Locating Trapped Miners Using Time Reversal Mirrors (TRM)

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Introduction

We present a Time Reversal Mirror (TRM) approach for locating trapped miners inside a collapsed mine. Two steps are used to locate the trapped miners: first seismically record a natural band-limited Green's function prior to the collapse, where source points are located inside the mine at specified communication stations and the wavefields are recorded along a line of receivers on the overlying ground surface. The second step is, after a collapse occurs, the trapped miners go to the nearest communication station and hammer an SOS signal against the mine wall. Their vibrations are recorded by the receivers on the ground surface, and using the previously recorded Green's functions for comparison, the location of the trapped miners can be identified. The outstanding features of this TRM approach are its resilience to a very low signal-to-noise ratio in the recorded SOS data and its tolerance for narrow recording apertures. Two data sets are collected to test this approach, the first is recorded over a steam tunnel at the University of Utah and the second is recorded over a mine near Tucson, Arizona. Results show that the TRM approach can successfully locate trapped miners at both sites, even with signal-to-noise ratios as low as 0.001. Tests also validated the super-resolution character in focusing scattered arrivals.

Trapped-Miners Approach - Results of the Field Tests

University of Utah Test (Field Test # 1)


Figure 1


Figure 2

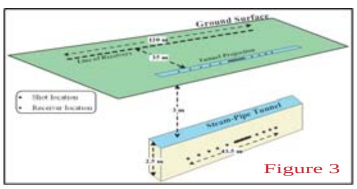

Figure 3

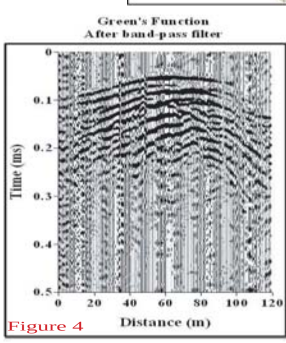

Figure 4

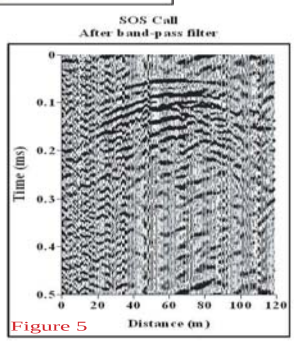

Figure 5

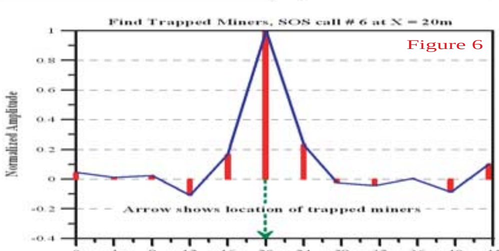

Figure 6

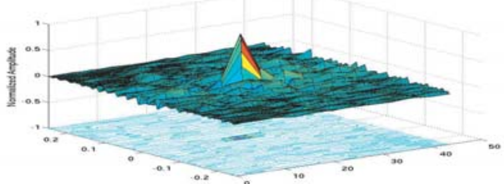

Figure 7

Two field experiments are collected to test the trapped miner approach. The first is conducted in an underground steam-pipe tunnel at the University of Utah (Figures 1 & 2), and the second is carried out at the San Xavier Mining Laboratory, Tucson, Az (Figures 8 & 9). For both experiments we used 25 shots with a shot interval of 4 m (shots 1 to 6 and shots 20 to 25) and 0.5 m (shots 6 to 20) for Utah test (Figure 3) and 0.5 m for the Tucson test (Figure 10). We used 120 receivers with a receiver interval of 1 m and 0.5 m for the Utah and Tucson tests, respectively. At each shot location, two different shot gathers were recorded, the first one represents the natural Green's functions (also called calibration Green's function and shown in Figures 4 & 11) , while the second file represents the miner SOS call (Figures 5 & 12). The result of a zero-lag cross correlation of a selected SOS shot gather with the recorded Green's functions at communication stations shows that the peak of the correlated record coincides with the actual location of the miners (Figure 6 and 13). Repeating the process for all SOS shot gathers gives the correct locations of the miners. A more realistic scenario is that the initiation time of the SOS source is unknown, so a time-shift is applied to the recorded data. These shifted data were then correlated with the calibration Green's function at different communication stations. The result is shown in Figure 7 and 14.

Tucson, Az. Test (Field Test # 2)


Figure 8


Figure 9

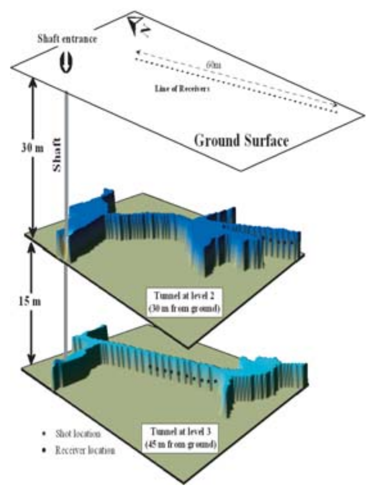

Figure 10

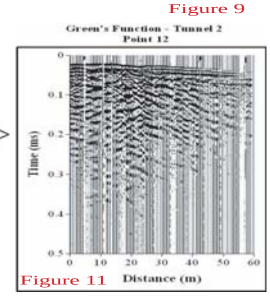

Figure 11

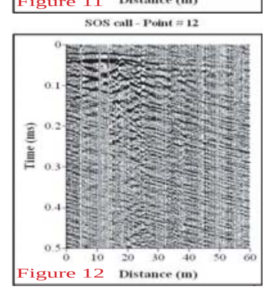

Figure 12

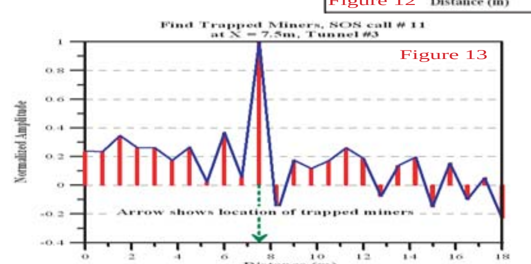

Figure 13

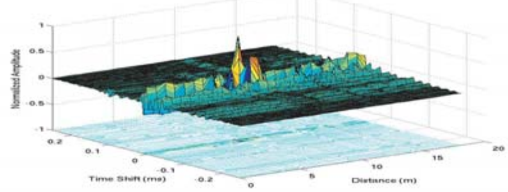

Figure 14

Super Stack Results

In an actual mine emergency, we do not expect the SOS call to have high or even a good signal/noise (S/N) ratio. To show that the TRM approach is insensitive to a low S/N ratio a super-stack test was made on both data sets, where random noise is added to the SOS call (Figures 15 and 16), which is then correlated with the 25 calibration Green's functions at different communication stations. Here, the S/N ratio of the SOS call is 1/1738 for the steam-tunnel test and 1/2670 for the Tucson Test. The resulting images in (Figures 17 and 18) show that we still are able to identify the location of the trapped-miner even in an environment with a low S/N ratio.

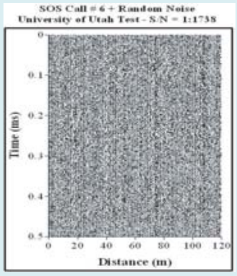

Figure 15

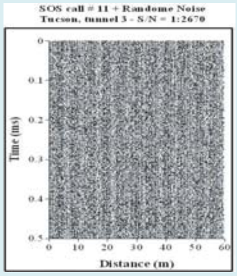

Figure 16

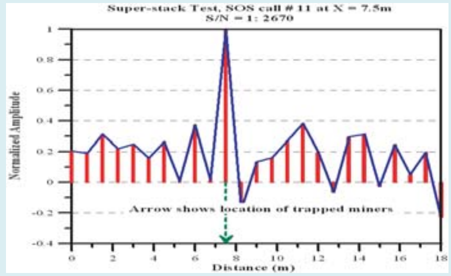

Figure 17

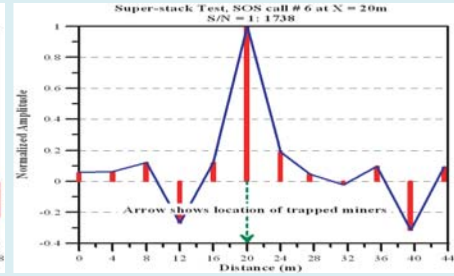

Figure 18

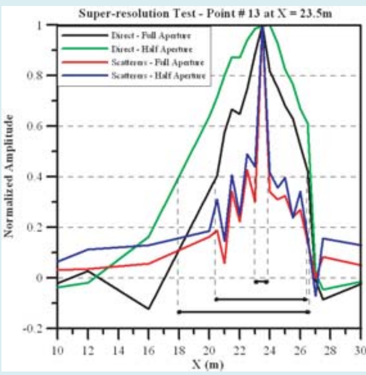

Figure 19

Super Resolution Results

The super-resolution property is evaluated for both the steam-tunnel and Tucson data sets. These shot gathers are separated into (1) a scattered shot gather where only scattered energy is present after removing the direct waves and (2) a direct shot gather, where only direct energy is present in the shot gather. Selected SOS scattered-only shot gathers are correlated with all scattered-only Green's functions and selected SOS direct-only shot gathers are correlated with all direct-only Green's functions. The results obtained using the full 120-trace aperture width are compared to those for a 1/2 aperture width of 60 traces. Figures 19 and 20 show the plot of m(x,0) computed from both the steam-tunnel and Tucson data.

Each plot contains 4 different curves:

1. Correlation results m(x,0) from traces that contain only direct waves using the full aperture width (120m and 60m at Utah and Tucson data sets, respectively).
2. Correlation results m(x,0) from traces that contain only direct waves using a half aperture width (60m and 30m at Utah and Tucson data sets, respectively).
3. Correlation results m(x,0) from traces that contain only scattered data using the full aperture width.
4. Correlation results m(x,0) from traces that contains only scattered data using a half aperture width.

The resulting images show that (1) the spatial resolution of traces with only-scattered events are much higher than traces with only-direct events and (2) if only direct arrivals are used, the spatial resolution decreases as the aperture is decreased. Our results using only scattered waves show a spatial resolution that is 5 to 7 times better than using only direct-wave arrivals and is somewhat insensitive to aperture width.

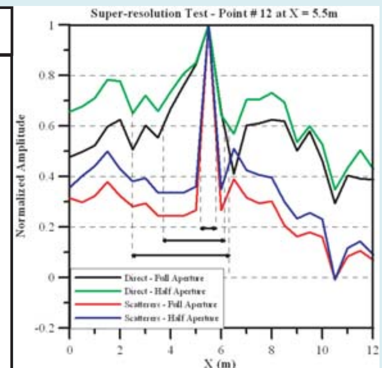

Figure 20

Summary

We have successfully introduced a TRM method to locate trapped miners in a collapsed mine. This approach consists of two stages; the first stage is to plant a group of surface receivers that overlie the mine. These receivers are used to record a natural Green's function for sources located at predefined communication stations inside the mine's tunnels. The second stage is, when a collapse occurs, the trapped miners should find the nearest communication station inside the mine, and then send a SOS call to the surface using a small hammer. Recording this SOS call with the fixed receiver line and cross correlating it with the previously recorded Green's functions will indicate the exact location of the trapped miners. This approach is similar to pattern matching where the calibration Green's functions are matched to the noisy Green's function of the miner.

There are two possible problems with this approach; (1) the zero time of the SOS is unknown and (2) the SOS call is expected to have a very low S/N ratio. The TRM approach mitigates both problems by time shifting the input data to allow for identification of the miners' location and the initiation time of the SOS call. Random noise is added to the SOS calls, and the results show that, even with a very low S/N ratio, the location of the trapped miner can be identified. In this work, we have demonstrated that the Rayleigh resolution limit can be exceeded if the multipath events are used in the TRM. To our knowledge, this is the first experimental verification of the super-resolution property with a realistic seismic experiment. We also believe that this is the first time the super-stack property is validated with field data. The success of this TRM approach depends mainly on recording Green's functions with high a S/N ratio

A final problem to be addressed is what happens to the calibration Green's function if there is a mine collapse? The answer is we do not know. However, we can expect that low-pass filtering of the Green's function will only retain the long-wavelength information in the data, which should not change the Green's function for a mine collapse of smaller dimension.

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