OBSERVATION AND MODELING OF RIPPLE-FIRED EXPLOSIONS AT THE CENTRALIA MINE, WASHINGTON

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ABSTRACT

One of the issues associated with the Comprehensive Nuclear-Test-Ban Treaty (CTBT) is the discrimination of large mining explosions from nuclear tests.

The Centralia coal mine is a significant source of seismic events in southwestern Washington. Some of the mine explosions have reported magnitudes as large as 3.5. We have assembled a set of waveform data from these explosions, derived from the Pacific Northwest Seismic Network and from broad band stations operated near the mine. These same stations also recorded nearby single explosions from the PASSCAL Southwest Washington Reflection/Refraction Experiment.

Detailed information on the geometry and delay pattern of the explosions was used to simulate the mine signals. The most common set of delays was 25 and 84 ms within and between rows, respectively. This leads to a spectral reinforcement at 12 and 40 Hz. The use of 500-ms down-hole delays introduces an additional ±3.5-ms scatter in the delay times, reducing but not eliminating the spectral peaks in the simulations.

The blast simulations also predict spectral modulations resulting from the total blasting duration and the aspect ratio of the blast geometry (square vs. rectangular). A similar spectral modulation is observed in binary spectrograms and cepstra of many of the mine-generated signals. These spectral characteristics occur at lower frequencies than those related to the delay times, and so could be useful in identifying ripple-fired explosions at regional distances.

An additional important source of low-frequency spectral modulation in the simulation is the ballistic duration of a spall source (material being lifted and re-impacting the surface). Properly modeling the spall source requires additional information about the explosion's effect on the blasted material that is difficult to document given the information typical in blasters' logs. Video documentation of the spall source may be the only way to accurately estimate the parameters of the spall source. Seismic signals from apparently very different source geometries sometimes have very similar waveforms, and additional information such as charge weight, hole depth, and free-face orientation are being examined for their relation to groups of similar-appearing explosion sources.

Key Words: discrimination, seismic sources, mining practices, ground truth

OBJECTIVE

The objective of this study is to develop a relationship between the details of ripple-fired explosions at the Centralia coal mine in southwestern Washington and characteristics of regional seismic signals. These characteristics include the amplitudes of body waves and surface waves (particularly Rg) and spectral scalloping.

The Centralia mine source has reported magnitudes as high as magnitude 3.5 as measured by the coda-length method used by the Pacific Northwest Seismic Network (PNSN), but these magnitudes are over-estimates of the true magnitude of the events. These magnitudes do not appear to be well related to the total amount of explosive used, nor to measures of the maximum explosive charge rate (Figure 1). One of the objectives is to develop an amplitude-based magnitude scale that measures the amount (or rate) of explosives being detonated, to provide a better estimate of the size of these explosions.

The mine operators have been very cooperative in providing to us the details of the spatial and temporal delay pattern and the location and orientation of the blasts, and these data are being used to compare the amplitudes and spectral characteristics of the explosions. Many of the explosions have a relatively simple geometry, square to rectangular, and usually have delays between shots in a row of 25 ms and either 42 or 84 ms between rows. Previous studies (e.g. Hedlin et al., 1990; Hedlin, 1998) have shown that inter-hole time delays can produce spectral peaks in spectra and spectrograms, here at 40, 24, and 12 Hz, respectively. In the western U.S., and western Washington in particular, there is relatively high attenuation and such frequencies are not easily observable at distances of 100 km and further, and this will also be true in the CTBT setting for other regions with high attenuation.

However, it has also been observed that there are spectral modulations from mining explosions at lower frequencies that can be propagated to farther ranges (e.g. Carr and Garbin, 1998) that may be diagnostic of the explosion source. Such modulations have been suggested to be the result of the finite but extended duration of the total sequence of shots (Chapman et al., 1992). Low frequency spectral modulation is usually evident for explosions at the Centralia mine. A second major objective is to understand how different geometric and temporal characteristics (or other parameters) of the explosions produce spectral scalloping at the frequencies seen in the recorded data.

RESEARCH ACCOMPLISHED

We have assembled a data set of seismic waveforms recorded by broadband instruments operated near the mine, regional seismic stations of the PNSN and, for one mine explosion, mine signals recorded on a regional U.S. Geological Survey refraction profile that passed just south of the mine. The single-hole explosions used as sources in the refraction profile were also recorded on the broadband and regional stations and provide a comparison of a significantly different type of explosion.

The data from the mine operators has been analyzed, summarized, and tabulated in terms of whether the explosions had a simple geometry and constant delay time, in which area and level of the mine they occurred, and the geometry of the explosion relative to a free face, if any. In discussions with the mine blasters, they indicate that there is a 3.5 ms scatter in the delay devices, primarily from down-hole delays of 0.5 seconds. The surface delays that sequence the down-hole delays add somewhat to this estimate. We have simulated this scatter in the delay firing system, and determined that this should not cause a total loss of spectral reinforcement at frequencies determined by the spacing (along the free face) or burden (perpendicular to the free face) delay firing. The shot holes are closely spaced for these explosions, (8-10 m) and the propagation delay between holes is small. The propagation delay is calculated at the apparent velocity of the recorded seismic phase. For compressional waves travelling to stations at 5 km/s, this is a maximum of 2 ms/hole. This can only change the frequencies at which spectral nulls occur by 10% as a function of azimuth.

Simulation of the explosions consists of superimposing a sequence of delta functions corresponding to the time delay for each shot hole. As a more realistic representation of the explosion source, or simply to simulate a band-limited reception of the signal, the impulse sequence can be high-cut filtered. This generates a progressive reinforcement of combined signal amplitude as more and more explosions are detonating closely spaced in time (Figure 2). There is often a ramp up, a steady plateau, and a ramp down. If the duration in the burden and spacing directions is comparable, this leads to a triangular pulse (the steady plateau is very short). If the duration in one direction is significantly different from the other, then the shape of the pulse is trapezoidal (ramp up, plateau and ramp down). Note that it is not the actual distance in each direction that determines the duration for these explosions. As before, the propagation delays that result from the spatial pattern are much smaller than the timing delays. This is true either between two adjacent holes or across the entire blasting area.

According to this model of the explosion sequence, there can actually be two characteristic durations that lead to low frequency spectral scalloping, for relatively simple patterns of explosions. The mine operators logs have been used to simulate several different, but simple, explosions for comparison to spectra and spectrograms measured from the seismic waveforms. This has to date been a discouraging comparison, and led to attempts to simulate a third possible effect that may have a predictable characteristic duration, the effect of spall (e.g. Anandakrishnam, 1997).

The spall source results from the blasted material being lifted from the surface, and after a time of ballistic flight, re-impacting the ground. This may be a larger and more coherent movement than the superposition of individual explosions attains. In fact, because this is the primary intent of the blasting process (to break up and "bulk" the material for removal), this may be a logical result of the experience and skill of the mine operators. The Centralia mine does not attempt "cast" blasting, where the explosions are designed to throw the material into a pit below the free face. Visual observations at the Centralia mine indicate that the duration of the spall source is relatively short, comparable to the duration of the blasting sequence itself. It is possible that there may be some unexamined parameters that are available in the blasting logs (e.g. hole diameter and depth, amount of tamping) that may indicate (in a relative way) the mass of material and how long it is ballistic. The strength and density of the material being blasted are variable, not currently available, and may be important, and the material being blasted interacts in a complicated way. It seems that direct observation of the spall process is needed in this situation, for example with high-speed video recording. In the case of the Centralia mine, where material is being "bulked", even this information may not be sufficient.

As an alternative to the "forward" modeling of similar or dissimilar explosions based on the blasting logs, seismic signals are being sorted for similar amplitude ratios, presence of and frequencies of spectral nulls etc. It is hoped that by approaching the classification of blasts by their seismic signals, that one or more of the controlling parameters producing such features can be explained.

CONCLUSIONS

The Centralia coal mine provides an opportunity to examine a type of ripple-fired explosion that is typical of many open-pit mines. High-frequency spectral reinforcement is difficult to observe in this region and will be in other areas of high attenuation. The use of long time delays relative to the spacing of the holes leads to a conclusion that the spatial extent of the explosions is much less important than the temporal duration of the shot sequence. The temporal duration of the blast sequence can be described as having two characteristic durations, resulting in two sets of low frequency spectral nulls in spectrograms from regional seismic stations. This type of explosion may be effective at producing a spall source, which generates strong surface waves. These surface waves may result in overestimates of energy based on signal duration. The spall source may not be easily parameterized in a way that spectral modulations expected from the duration of the spall can be predicted.

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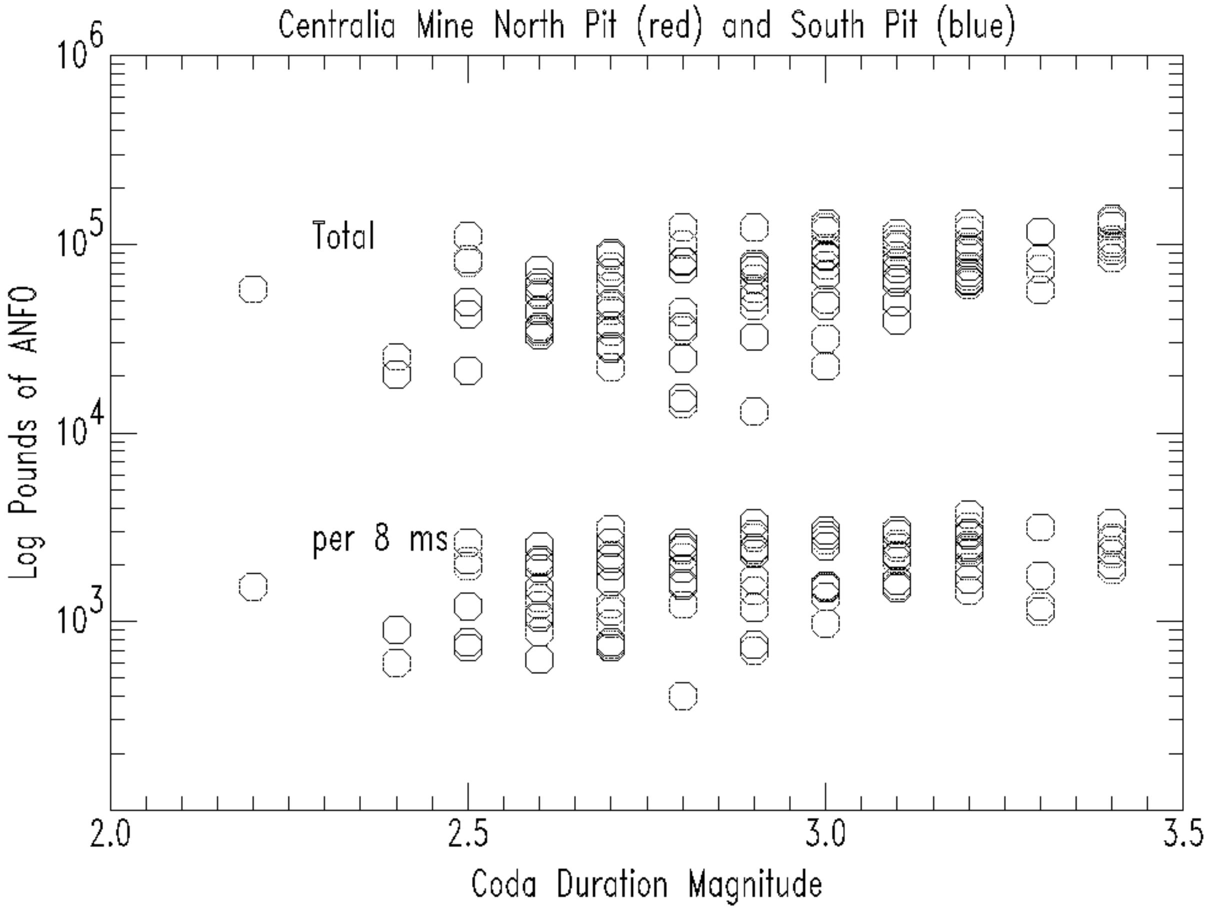

Figure 1. Comparison of PNSN magnitudes with total yield and yield within 8 ms. The latter is used by the mine to estimate peak amplitudes at surrounding points. (Note color is not reproduced in this presentation.)

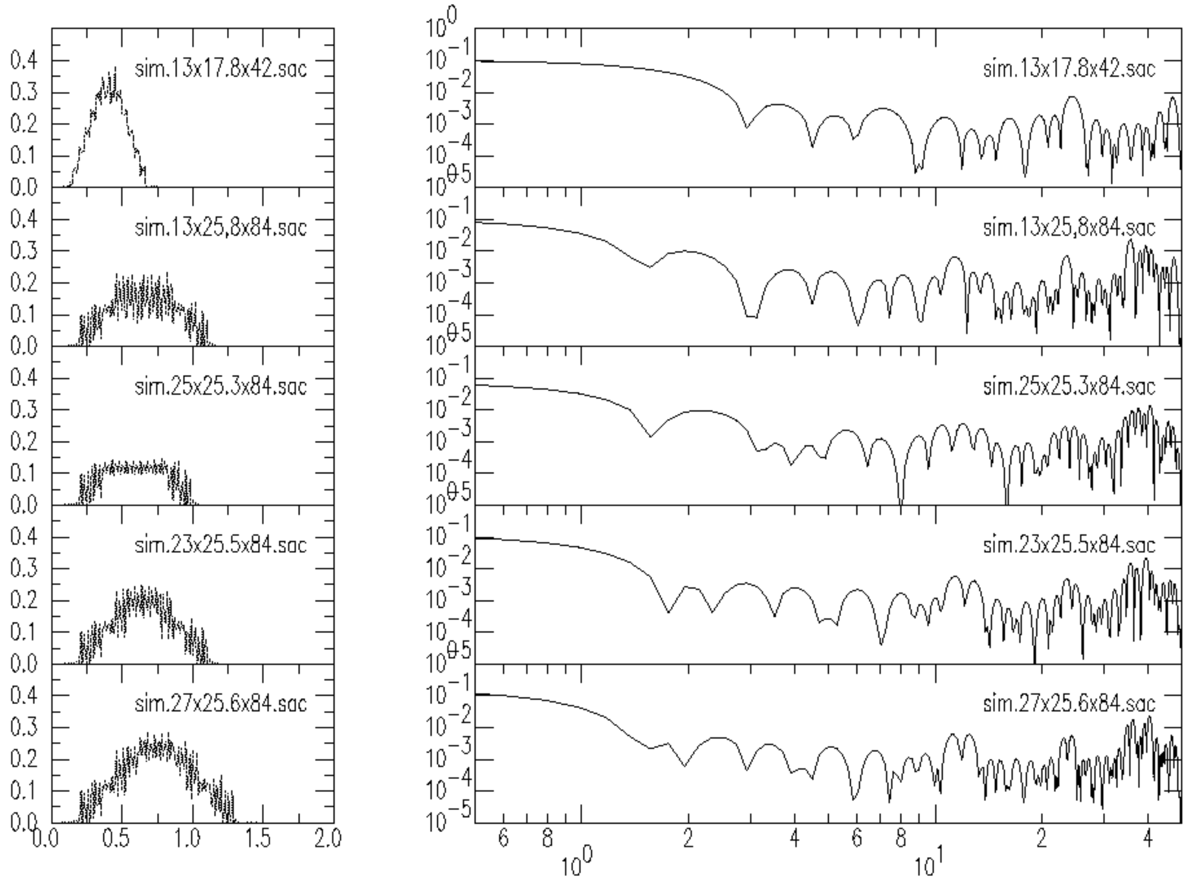

Figure 2. Example source time histories and spectra showing range of source shape and spectral modulations. The source function varies from triangular to trapezoidal depending on how different the total delay are in the spacing and burden directions.

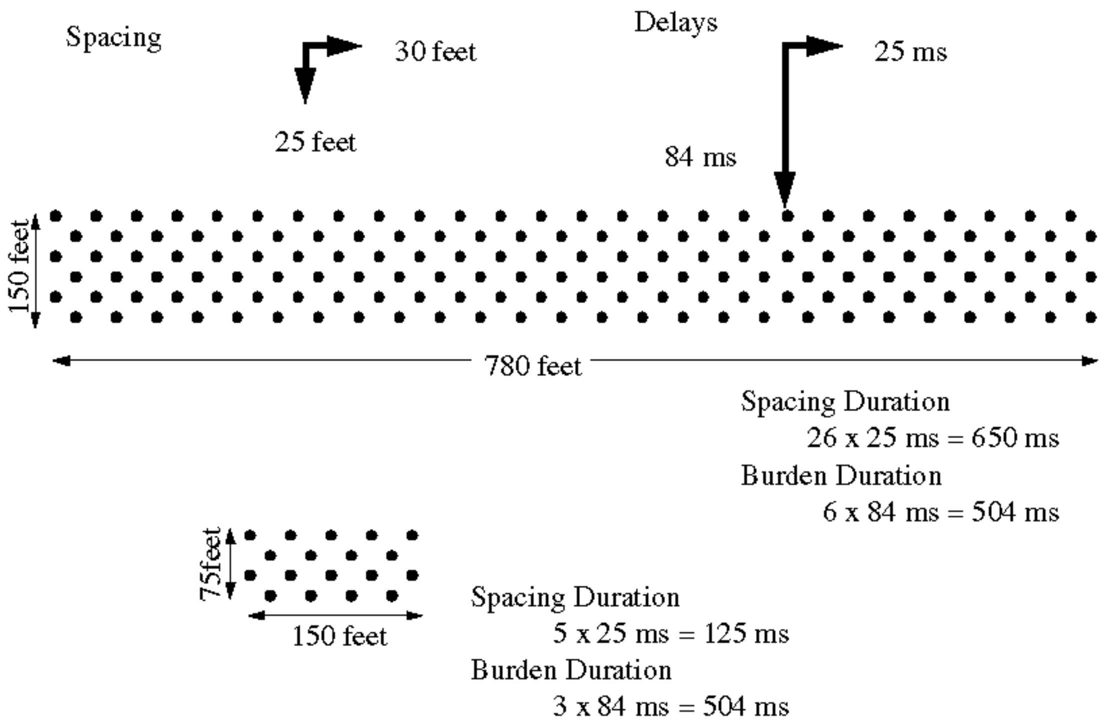

Figure 3. A diagram of two highly different but simple blasting patterns from the Centralia mine blaster's logs.

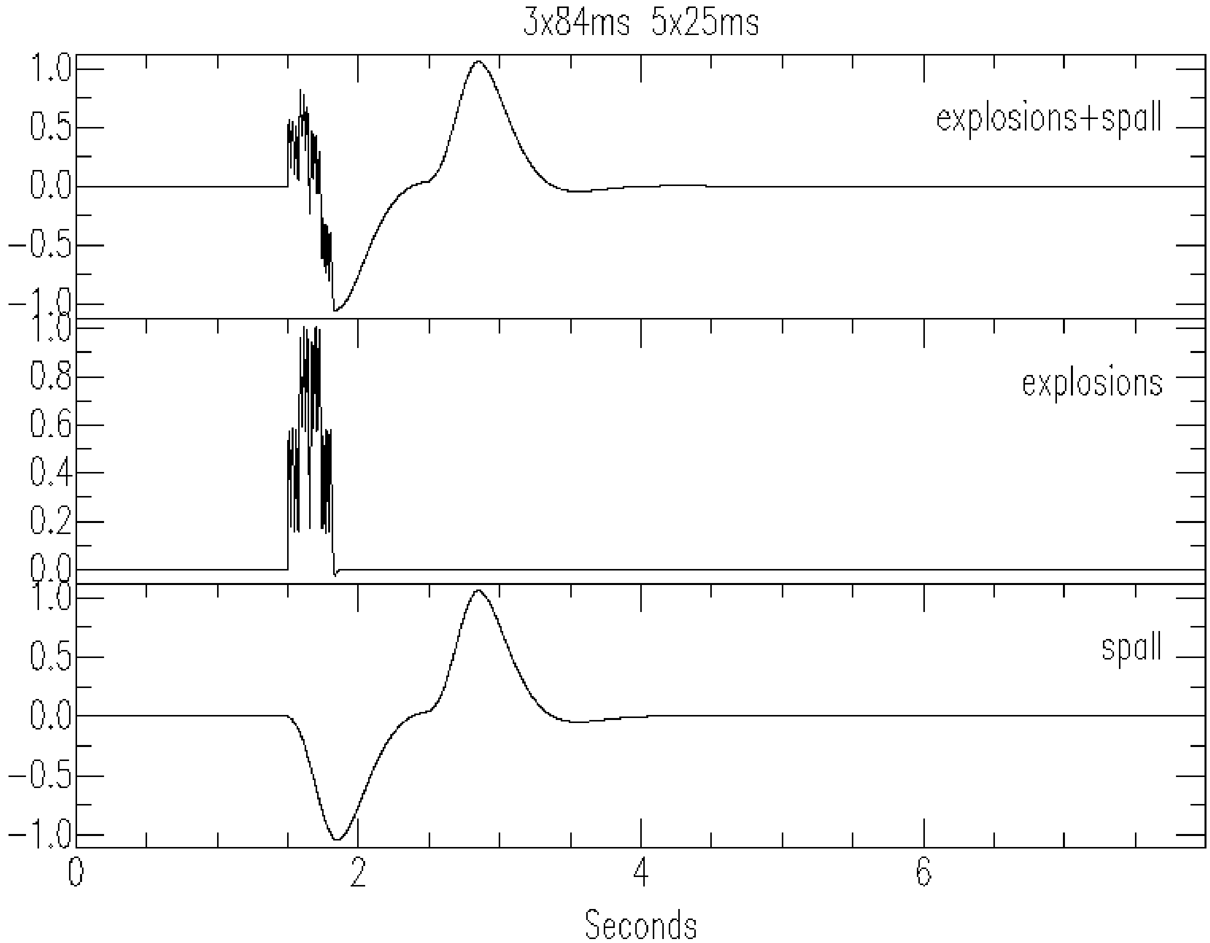

Figure 4. Simulation of the shorter source function of the two blasting patterns in Figure 3. Spall duration is assumed to be 1 second.

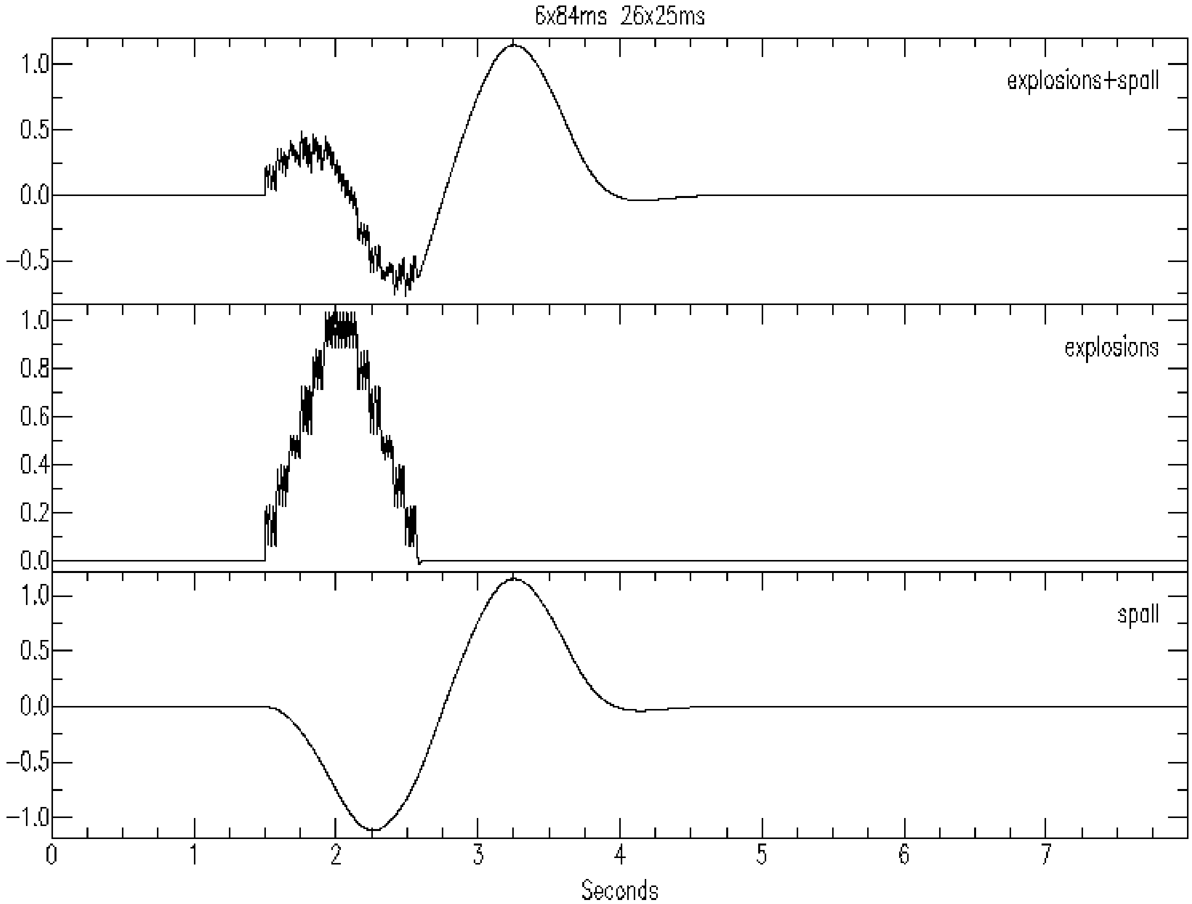

Figure 5. Simulation of the longer source function for the two blasting patterns in Figure 3. Spall duration is assumed to be 1 second.

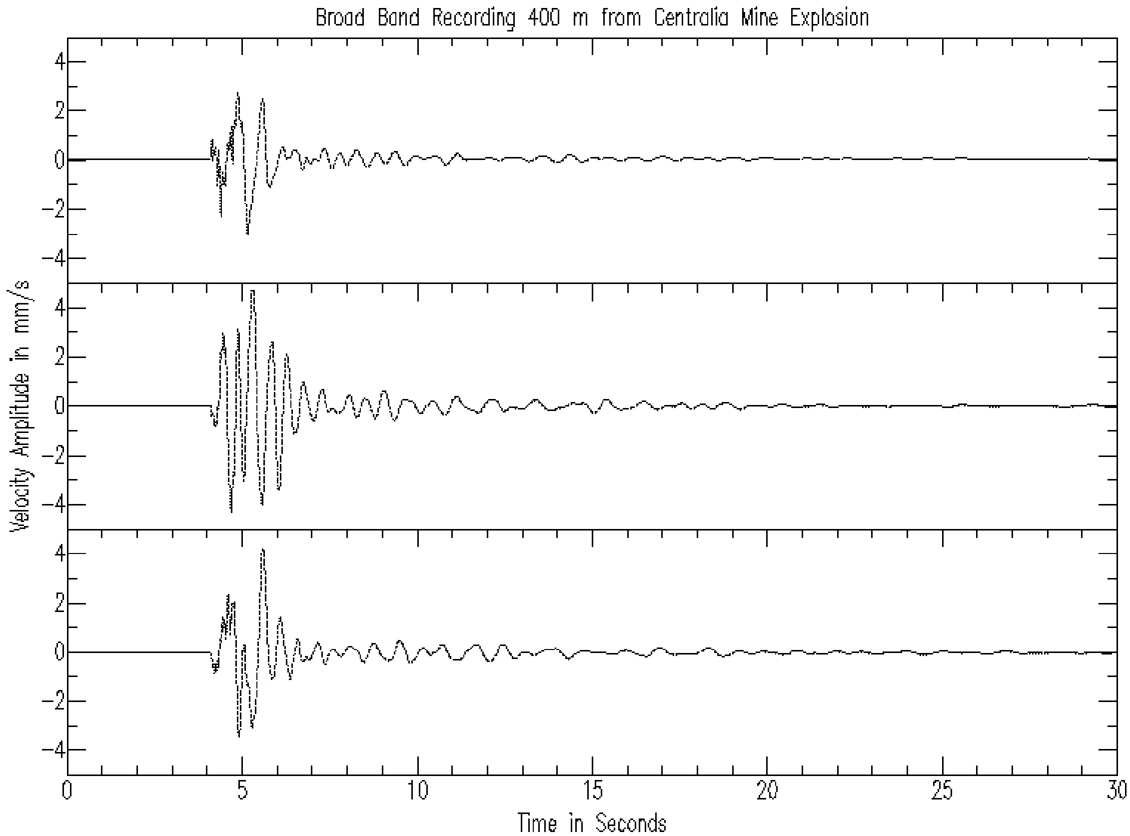

Figure 6. Recorded time series using broadband recorder 400m from Centralia mine blast. This is similar to the longer blast simulated in Figure 5.