A STUDY OF REGIONAL WAVE EXCITATION BY CLUSTERED UNDERGROUND EXPLOSIONS USING A RECIPROCAL THEOREM

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

Contract No. DE-FC52-03NA99514

ABSTRACT

Hundreds of clustered underground nuclear explosions (UNE) in central Asia and Nevada between 1970 and 1990 were recorded at common regional stations. Under a reciprocal theorem, these waveforms provide a dense time-space domain sampling of the wavefield in the near source region. We propose a three-stage study of the waveforms. In the first stage we shall use the source array to conduct a frequency-slowness power spectra (FSPS) analysis to determine the plane-wave composition of regional P and S waves as they leave the sources. In each frequency band we shall estimate the powers of various wavelets, including the direct, “diving” body wavelets and the scattered/multipathed waves, such as the lower frequency Rg waves. In the second and third stages we shall examine the compatibility between the observed FSPS and each of the previously proposed physical mechanisms for regional wave excitations by explosions. We will then attempt to improve the best-fit source model and develop better explosion discriminants.

Our efforts have been focused on three tasks. First we have been collecting data from the Borovoye Digital Seismogram Archive (1964-1989). Waveforms were recorded with older, narrow band, low dynamic range systems. Certain critical channels were very often contaminated by random spurious spikes. We have developed and applied a simple algorithm to rapidly, and reliably remove the spikes, resulting in a large number of cleaned waveforms. Second, we have been collecting information on accurate source locations, depths and origin times of the Balapan explosions. This information is critical to a successful reciprocal analysis. Third, we have been developing and implementing the FSPS algorithm. We plan to obtain the FSPS of the Balapan regional waves in the next several months.

OBJECTIVE

The primary objective of this research project is to better understand how regional P (Pn, Pg) and S waves (Sn, Lg) are generated by underground nuclear explosions (UNE) of various sizes, with various depths and testing styles, in various frequency bands and geological environments. This understanding will be achieved by using clustered historical UNEs, recorded by regional single-stations, as source arrays in a reciprocal geometry. A frequency-slowness power spectral (FSPS) analysis will be applied to the array recordings of the regional waves in the reciprocal geometry.

Research prior to this project already show that for UNE in central Asia, the source corner frequencies (fc) of regional P and S waves are very different. This difference explains why there has been an observed, statistical trend for the Pn/Lg ratios to be dependent on the frequency and explosions' magnitudes. To explore why there is such a difference in fc values of regional P and S waves, we shall conduct a comprehensive study to understand different excitation processes of the regional P and S waves from UNEs. Hundreds of clustered UNEs in central Asia and Nevada between the 1970s and 1990s were recorded at common regional stations. Under a reciprocal theorem, these waveforms provide dense time-space domain sampling of the wavefields in the near source region. We shall conduct a three-stage study of the waveforms. Firstly we shall use the source array to conduct a frequency-slowness power spectra (FSPS) analysis to determine the plane-wave composition of regional P and S waves as they leave the sources. In each frequency band we shall estimate the powers of various wavelets, including the direct, "diving" body wavelets and the scattered/multipathed waves, such as the lower frequency Rg waves. A bi-product of this stage will consist of improved depth estimates of the UNEs in central Asia.

In the second stage we shall examine the compatibility between the observed FSPS and each of the previously proposed physical mechanisms for regional wave excitations. The best-fit mechanism will be found for each phase, in each frequency band and test site.

In the third stage we shall replace our simplified mathematical model of explosion sources by better models corresponding to the best excitation mechanisms determined in the second stage. We shall use the improved model to estimate source spectral parameters, including seismic moments and corner frequencies. We shall develop scalings of these parameters with event magnitudes and depths, and explore the dynamic relations among all these parameters and testing styles, local structures, and geological environments. Accordingly, dynamic correction procedures will be developed for transporting the P/S spectral ratio discriminant across different frequencies, magnitudes and testing conditions.

RESEARCH ACCOMPLISHED

We are only in the beginning stage of this research project. In the following paragraphs, we summarize the developments in the first few months.

Algorithm development on the reciprocal theorem and f-k spectra

In this research we collect regional waveforms from multiple clustered UNEs conducted between 1970s and 1990s. If the source locations can be determined with a theoretically tolerable precision, then we can apply a reciprocal theorem, in which the physical UNE sources become fictitious sites of "array stations", and the physical recording station becomes a fictitious "source". We can then form frequency-wavenumber (f-k) spectra in an array analysis in the reciprocal geometry and examine the frequency-slowness composition of the fictitious "incoming" regional waves. Physically, in the true geometry, the latter examination is roughly equivalent to an examination of the frequency-slowness composition of the regional waves as they leave the explosion sources. Below we give a more rigorous description of the reciprocal theorem and formation of the f-k spectra.

The reciprocal property of path Green's functions involving ground motions from double couple sources is developed by Spudich and Bostwick (1987); that involving motions from explosions is derived by Nowack and Chen (1999). There is some subtlety about which wavefields (e.g., divergence or strain of motion) are theoretically involved, but the plane-wave decomposition can be conducted directly to ground displacement or velocity (Spudich and Bostwick, 1987). We re-write and slightly modify the method of slowness power spectral analysis developed by Spudich and Bostwick (1987) below.

Assume that a number, N_e, of clustered explosions generated ground motion (e.g., velocity) seismograms at a station. We will denote a component (e.g., vertical) of the ground motion from the *i*th source as $v(\xi_i, t_i)$, where ξ_i and t_i are the location of, and travel time from, the *i*th source (i=1,2,..., N_e). These seismograms can be translated into the frequency-wave number domain by simple Fourier Transforms to obtain the spectra (also cf., Aki and Richards, 1980)

$$v(\xi_i, t_i) \rightarrow \text{FT from time to } \omega \rightarrow \text{FT from location to } \mathbf{k} \rightarrow V(\mathbf{k}, \omega),$$

where ω and $\mathbf{k}$ are angular frequency and wave number vectors, respectively, and $V(\mathbf{k}, \omega)$ is the ground motion spectra in the frequency-wave number domain. We can replace the wave number vector $\mathbf{k}$ by $\omega\mathbf{s}$, where $\mathbf{s}$ is the slowness vector, and form power spectrum from $V(\mathbf{k}, \omega)$:

$$P(\omega\mathbf{s}, \omega)=V^2(\mathbf{k}, \omega).$$

The frequency-slowness power spectrum (FSPS), $P(\omega\mathbf{s}, \omega)$, thus formed is directly calculated from data. In practice, weighting of slowness power spectra is usually applied. There is an abundant literature on various weighting procedures and we will not discuss the issue of weighting here.

In the past few months we have modified some previous software developed by Xie et al. (1996) for forming the f-k spectra under the reciprocal theorem. The modified software is nearly ready to be used for the current project.

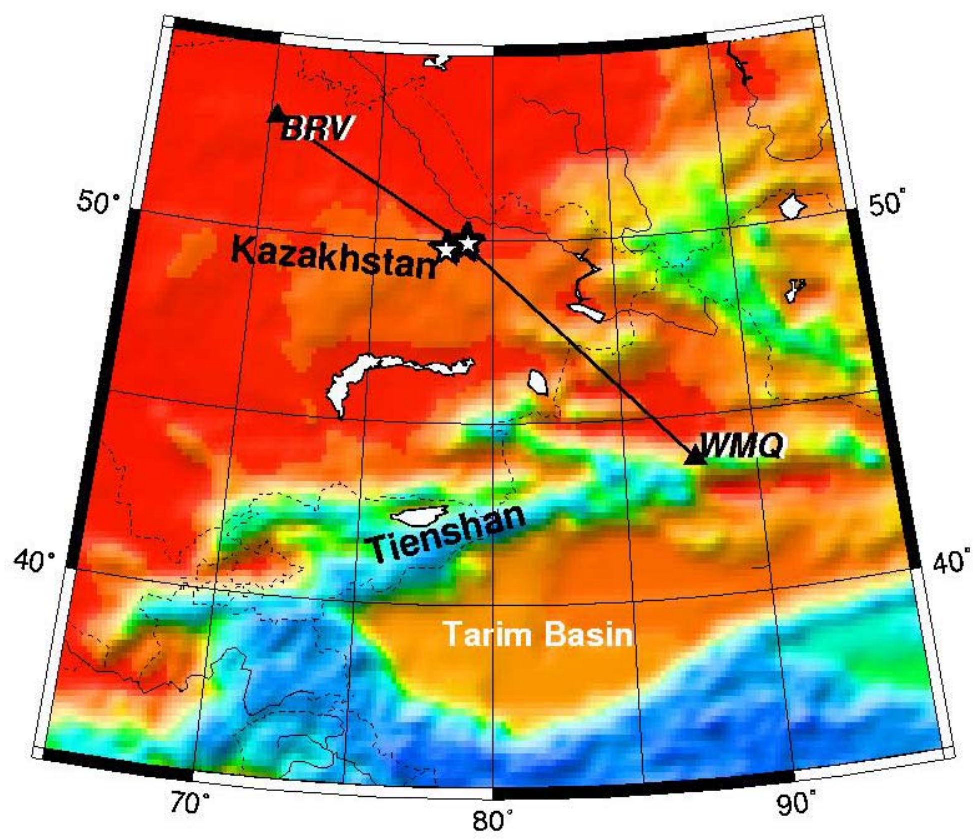

Figure 1. Map showing locations of the Borovaye observatory (BRV) station WMQ (triangles), and explosions in the Balapan and Degelen Mountain Test Sites. Also shown are representative, regional-distance paths from Balapan to BRV and WMQ. Topography is color-coded with blue represent elevations larger than 5000 M (those in the regions of Tienshan and Tibetan Plateau).

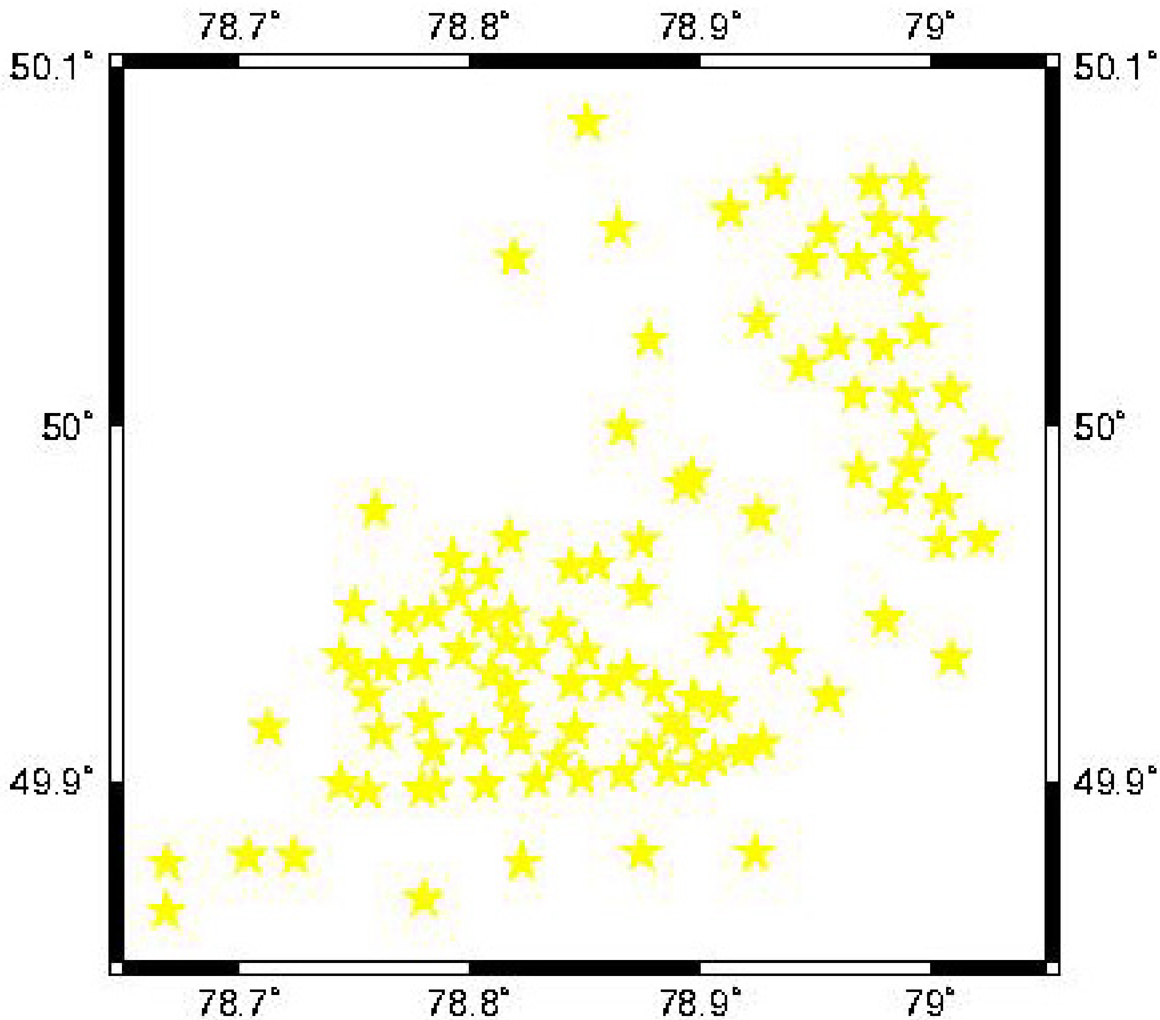

Figure 2. Map showing locations of the vertical shafts in the Balapan region of the Semipalatinsk Test Site. Between 1964 and 1989, 106 underground nuclear explosions were conducted in these shafts. The locations were determined using GPS survey.

Collection of ground truth information of UNEs from the Semepalitinsk test site

The first data set we will use consists of regional wave seismograms from the historic Soviet UNEs contained in the Borovoye Digital Seismogram Archive (Kim et al., 2001; available at the LDEO's ftp site). There are two groups of STS explosions (Figure 1). The first group consists of Balapan explosions in shafts. Figure 2 shows detailed locations of 106 tests of in the Balapan region of the Semipalatinsk Test Site. The tests were conducted between 1964 and 1989 in vertical shafts, which were located by GPS surveys (personal communication between Vitali Khalturin at LDEO and Prof. Natalya N. Mikhaylova, Director of Kazakh National Data Center, Kurchatov, Kazakhstan; December, 2002). We believe that the locations of the shafts are within 200 m of the actual tests. Thurber et al. (2001) provided joint relocations of these events using ground truth information of hypocenters and some origin times, as well as teleseismic time picks. They provided a set of the original time estimates, at a precision of 0.1 s or better. These estimates of origin times are considered as the best, or one of the best, estimates openly available (Vitally Khalturin, personal communication, April, 2004). Many of these explosions were recorded by the Borovoye Digital Seismogram Archive at regional distances. About ten of these explosions between 1987 and 1989 were also recorded at the CDSN station WMQ (Xie, 2002).

The second group of explosions consists of those from the Degelen Mountain region in tunnels. Between Oct. 1961 and Oct. 1989, 209 explosions are detonated in 181 tunnels. Owing to the tunnel testing style the locations are subject to larger (up to ~1 km) uncertainties. The estimates of the origin time estimates of these explosions by Trabant et al. (2002) are probably the best, or close to the best, estimates that are openly available.

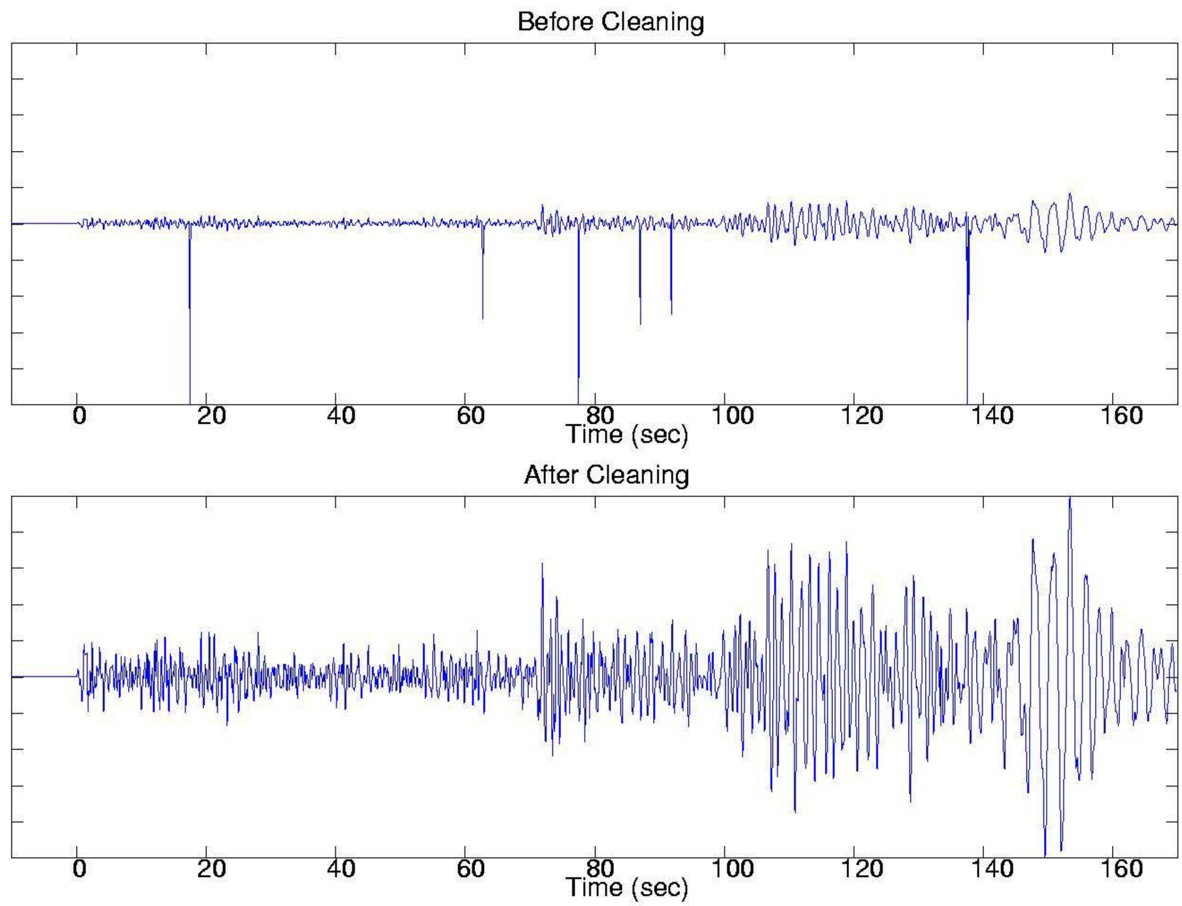

Figure 3. An example of the Borovoye regional waveforms from Balapan explosions before (top panel) and after (bottom panel) being processed with our cleaning procedure for spike-removal.

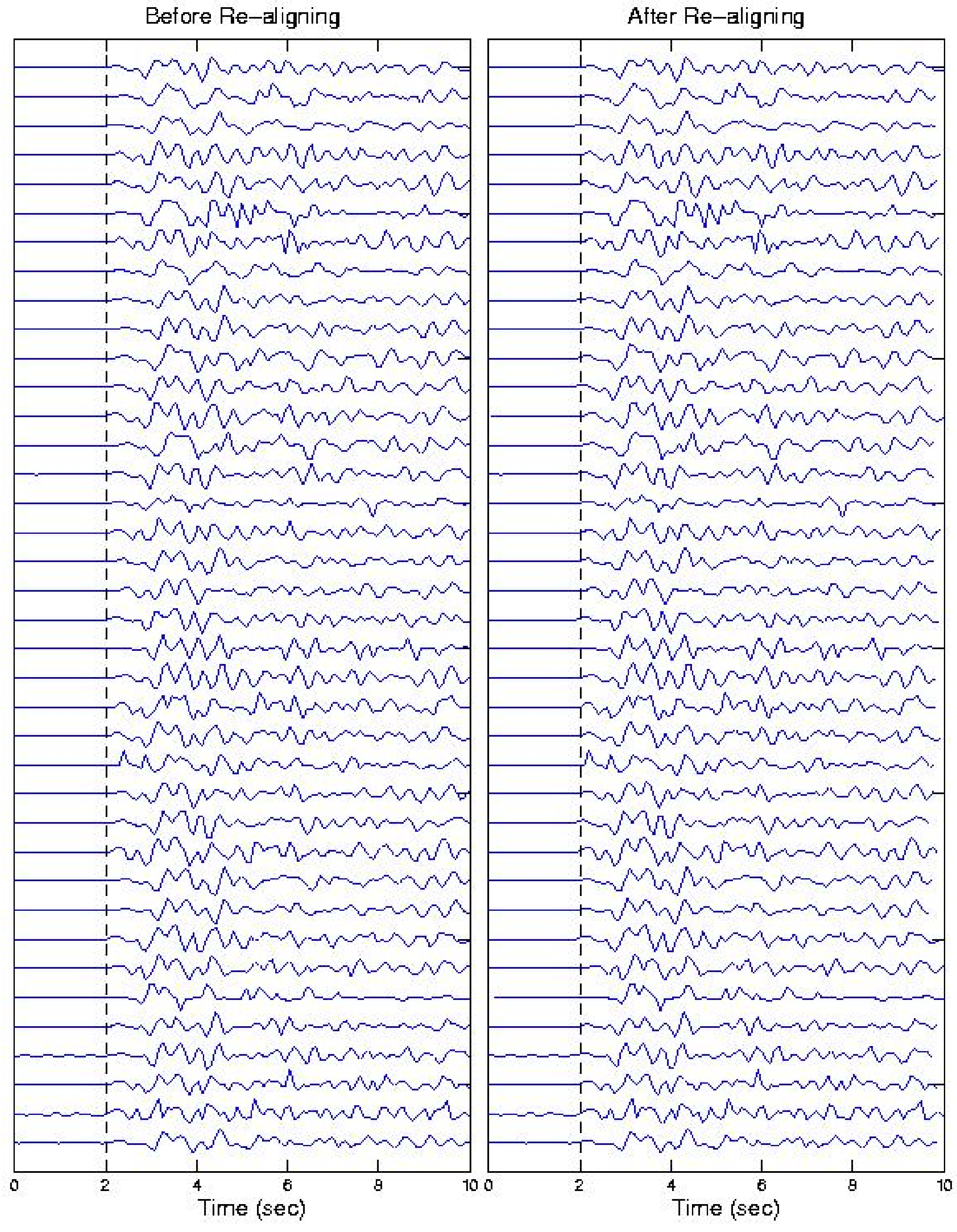

Figure 4. (Left panel) A record section that contains Pn waves from 38 Balapan explosions recorded between 1982 and 1989 by sensor S06Z of the BRV multi-sensor recording system. (Right) Same as left but with Pn wave re-aligned using a cross-correlation procedure.

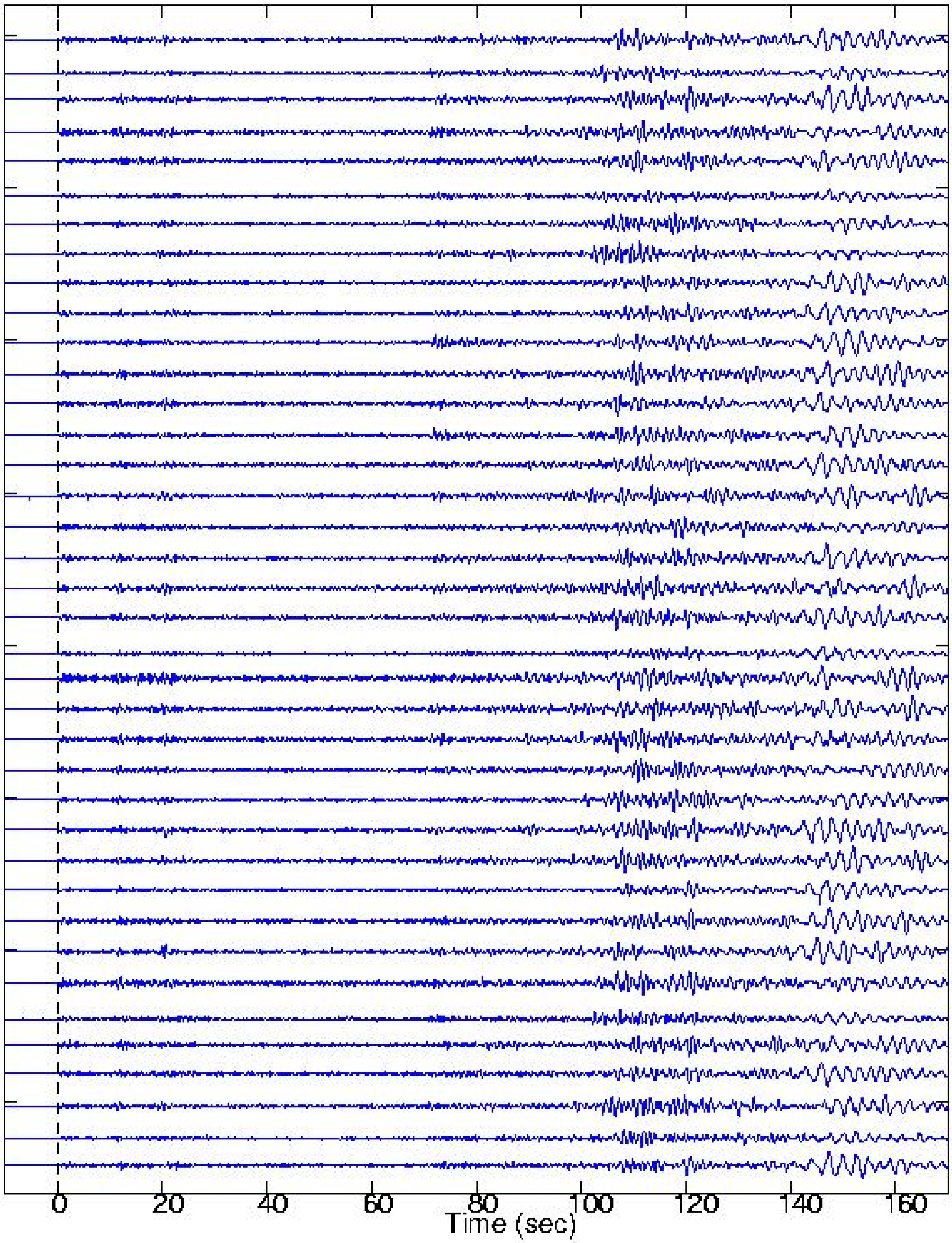

Figure 5. Same as the right panel of Figure 4, except a longer time duration is shown so that more phases, such as short-period surface waves, can be seen.

Processing of regional seismograms from the Borovoye historical archives

We have been collecting waveform data from the Borovoye Digital Seismogram Archive (1964-1989) from the LDEO website (Kim et al., 2001). These waveforms were recorded with older, narrow band, low dynamic range systems. Certain critical channels were very often contaminated by random spurious spikes. We have developed and applied a simple algorithm to rapidly, and reliably, remove the spikes, resulting in a large number of cleaned waveforms. The algorithm is designed to first detect triangularly, or trapezoidly, shaped spikes by defining these spikes as "peaks" or "troughs" that exceeds a specified height. Once detected, the value of the spurious peak or trough is replaced by a value found by interpolating those of the neighboring points. Figure 3 shows an example of the short-period Borovoye waveforms former Soviet UNEs between 1982 and 1989, collected from one of the several Borovoye sensors, before and after the spike removals. We have started cross-correlating the Pn waveforms to re-align the seismograms recorded by this sensor (S06Z), as shown in Figures 4 and 5.

CONCLUSIONS AND RECOMMENDATIONS

The past few months mark an initial phase of this research. During this time period, we have been implementing the frequency-slowness power spectral algorithm under a reciprocal theorem. This algorithm will soon be used to study regional wave excitation by clustered underground nuclear explosions. We have also been collecting information on precise source locations, depths and origin times of the historic Soviet explosions (1964-1989) at Balapan, which generated regional waves at the Borovoye Observatory. Finally, we have developed and applied a simple algorithm to rapidly and reliably remove spikes contained in the Borovoye Digital Seismogram Archive (1964-1989). We have started to re-align the Pn waves of the Borovoye seismograms using a cross-correlation method.

ACKNOWLEDGEMENTS

We thank Drs. Vitali Khalturin, W.Y. Kim and Paul Richards for their assistance on finding the Balapan source information, and on various aspects of the BRV historical data.

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