Locating Trapped Miners Using Super-stacking and Super-resolution properties of Time Reversal Mirrors

Sherif M. Hanafy1, Weiping Cao2, Kim McCarter3, and Gerard T. Schuster2

1 Geophysics Department, Faculty of Science, Cairo University, Egypt
2 Department of Geology and Geophysics, University of Utah, Salt Lake City, UT 84112
3 Department of Mining, University of Utah, Salt Lake City, UT 84112

SUMMARY

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 record a natural seismic 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. The vibrations are recorded by the receivers on the ground surface, and using the previously recorded band-limited Green’s functions for comparison, the location of the trapped miners can be identified. The outstanding feature of this TRM approach is its resilience to a very low signal-to-noise ratio in the recorded SOS data and its tolerance for limited aperture widths in the recording array, successfully. This method is tested using two field data sets.

INTRODUCTION

One of the most dangerous problems for miners is a mine collapse. It may occur at any mine and at any time, and often leads to fatalities. Deadly mine collapses have recently occurred in West Virginia (January 2007, 2 miners were dead), Russia (March 2007, 106 miners were dead), Utah (August 2007, 6 miners and 3 from a rescue team were dead) and Colombia (October 2007, 24 miners were dead). Locating trapped miners as soon as the collapse occurs will help save lives and avoid dangerous searches in the wrong places.

Over the last two decades many methods have been proposed for finding trapped miners. One such method is the echo location technique, where seismic emissions excited from a trapped miner are recorded by surface geophones, direct arrival times are picked, and then used to triangulate to the miner. Unfortunately, such a method has not proven to be reliable partly because the signal-to-noise ratio (S/N) of the miner’s vibrations is too weak for conventional imaging methods. To overcome this problem we propose to apply the principle of Time Reversal Mirrors (TRM) to seismic data as a means for locating trapped miners inside a collapsed mine. The key idea is to estimate the earth’s natural band-limited Green’s functions by using hammer sources at predefined locations inside the mine and recording the seismograms with receivers on the earth’s free surface. These natural band-limited Green’s functions can be used as a TRM to identify the location of the trapped miners. The natural band-limited Green’s function overcomes the poor S/N problem by coherently stacking all transmitted scattered and reflected events in the data.

Two field tests are made to test the feasibility of TRM in the noise environment. Results show that the TRM approach can successfully locate trapped miners at both sites, even with signal-to-noise ratios as low as 0.0005. Tests also validate the super-resolution character in focusing scattered arrivals and the super-stacking property that makes the method resilient to high levels of random noise.

METHOD

Gajewski and Tessmer (2005) presented a seismic migration method to image unknown source locations with hidden excitation times. A problem with their approach is that passive data are often very noisy so that a migration image contains an ambiguous maximum, leading to poor resolution of the source location. Another problem is that the velocity model must be known in order to accurately compute seismic data. To overcome these problems we propose to migrate the passive data with the earth’s natural Green’s function, i.e.,

\[ m(x,t) = \sum_g d(g,t(s,t_{source})) \ast g(x,-t|g,0), \]  

where \( m(x,t) \) is the migration image, \( d(g,t(s,t_{source})) \) represents the time-differentiated passive data recorded at location \( g \) for a source at \( s \) with unknown excitation time \( t_{source} \), and \( g(x,t|g,0) \) is the band-limited Green’s function of the earth. This band-limited Green’s function accounts for the direct wave but also contains all of the primaries and multiples.

SPATIAL RESOLUTION

Spatial resolution is defined as the ability to separate two features that are very close together, i.e., the minimum separation of two bodies before their individual identities are lost. The distance between the two features must be, roughly, greater than or equal to \( \frac{1}{2} \) of the dominant wavelength \( \lambda \). More precisely, the horizontal Rayleigh resolution limit \( \Delta x \) for imaging zero-offset seismic data is given as:

\[ \Delta x = \frac{\lambda L}{2Z}, \]  

where \( Z > \frac{\lambda^2}{\pi} \), \( L \) is the length of the receiver line, and \( Z \) is the depth of the point source. To overcome the restrictive limi-
Locating Trapped Miners

tion of the Rayleigh resolution limit, the TRM utilizes all scattered waves, instead of focusing only the direct waves, with a quasi-uniform distribution of incidence angles (de Rosny and Fenk, 2002 and Lerosey et al., 2007).

FIELD DATA TESTS

Two sets of data are collected to test the TRM approach. The first is recorded over an underground steam-pipe tunnel at the University of Utah campus, while the second one is collected at the San Xavier Mining Laboratory, Tucson, Arizona. A Bison 24000 with 120 channels is used to record the seismic data and a sledge hammer (16 lbs.) is used as the seismic source. At each shot location, two different files were recorded: the first one is a one-stack CSG that represents the recorded vibrations from the miners which we will call the SOS data, while the second file represents the natural Green’s functions which are obtained by stacking 20 shot gathers with the shot at the same location.

**University of Utah Steam-Tunnel Test**

To test the TRM approach, 25 shots were used: shots 1 to 6 and shots 20 to 25 having a shot interval of 4 m, while shots 6 to 20 have dense shot intervals of 0.5 m. The dense shot distribution is used to test the super-resolution property of TRM. The receiver interval is 1 m, and the receiver line is located on the surface at a distance of 35 m from the tunnel. Two processing steps were used to prepare the data for interpretation: 1) a 5-100 Hz band-pass filter is used to remove high frequency noise from the recorded data; 2) Each CSG is traced normalized, where the amplitude values of each trace are divided by the maximum absolute amplitude of that trace (Figures 3c and 3d).

Applying the TRM approach to the SOS signal \(d(g, t)/s\) in eq. 2 yields the migration image shown in Figure 1. Repeating the process for all SOS shot gathers gives the correct locations of the miners. These results demonstrate that locating trapped miners using the TRM approach is successful for all 25 SOS locations.

A more realistic scenario is that the initiation time of the recorded SOS data source is unknown, so a time-shift is applied to the recorded data. These shifted data are then migrated using equation (2), and the plot of \(m(x, t)\) in Figure 2 shows the maximum value at the correct source location and excitation time.

**Tucson, Arizona Test**

The receiver interval in this test is 0.5 m. A total of 25 hammer stations were placed at 0.75 m intervals. We used two processing steps to prepare these data for interpretation; (1) applying a 100-160 Hz low pass filter to the data and (2) trace normalization in each shot gather.

Equation 2 can be interpreted as the zero-lag cross correlation of any SOS shot gather with the calibration Green’s functions. Applying this equation to the Arizona data results in the identification of the exact location of that SOS shot point as illustrated in (Figure 3). These results are similar to the steam tunnel results in the sense that the time shift test identifies the correct SOS location as well as its excitation time (Figure 4).

**Super-stack Results**

In an actual mine emergency, we do not expect the SOS call to have a 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-stacking test (Cao et al., 2007) was made on both data sets, where random noise is generated and then filtered using the same band-pass parameters used to filter the recorded data. The resulting filtered random noise is added to the recorded SOS calls, and the final result is then correlated with the 25 Green’s functions. Here, the S/N ratio of the SOS call are
Locating Trapped Miners

Figure 3: One example shows $m(x,0)$ vs $x$ computed for Tucson data at $X = 10.5$ m, actual SOS location coincides with the maximum value of the curves.

Figure 4: The migration image $m(x,t)$ for Tucson data. The peak corresponds to the actual SOS location and the correct excitation time.

1/1738 and 1/2670 for the steam tunnel and Tucson tests, respectively. The resulting images in Figures 5a and 5b show that the location of the trapped-miner can still be identified even in an environment with a low S/N ratio.

Super-resolution Test
The super-resolution property is evaluated for both field data sets. All 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-wave shot gather, where only direct-wave energy is present in the shot gather. Selected SOS scattered-only shot gathers are correlated with all scattered- 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 6a and 6b 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 $m^{dir}(x,0)$ from traces that contain only direct waves using the full aperture width. 2. Correlation results $m^{scatt}(x,0)$ from traces that contain only direct waves using a half aperture width. 3. Correlation results $m^{scatt}(x,0)$ from traces that contain only scattered data using the full aperture width. 4. Correlation results $m^{scatt}(x,0)$ from traces that contain only scattered data using a half aperture width.

If we define the spatial resolution to be the main lobes (see arrows in Figures 6a and 6b) then the resulting images show that (1) the spatial resolution of $m^{scatt}(x,0)$ and $m^{scatt}(x,0)$ are much higher than $m^{dir}(x,0)$ and $m^{dir}(x,0)$ and (2) if only direct arrivals are used, the spatial resolution decreases as the aperture is decreased. The results using only scattered waves show a spatial resolution that is 5 to 7 times better than using only direct-wave arrivals, which is 5 to 7 times better than the Rayleigh resolution limit.

CONCLUSIONS
We have successfully introduced a TRM method to locate trapped miners in a collapsed mine, where (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.

We also demonstrated that the Rayleigh resolution limit can be exceeded if the multipath events are used in conjunction with 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 that the super-stack property is recognized and validated with field data. The success of this TRM approach depends mainly on recording calibration Green’s functions with high S/N ratios.

ACKNOWLEDGMENTS
We would like to thank the American Chemical Society and the 2007 sponsors of the University of Utah Tomography and Model/Migration (UTAM) Consortium for their support. We would like also to thank N. Aoki, C. Boonyasiriwat, S. Dong, S. Liu, G. Zhan, X. Xiao, and Y. Xue for helping in data acquisition. Finally, we would like to thank Dr. Ross Hill the director of San Xavier Laboratory for his help during data acquisition.
Locating Trapped Miners

Figure 5: The results after using the low S/N as input into the TRM algorithm: (a) steam tunnel test with S/N = 1/1738 and (b) Tucson data set with S/N = 1/2670.

Figure 6: The super resolution results from the a) steam tunnel field test and the b) Tucson field test. Both results suggest that the Rayleigh resolution limit can be exceeded by a factor of 3 or more if all scattered events are used for focusing.
EDITED REFERENCES
Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2008 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES