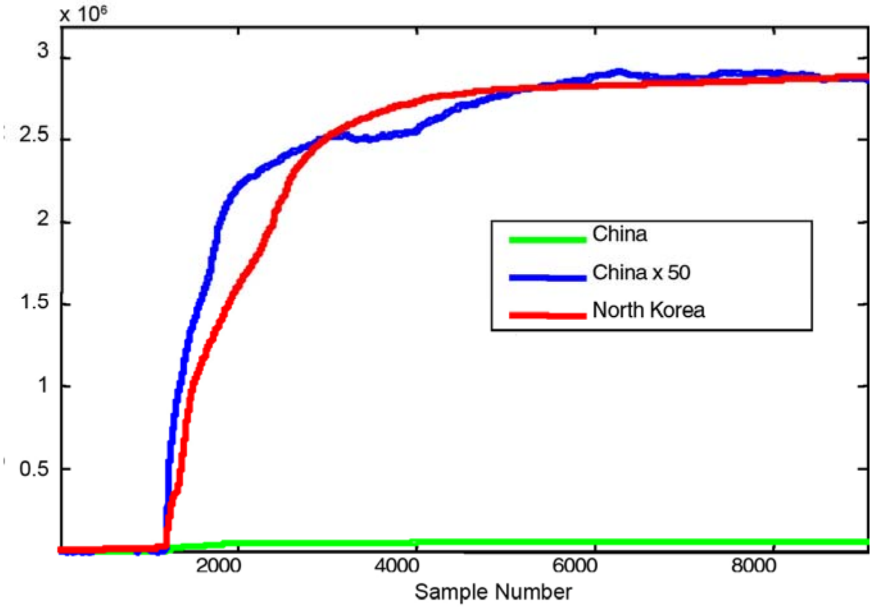

Figure 8. The integrated energy envelope for the waveform data from the North Korean test (red), the China experiment (green), and the scaled China experiment (blue). A scaling factor of 50 was used.

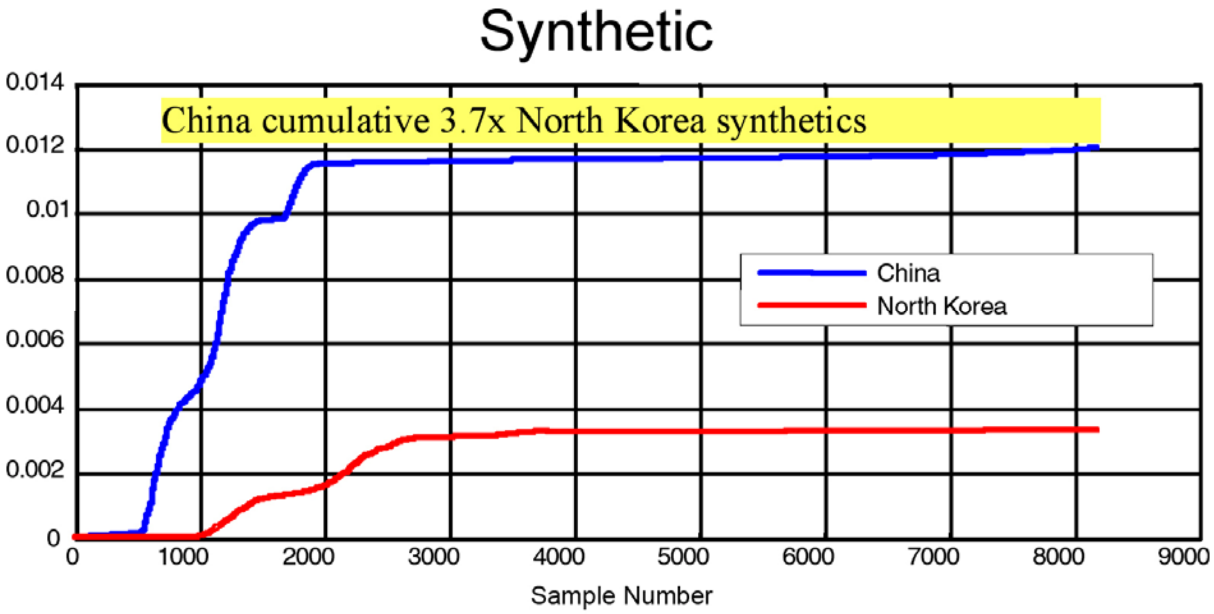

Figure 9. The integrated energy envelope for the synthetic waveforms from the North Korean test (red) and the China experiment (blue). The curve differences result from the differing event-station distances (390 vs. 190 km).

Applying the empirical approach, and using synthetic seismograms that were computed using the IASPEI velocity model (Kennett and Engdahl, 1991) and Herrmann’s (2002) wave number integration software for source depths of 0.5 km at ranges of 190.5 m (China) and 369.5 km (North Korea). The empirical filtering was then used to transform the synthetic for China, and a scaling factor was determined by (1) windowing both the empirically filtered synthetic and the observed data using a window based on the signal to noise levels, and(2) summing the windowed envelopes.

Noise reduction

As an alternative to using the high-pass filtering to improve the signal-to-noise ratio of the China test, we investigated using a Savitzky-Golay smoothing filter (Orfanidis, 1996) to characterize the noise. The noise is then subtracted from the observed waveform for further processing. The results, shown in Figure 10, indicate that this approach can be used to minimize the longer period noise. The reduced long-period noise will allow for the processing at longer periods. These results are shown in Figure 11, and listed in Table 1.

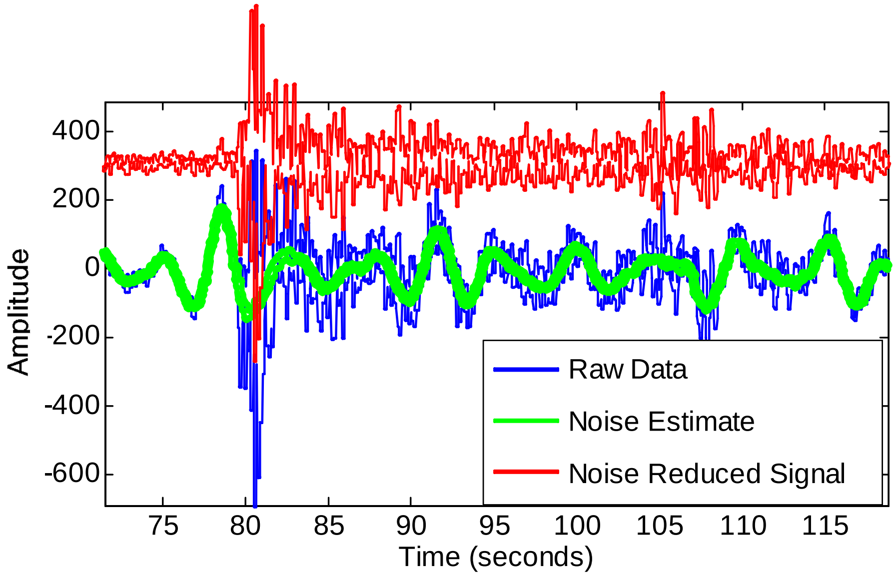

Figure 10. The raw data (blue), the noise estimate (green), and the residual (red) indicates that the Savitzky-Golay smoothing filter is successful in modeling the noise, allowing us to remove the noise from the data.

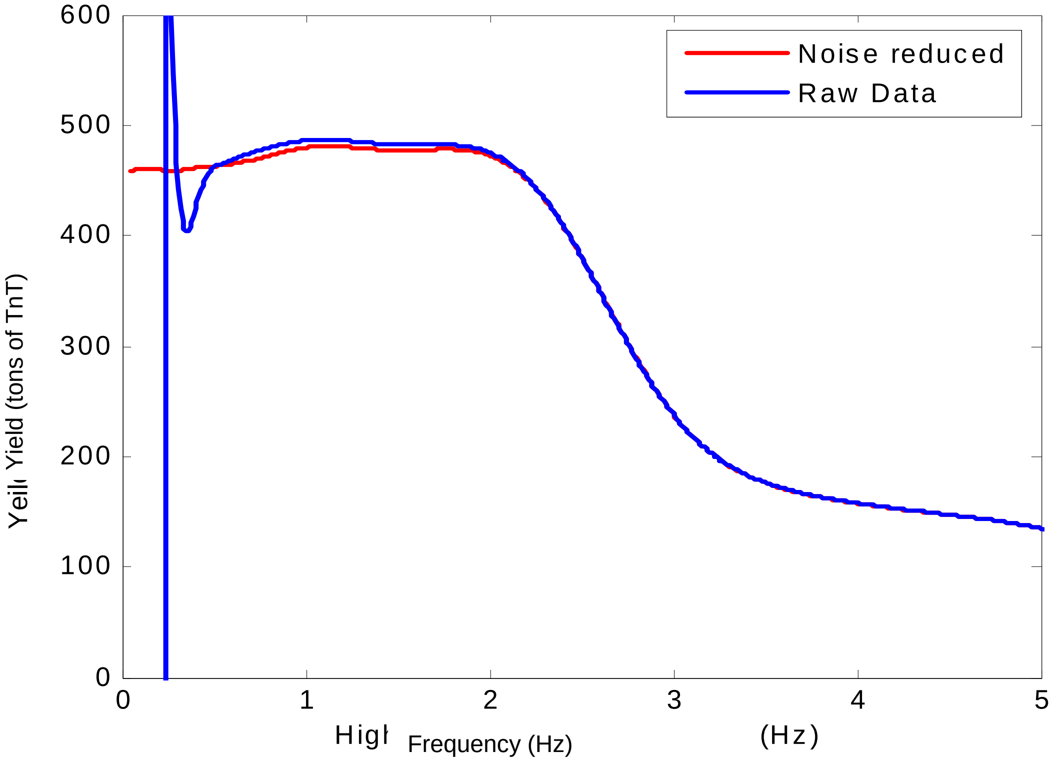

Figure 11. Yield estimates (in tons, vertical axis) based on the noise-corrected data as a function of high-pass filtered corner frequency. This shows, that at higher frequencies, the yield estimates are lower than a more broadband solution.

Table 1: Yields with the different approaches.

Approach	Yield (1.2 t ref)	Yield (1.5 t ref)
Integrated Energy Envelopes	222	277
Semi-empirical, high-passed at 2 Hz, non-corrected.	213	267
Noise-corrected semi-empirical approach, broad band	372	465

CONCLUSIONS AND RECOMMENDATIONS

In this and prior publications, we have demonstrated the utility of semi-empirical Green's functions for both source locations and source parameter extraction. In particular, we have showed that when a reference event and new event are nearly co-located, we can use a high frequency whole waveform approach to determine location to within ½ km. Once the two events are separated by more than a few kilometers, the differential propagation velocities of the various seismic phases requires a phase-by-phase (wave number based) approach. With such an approach, we are able to locate events to within GT5 even when the events have different mechanisms and are separated by more than 50 km. Furthermore, we demonstrated the ability to use the approach in a variety of regions: Central California, NTS, and Lop Nor, China. We also demonstrated the ability to use the semi-empirical approach to determine source parameters (Yield) for the 2006 North Korean Explosion, even though the reference event was 180 km away.

The technique is promising. As is, it could provide the capability to enhance locations to GT5 levels in regions of interest. With additional focused research, it is likely that the approach would allow for accurate (GT2 or better) locations in many regions of interest. In addition, the ability of this approach to allow for varying mechanisms could be combined with subspace detection technology (Harris, 2006) to provide a subspace detector whose basis functions are moment tensor elements. Finally, it would be worthwhile to apply the yield estimate approach to areas with known yields, such as NTS, to provide increased confidence in the approach.

ACKNOWLEDGEMENTS

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REFERENCES

Fisk, M. (2002). Accurate locations of nuclear explosions at the Lop Nor Test Site using alignment of seismograms and IKONOS satellite imagery, *Bull. Seism. Soc. Am.* 92: 2911–2922.

Harris, D. (2006). Subspace detectors: Theory, Lawrence Livermore National Laboratory report #UCRL-TR-222758.

Herrmann, R. H. (2002). *Computer Programs in Seismology*, http://www.eas.slu.edu/People/RBHerrmann/CPS330.html

Kennett, B. and Engdahl, E. (1991). Travel times for global earthquake location and phase identification, *Geophys. J. Int.* 105: 429–465.

Orfanidis, S. J. (1996). *Introduction to Signal Processing*. (Englewood Cliffs, NJ: Prentice-Hall).

Salzberg, David H., Simultaneous inversion of moderate earthquakes using body and surface waves: Methodology and applications to the study of the tectonics of Taiwan, Ph.D. thesis, State University of New York at Binghamton, Binghamton, NY.

Salzberg, David H., Karen E. Votaw, and Margaret E. Marshall (2005). Seismic source locations and parameters for sparse networks by matching observed seismograms to semi-empirical synthetic seismograms, in *Proceedings of the 27th Seismic Research Review: Ground-Based Nuclear Explosion Monitoring Technologies*, LA-UR-05-6407, Vol. 1, pp. 454–462.

Salzberg, David H. and Margaret E. Marshall (2006). Seismic source locations and parameters for sparse networks by matching observed seismograms to semi-empirical synthetic seismograms, in *Proceedings of the 28th Seismic Research Review: Ground-Based Nuclear Explosion Monitoring Technologies*, LA-UR-06-5471, Vo 1, pp. 484–492.