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MineSeis — A MATLAB® GUI Program to Calculate Synthetic Seismograms from a Linear, Multi-shot Blast Source Model

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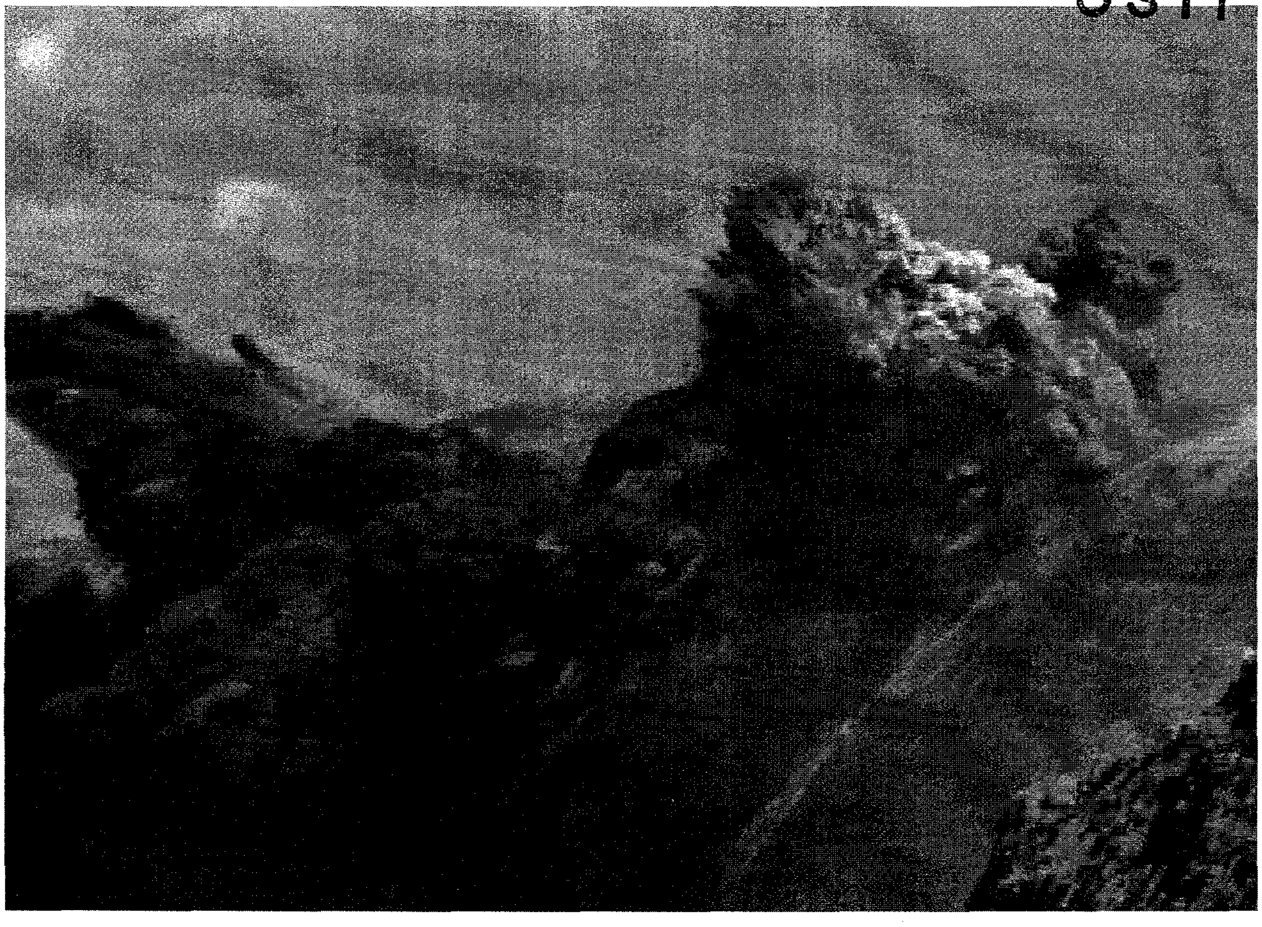

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Introduction

Large scale (up to 5 kt, Anandakrishnan *et al.*, 1997) chemical blasts are routinely conducted by mining and quarry industries around the world to remove overburden or to fragment rocks. Because of their ability to trigger the future International Monitoring System (IMS) of the Comprehensive Test Ban Treaty (CTBT), these blasts are monitored and studied by verification seismologists for the purpose of discriminating them from possible clandestine nuclear tests. One important component of these studies is the modeling of ground motions from these blasts with theoretical and empirical source models. The modeling exercises provide physical bases to regional discriminants and help to explain the observed signal characteristics.

Since industrial chemical blasts of large enough magnitude to trigger the IMS are all multi-shot, delay-fired explosions, a convenient way to model them is to linearly superimpose individual shot sources in the shot array with corresponding time delays (Chapman *et al.*, 1992; Reamer *et al.*, 1992; Barker and McLaughlin, 1992). The superposition assumes a linear relationship between signals from individual shots. This linearity was experimentally validated for small chemical explosions (2.27 kg) with scaled source separation of 147 $m/kt^{1/3}$ (Stump and Reinke, 1988).

Important to the modeling of multi-shot blasts is the modeling of the single shot sources in the multi-shot array. Several source models have been proposed for the single shot sources in a blast. Chapman *et al.* (1992) used Brune's (1970) earthquake model for convenience. Reamer *et al.* (1992) modeled the cylindrical geometry of the single shot by superimposing a series of spherical explosions along the charge column. Considering the physical processes which occur during a near-surface industrial explosion, especially a cast blast, a source model that combines a spherical explosion and a spall source has been proposed (Barker and McLaughlin, 1992; Anandakrishnan *et al.*, 1997). The spherical explosion model was usually adopted from models for underground nuclear explosions. Whereas the spall model proposed was also similar to the model of spall accompanying underground explosions, there have been several extensions and modifications.

The program MineSeis has been developed to implement the synthetic seismogram modeling of multi-shot blast sources with the linear superposition of single shot sources. Single shot sources used in the modeling are the spherical explosion plus spall model mentioned above. Mueller and Murphy's (1971) model is used as the spherical explosion model. A modification of Anandakrishnan *et al.*'s (1997) spall model is developed for the spall component. The program is implemented with the MATLAB® Graphical User Interface (GUI), providing the user with easy, interactive control of the calculation.

Formulation

Time function of single shot explosion

The explosion model used in this program is Mueller and Murphy's (1971) source time function for isotropic explosion sources. In the frequency domain, the function is expressed as (Stump, 1985; Yang, 1997)

$$\overline{\psi}(\omega) = \frac{r_{el} v_p^2}{4\rho v_s^2} \frac{\left[\frac{(P_{0s} - P_{0c})\alpha \quad v_p / r_{el}}{\left(\alpha \quad v_p / r_{el}\right)^2 + \omega^2} + P_{0c}\pi\delta(\omega) \right] - i \left[\frac{(P_{0s} - P_{0c})\omega}{\left(\alpha \quad v_p / r_{el}\right)^2 + \omega^2} - \frac{P_{0c}}{\omega} \right]}{\left(\frac{v_p}{r_{el}}\right)^2 - \frac{1}{4}\left(\frac{v_p}{v_s}\right)^2 \omega^2 + i\frac{v_p}{r_{el}}\omega} \tag{1}$$

where

v_p	=	P wave velocity of source region medium
v_s	=	S wave velocity of source region medium
ρ	=	density of source region medium
r_{el}	=	elastic radius of source
P_{0s}	=	peak shock pressure at elastic radius
P_{0c}	=	static pressure at elastic radius
α	=	pressure decay constant
ω	=	angular frequency

Among these parameters, elastic radius r_{el}, peak pressure P_{0s} and static pressure P_{0c} need to be estimated from equations in Mueller and Murphy (1971) paper. The elastic radius is related to the source yield W (kt) and source depth h (m) as

$$r_{el} = 1999\left(\frac{A}{A_{cal}}\right)^{1/2.4} \frac{W^{1/3}}{(\rho h)^{1/2.4}}$$

where the ratio A/A_{cal} is medium dependent and is unity for tuff and rhyolite. The peak pressure is

$$P_{0s} = 1.5\rho g h$$

where g is the gravitational acceleration. The static pressure is

$$P_{0c} = \frac{4\mu}{3} d \left(\frac{r_c}{r_{el}} \right)^3$$

where μ is the shear modulus, d is a medium dependent compaction factor and is 0.6 for tuff and rhyolite. r_c is the source cavity radius and

$$r_c = 16.3 W^{0.29} E^{0.62} \rho^{-0.24} \mu^{-0.67} h^{-0.11}$$

where E is Young's modulus.

The inverse Fourier transform of Equation 1 (or the time function), $\psi(t)$, is called the reduced displacement potential (RDP). Its relationship with the source moment for a point source is

$$M(t) = 4\pi\rho v_p^2 \psi(t) \tag{2}$$

Time function of single shot spall

To model the spall phenomenon in a cast blast, Barker *et al.* (1993) extended the force model of spall accompanying an underground explosion proposed by Day *et al.* (1983) to include 1) the effect of potential energy loss due to the falling of spalled material to the pit and 2) a horizontal term due to the horizontal mass movement. The expression of the vertical force f_z and horizontal force f_h of their spall model is

$$\begin{aligned} f_z &= f_{z1} + f_{z2} + f_{z3} \\ &= \{m_T V_{0z} \delta(t)\} - \\ &-\{m_T g[H(t) - H(t - T_s)]\} + \\ &+\{m_T V_{1z} \delta(t - T_s)\} \end{aligned} \tag{3a}$$

$$f_h = m_T V_h [\delta(t) - \delta(t - T_s)] \tag{3b}$$

where
m_T = spalled mass
V_{0z} = vertical escape velocity of spalled mass
V_{1z} = vertical impact velocity of spalled mass
V_h = horizontal velocity of spalled mass
T_s = dwell time
$\delta(t)$ = delta function
$H(t)$ = Heaviside step function

According to ballistic dynamics, $V_{1z} = (V_{0z}^2 + 2h_{ff}g)^{1/2}$ and $T_s = (V_{0z} + V_{1z})/g$. h_{ff} is the final vertical position change of the spalled material. Although there is kinetic energy change in the system, the model conserves momentum.

In real situations, the spall initiation and impact are smoother than delta like. A smoothed version of this source model with finite spall rise and spall impact pulses of equal widths is

$$
\begin{aligned}
f_z &= f_{z1} + f_{z2} + f_{z3} \\
&= \left\{ m_T V_{0z} \left(\frac{30t^4}{T_{sr}^5} - \frac{60t^3}{T_{sr}^4} + \frac{30t^2}{T_{sr}^3} \right) [H(t) - H(t - T_{sr})] \right\} - \\
&\quad - \left\{ m_T g \left[\begin{array}{l} \left(\frac{6t^5}{T_{sr}^5} - \frac{15t^4}{T_{sr}^4} + \frac{10t^3}{T_{sr}^3} \right) [H(t) - H(t - T_{sr})] + [H(t - T_{sr}) - H(t - T_s)] + \\ + \left(1 - \left(\frac{6(t - T_s)^5}{T_{sr}^5} - \frac{15(t - T_s)^4}{T_{sr}^4} + \frac{10(t - T_s)^3}{T_{sr}^3} \right) \right) [(H(t - T_s) - H(t - T_s - T_{sr})] \end{array} \right] \right\} + \\
&\quad + \left\{ m_T V_{1z} \left[\frac{30(t - T_s)^4}{T_{sr}^5} - \frac{60(t - T_s)^3}{T_{sr}^4} + \frac{30(t - T_s)^2}{T_{sr}^3} \right] [H(t - T_s) - H(t - T_s - T_{sr})] \right\}
\end{aligned}
\tag{4a}
$$

$$
\begin{aligned}
f_h &= f_{h1} + f_{h2} \\
&= \left\{ m_T V_h \left(\frac{30t^4}{T_{sr}^5} - \frac{60t^3}{T_{sr}^4} + \frac{30t^2}{T_{sr}^3} \right) [H(t) - H(t - T_{sr})] \right\} - \\
&\quad - \left\{ m_T V_h \left[\frac{30(t - T_s)^4}{T_{sr}^5} - \frac{60(t - T_s)^3}{T_{sr}^4} + \frac{30(t - T_s)^2}{T_{sr}^3} \right] [H(t - T_s) - H(t - T_s - T_{sr})] \right\}
\end{aligned}
\tag{4b}
$$

where T_{sr} is the rise or impact pulse width and $T_{sr} \leq T_s$. The source process of a cast blast could be more complex with sub-processes such as material bulking and void collapse upon impact. These complexities can be accounted for to some degree by a spall model with the impact pulse width wider than the rise pulse width. If we desire a smoothed spall model with different rise and impact pulse widths, a model that conserves momentum is

$$f_z = f_{z1} + f_{z2} + f_{z3}$$

$$= \left\{ m_T V_{0z} \left(\frac{30t^4}{T_{sr}^5} - \frac{60t^3}{T_{sr}^4} + \frac{30t^2}{T_{sr}^3} \right) [H(t) - H(t - T_{sr})] \right\} -$$

$$-\left\{ m_T g \left[\begin{array}{l} \left(\frac{6t^5}{T_{sr}^5} - \frac{15t^4}{T_{sr}^4} + \frac{10t^3}{T_{sr}^3} \right) [H(t) - H(t - T_{sr})] + [H(t - T_{sr}) - H(t - T'_s)] + \\ + \left(1 - \left(\frac{6(t - T'_s)^5}{T_{sf}^5} - \frac{15(t - T'_s)^4}{T_{sf}^4} + \frac{10(t - T'_s)^3}{T_{sf}^3} \right) \right) [(H(t - T'_s) - H(t - T'_s - T_{sf})] \end{array} \right] \right\} + \tag{5a}$$

$$+ \left\{ m_T V_{1z} \left[\frac{30(t - T'_s)^4}{T_{sf}^5} - \frac{60(t - T'_s)^3}{T_{sf}^4} + \frac{30(t - T'_s)^2}{T_{sf}^3} \right] [H(t - T'_s) - H(t - T'_s - T_{sf})] \right\}$$

$$f_h = f_{h1} + f_{h2}$$

$$= \left\{ m_T V_h \left(\frac{30t^4}{T_{sr}^5} - \frac{60t^3}{T_{sr}^4} + \frac{30t^2}{T_{sr}^3} \right) [H(t) - H(t - T_{sr})] \right\} - \tag{5b}$$

$$-\left\{ m_T V_h \left[\frac{30(t - T'_s)^4}{T_{sf}^5} - \frac{60(t - T'_s)^3}{T_{sf}^4} + \frac{30(t - T'_s)^2}{T_{sf}^3} \right] [H(t - T'_s) - H(t - T'_s - T_{sf})] \right\}$$

where T_{sr} is the rise pulse width; T_{sf} is the impact pulse width, and $T_{sf} \geq T_{sr}$. $T'_s = T_s - (T_{sf} - T_{sr})/2 > 0$. The conditions $T_{sr} \leq T'_s$ and $T'_s > 0$ impose constraints on T_{sr} and T_{sf}. This model is a modification of Anandakrishnan *et al.*'s (1997) spall model. A special case is when there is no horizontal spall and no vertical position change. In this case, $V_h = 0$; $V_{1z} = V_{0z}$, and the model can be used to model those blasts where there is no material cast. Further, if $T_{sf} = T_{sr}$, the model simplifies to the model proposed by Stump (1985) for underground explosions.

According to Day and McLaughlin (1991), if we use equation (3.20) of Aki and Richards (1980) to calculate the spall moment tensor, the force representation of spall $f_s(t)$ can be approximated by its moment tensor representation $M_s(t)$ as

$$f_s(t) = \rho h \frac{d^2}{dt^2}\left[M_s(t)\right] \tag{6}$$

where ρ is the density and h is the depth of the spall surface during an underground explosion. For the spall model of near-surface industrial blasts, Equation 6 is also valid if we treat h as the distance perpendicular to the spall surface. This distance is commonly referred to in the mining industry as "burden".

Single shot source representation

In MineSeis, the single shots in a multi-shot blast are modeled as point sources with second order source moment tensor representations for both the explosion and the spall. Equation (3.20) of Aki and Richards (1980) is used to calculate the moment tensors. The coordinate system is set up with x_1 axis positive to the north, x_2 axis positive to the east and x_3 axis positive down. For the isotropic explosion, the moment tensor is $M_e(t)\mathbf{I}$, where $\mathbf{I}$ is the unity second order tensor and $M_e(t)$ is the source time function (Equation 2). The spall source consists of two components representing the vertical and horizontal movement of the cast material. The moment tensor representation of the vertical spall is

$$M_{sz}(t)\begin{bmatrix} \lambda & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & \lambda+2\mu \end{bmatrix} \tag{7a}$$

where λ and μ are Lamé constants. This representation is based on the assumption that the vertical spall can be modeled as a horizontal opening crack. Based on the same assumption, the horizontal spall moment tensor is derived as

$$M_{sh}(t)\begin{bmatrix} \lambda+2\mu\cos^2\phi & 2\mu\sin\phi\cos\phi & 0 \\ 2\mu\sin\phi\cos\phi & \lambda+2\mu\sin^2\phi & 0 \\ 0 & 0 & \lambda \end{bmatrix} \tag{7b}$$

where ϕ is the angle between the direction of the horizontal movement of the cast material and x_1 (north). The angle is measured clockwise from x_1 (Anandakrishnan *et al.*, 1997). $M_{sz}(t)$ and $M_{sh}(t)$ are source time functions calculated with Equation 6 from f_z and f_h respectively. If there is no material cast, $M_{sh}(t) = 0$. The direction of the horizontal mass movement could be different than the direction of the normal of the bench face depending on the firing pattern, because previously fired shots may create new free faces with different normal directions for subsequent shots. In the program, I assume that these new face normals are a constant vector for all the single shots.

Synthetics

Single shot synthetic seismogram components can be expressed in the frequency domain as (Yang, 1997)

$$u_r = M_{11}\left[\frac{SS_r}{2}\cos 2\theta + \frac{EX_r + LD_r}{3}\right] +$$
$$+M_{12}[SS_r \sin 2\theta] -$$
$$-M_{22}\left[\frac{SS_r \cos 2\theta}{2} - \frac{EX_r + LD_r}{3}\right] - \qquad (8a)$$
$$-M_{33}\left[\frac{2}{3}\left(LD_r - \frac{EX_r}{2}\right)\right]$$

$$u_t = -M_{11}\left[\frac{SS_t}{2}\sin 2\theta\right] +$$
$$+M_{12}[SS_t \cos 2\theta] + \qquad (8b)$$
$$+M_{22}\left[SS_t \frac{\sin 2\theta}{2}\right]$$

$$u_z = M_{11}\left[\frac{SS_z}{2}\cos 2\theta + \frac{EX_z + LD_z}{3}\right] +$$
$$+M_{12}[SS_z \sin 2\theta] -$$
$$-M_{22}\left[\frac{SS_z \cos 2\theta}{2} - \frac{EX_z + LD_z}{3}\right] - \qquad (8c)$$
$$-M_{33}\left[\frac{2}{3}\left(LD_z - \frac{EX_z}{2}\right)\right]$$

where θ is the azimuth of the receiver clockwise from x_1 (north). u_r, u_t and u_z are radial-, transverse- and vertical-components respectively. Detailed descriptions of the canonical Green's functions SS, EX and LD can be found in Yang (1997). Because the program is designed to model regional and near regional data, I assume that differences in Green's functions due to the source spatial finiteness can be neglected and use the same Green's functions for all the single shots in the blast. If the program is to be used to model near-source data with source-receiver distance comparable with the source dimension, the error introduced by the approximation should be assessed.

Superposition

In addition to the time delay of the firing sequence, the time delay due to the location differences of the single shots needs to be taken into account when single shot synthetics are superimposed. These source-spatial-finiteness introduced delays can be comparable to or even larger than the delays due to the delay-firing. Considering both delays, the superimposed signal is expressed as

$$U(t) = \sum_{i=1}^{P} A_i u(t - T_i - \tau_i) \tag{9}$$

where u is the single shot synthetics; P is the total number of shots in the blast; A_i is a scaling factor and T_i is the time delay between i^{th} shot and the reference shot (first shot) because of delay-firing. τ_i is the P wave travel time difference between i^{th} shot and the reference shot due to their location difference and

$$\tau_i = \frac{r_0 \sin\chi}{v_{p0}} \left[\left(1 + \frac{r_i^2}{r_0^2} - \frac{2r_i \cos\zeta_i}{r_0} \right)^{1/2} - 1 \right] \tag{10}$$

where r_0 is the distance between the receiver and the reference shot; r_i is the distance between i^{th} shot and the reference shot; ζ_i is the angle between the line connecting the i^{th} shot and the reference shot, and the line connecting the receiver and the reference shot; v_{p0} is the P wave velocity of the source region medium and χ is the P wave take-off angle (Figure 1). Since the term $\sin\chi / v_{p0}$ is the ray parameter for a planar layered velocity model, it can be replaced with the P wave velocity at depth. The parameters r_i and ζ_i in (10) can be calculated from the burden a and spacing b of the shots in the shot array with the assumption that the shot array has a simple, rectangular shape with

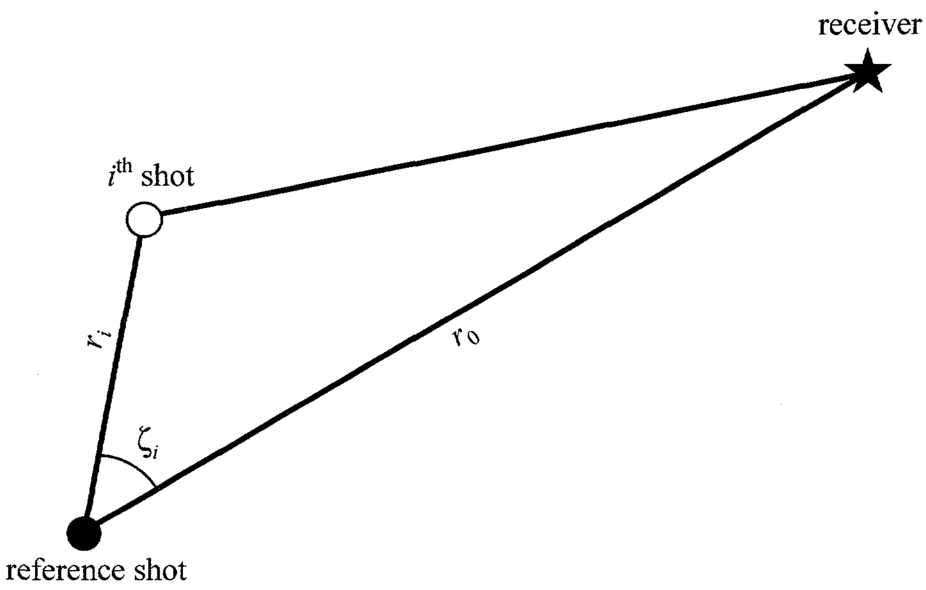

Figure 1

parallel straight rows. More complex shot patterns, such as chevron shaped patterns, can not be modeled by the program.

Within the above mentioned pattern category, there are two sub-patterns: rectangular and staggered, with square and offset patterns as special cases (Chiappetta *et al.*, 1987). In a rectangular pattern, shots in different rows are aligned. In a staggered pattern, shots in adjacent rows are offset. Calculations of r_i and ζ_i are slightly different for these two different patterns. Suppose that there are N rows and M columns of shots in a array with (n, m) being the location of i^{th} shot at n^{th} row and m^{th} column and the reference shot at (1, 1). For a rectangular pattern and odd numbered rows in a staggered pattern, we have

$$r_i = \sqrt{[(n-1)a]^2 + [(m-1)b]^2}\ .$$

For even numbered rows in a staggered pattern,

$$r_i = \sqrt{[(n-1)a]^2 + [(m-0.5)b]^2}\ .$$

Here I assume that the offset B between the first shot in any even numbered row and the reference shot in a staggered pattern is 0.5b.

To calculate ζ_i, I first rotate the coordinate system such that x_2 axis is parallel to the normal of the vertical bench face. The azimuth of the receiver θ' is now calculated with respect to the new x_1 axis that is now parallel to the strike of the vertical bench face. I then decide if the firing sequence is to the "north" (the strike of the vertical bench face) or to the "south". If the firing sequence is to the "north" (Figure 2), for a rectangular pattern and odd numbered rows in a staggered pattern, I have

$$\zeta_i = \theta' + \tan^{-1}\left[\frac{(n-1)a}{(m-1)b}\right].$$

For even numbered rows in a staggered pattern,

$$\zeta_i = \theta' + \tan^{-1}\left[\frac{(n-1)a}{(m-0.5)b}\right].$$

If the firing sequence is to the "south" (Figure 3), I have

$$\zeta_i = 180^\circ + \theta' - \tan^{-1}\left[\frac{(n-1)a}{(m-1)b}\right]$$

for a rectangular pattern and odd numbered rows in a staggered pattern and

$$\zeta_i = 180^\circ + \theta' - \tan^{-1}\left[\frac{(n-1)a}{(m-0.5)b}\right]$$

for even numbered rows in a staggered pattern.

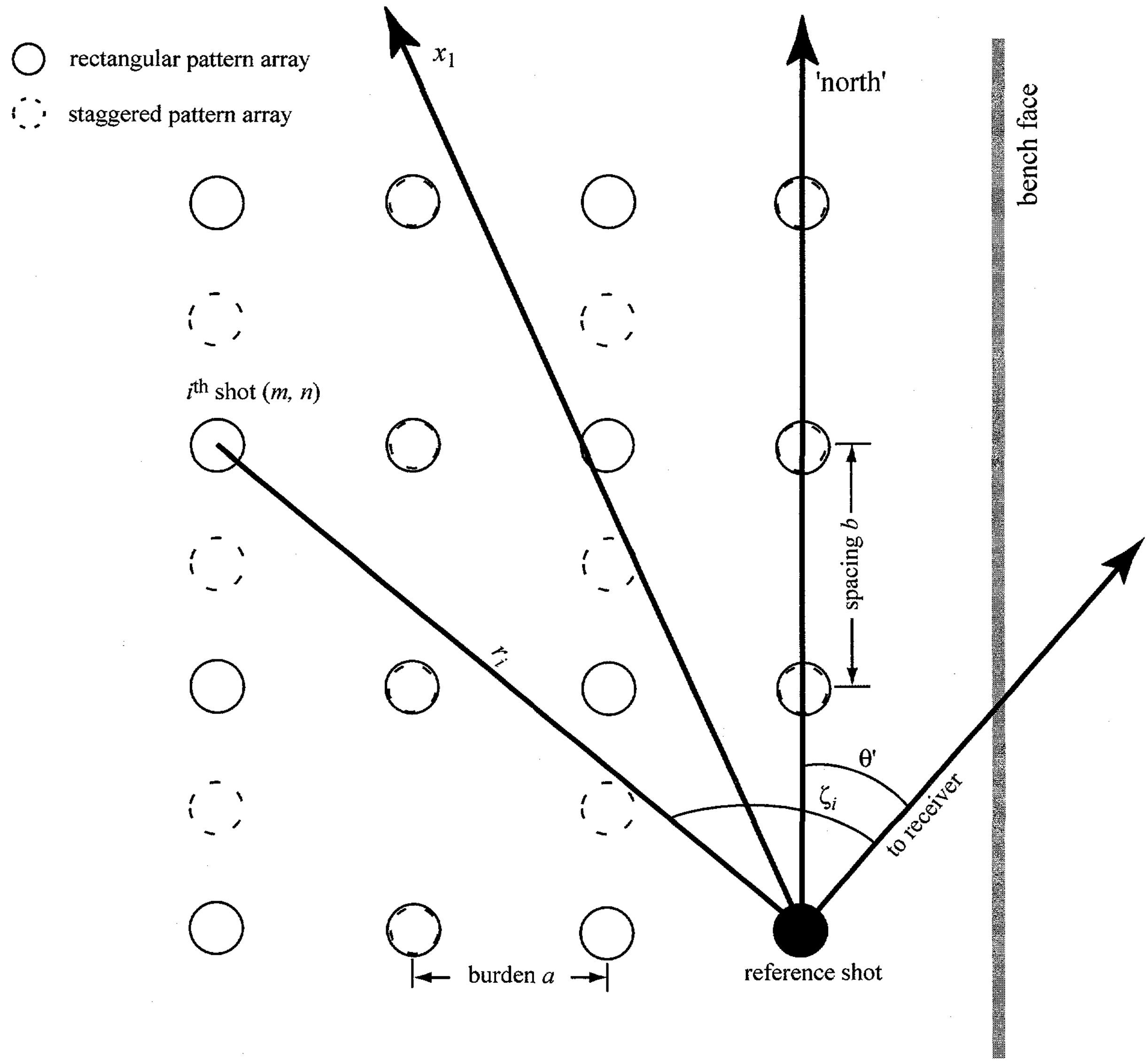

Figure 2

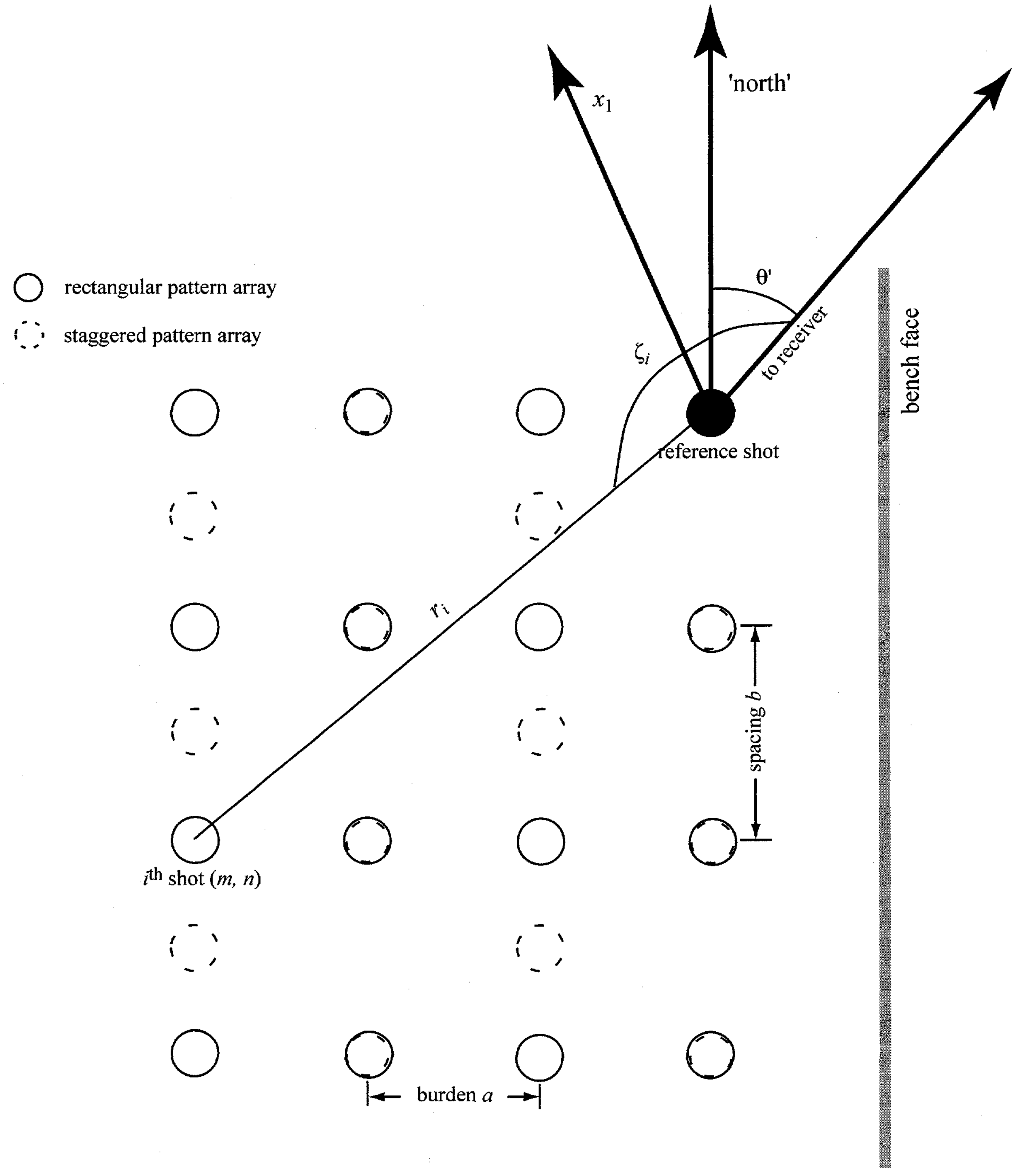

Figure 3

If the condition $B = 0.5b$ is not satisfied, I fill in the pattern with shots of zero yield to meet the condition.

Implementation

The program was written with MATLAB Graphical User Interface (GUI) technique to facilitate user interaction with the program. MATLAB is a commercial computer language oriented toward technical computing and data visualization. The program consists of four main figure windows containing plotting panels, User Interface Controls (Uicontrols) and User Interface Menus (Uimenus). The first window is for viewing, filtering and printing of time series and their spectra resulting from different stages of the calculation. The other three windows are for inputting source and path parameters and for calculating the source time functions, impulse superposition and synthetic seismograms. The user can input source parameters either by moving sliders or by typing in numbers. For source time functions, the up-dated results are plotted in the first window every time any one of the source parameters is changed. It gives the user a visual idea of how the source parameters affect the source time function. In addition to being plotted on the screen, the results from each stage of the calculation can be filtered (if they are seismograms), saved to disk or printed as hard copies.

Whereas the program obtains most of its input parameters from the Uicontrols and Uimenus, it does require a Green's function file, a firing sequence file and a yield sequence file to complete the calculation. The Green's function file can be constructed by converting the output of any synthetic seismogram calculation code. The firing sequence file and the yield sequence file must be constructed manually.

MineSeis was programmed on a Sun Ultrasparc workstation and has been ported to PC and Macintosh platforms. A detailed Program Usage is provided in the Appendix.

Conclusion

Modeling industrial chemical blasts is an important tool in understanding their seismic characteristics. This MATLAB GUI program enables the user to model these blasts in a convenient and interactive manner. In addition to modeling mining blast, the program can also be used to study explosion and spall models, for example, examining the depth effect, source scaling, etc..

Acknowledgments

Program improvement suggestions and comments by Karl Koch, Michael Hedlin and Brian Stump are appreciated. It was Brian Stump's original idea to write a program to analyze mining blast signals. Craig Pearson and Steve Taylor are thanked for reviewing the manuscript. This work is performed under the auspices of the U.S. Department of Energy by LANL under contract W-7405-ENG-36.

References

Anandakrishnan, S., S. R. Taylor and B. W. Stump (1997). Quantification and characterization of regional seismic signals from cast blasting in mines: a linear elastic model, *Geophys. J. Int.* **131,** 45-60.

Aki, K. and P. G. Richards (1980). *Quantitative Seismology: Theory and Methods,* W. H. Freeman, New York.

Barker, T. G. and K. L. Mclaughlin (1992). Numerical model of quarry blast sources, in *Proc. 14th Annual PL/DARPA Seismic Research Symposium,* 16-18 September 1992, Tucson, Arizona, 15-21.

Barker, T. G., K. L. McLaughlin and J. L. Stevens (1993). Numerical simulation of quarry blast sources, *Technical Report*, S-CUBED, La Jolla, California.

Brune, J. N. (1970). Tectonic stress and the spectra of seismic shear waves from earthquakes, *J. Geophys. Res.* **75,** 4997-5009.

Chapman, M. C., G. A. Bollinger, and M. S. Sibol (1992). Modeling delay-fired explosion spectra at regional distances, *Bull. Seism. Soc. Am.* **82,** 2430-2447.

Chiappetta, R. F., D. G. Borg and V. A. Sterner (1987). *Explosives and Rock Blasting,* Atlas Powder Company, Dallas, Texas.

Day, S. M., N. Rimer and J. T. Cherry (1983). Surface waves from underground explosions with spall, *Bull. Seism. Soc. Am.* **73,** 247-264.

Mueller, R. A., and J. R. Murphy (1971). Seismic characteristics of underground nuclear detonations part I. Seismic spectrum scaling, *Bull. Seism. Soc. Am.* **61,** 1675-1692.

Reamer, S. K., K. G. Hinzen, and B. W. Stump (1992). Near-source characterization of the seismic wavefield radiated from quarry blasts, *Geophys. J. Int.* **110,** 435-450.

Stump, B. W. and R. E. Reinke (1988). Experimental confirmation of superposition from small-scale explosions, *Bull. Seism. Soc. Am.* **78,** 1059-1073.

Stump, B. W. (1985). Constraints on explosive sources with spall from near-source waveforms, *Bull. Seism. Soc. Am.* **75**, 361-377.

Yang, X. (1997) Mining explosion and collapse source characterization and modeling with near-source seismic data, *Ph.D. Thesis*, Southern Methodist University, Dallas, Texas.

APPENDIX

Program Usage

The program MineSeis is intended for users familiar with source models for explosions, spall and multi-shot industrial blasts. It is also assumed that the user has reasonable knowledge of MATLAB®, a computer language. The program uses MATLAB Graphical User Interface (GUI) technique to facilitate interactions between the user and the program. MineSeis consists of four figure windows for parameter input, and result plotting and filtering. It is launched by typing "mineseis" at the MATLAB prompt in a MATLAB command window. After the user launches the program and changes the working directory, the first window "Plot Panel" appears on the screen. All subsequent commands thereafter are issued through the GUIs. Figure a1 shows the "Plot Panel" before any calculation and plotting. The upper panel is for time series plotting and the lower panel is for spectrum plotting. Both plots can be printed from the "Print" pull-down menu on the menu bar. The program uses a global sampling rate for all its calculations which can be set from the "dt" pull-down menu. The default sampling rate is 1000 samples per second. The user can use the "Filter" pull-down menu to filter displayed seismograms. High-pass, low-pass, band-pass and band-stop Butterworth filters are available. The pull-down menu "Spectrum-Scale" is used to toggle the scale of the spectrum plot between logarithm and linear. The user can also zoom into certain areas of the plots by turning the "Zoom" menu on, then click (and drag) the left mouse button in the plots. MATLAB zooming method is used. Note that on Macintosh platform, pull-down menus of all active windows appear on the Macintosh Menu Bar at the top of the screen.

Clicking the left three buttons at the bottom of the "Plot Panel" window brings up corresponding windows. They are shown in Figure a2. The left most window is the "Explosion Source Panel" used to calculate the single shot explosion source time function. To calculate the Mueller-Murphy explosion source time function, the user is required to input *P*-wave velocity, *S*-wave velocity and density of the source region medium, the source depth and the source yield. These parameters can be input either by moving the sliders under the parameter titles on the left or typing the numbers in the input boxes on the right. The numbers under the sliders mark the corresponding minimum and maximum values. On the menu bar, the user can choose different medium types from the pull-down menu. The default medium type is rhyolite. Figure a3 shows the available medium types. The program will make one source time function calculation and plot the results every time any one of the source parameters is changed. That way, the effects of individual source parameters on the source time function can be examined. The resulting source time function, or the reduced displacement potential, can be saved to disk in MATLAB data format by clicking the "Save" button. The source time function is also stored in memory. If a previously saved source time function is needed, it can be loaded into memory by clicking the "Load" button. Once the file is loaded, source parameters in the window will be changed according to the values from the file and the loaded source time function will be plotted.

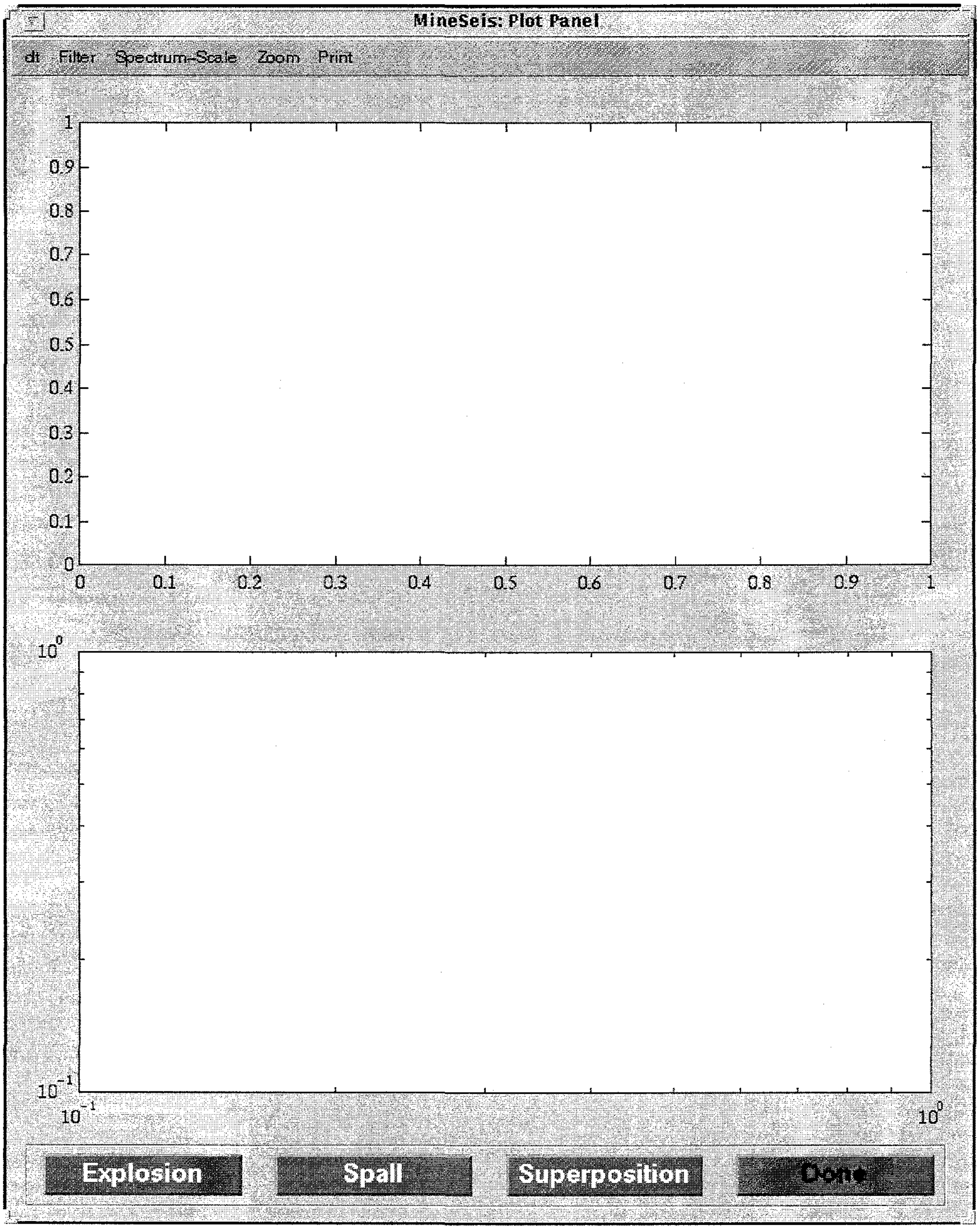

Figure a1

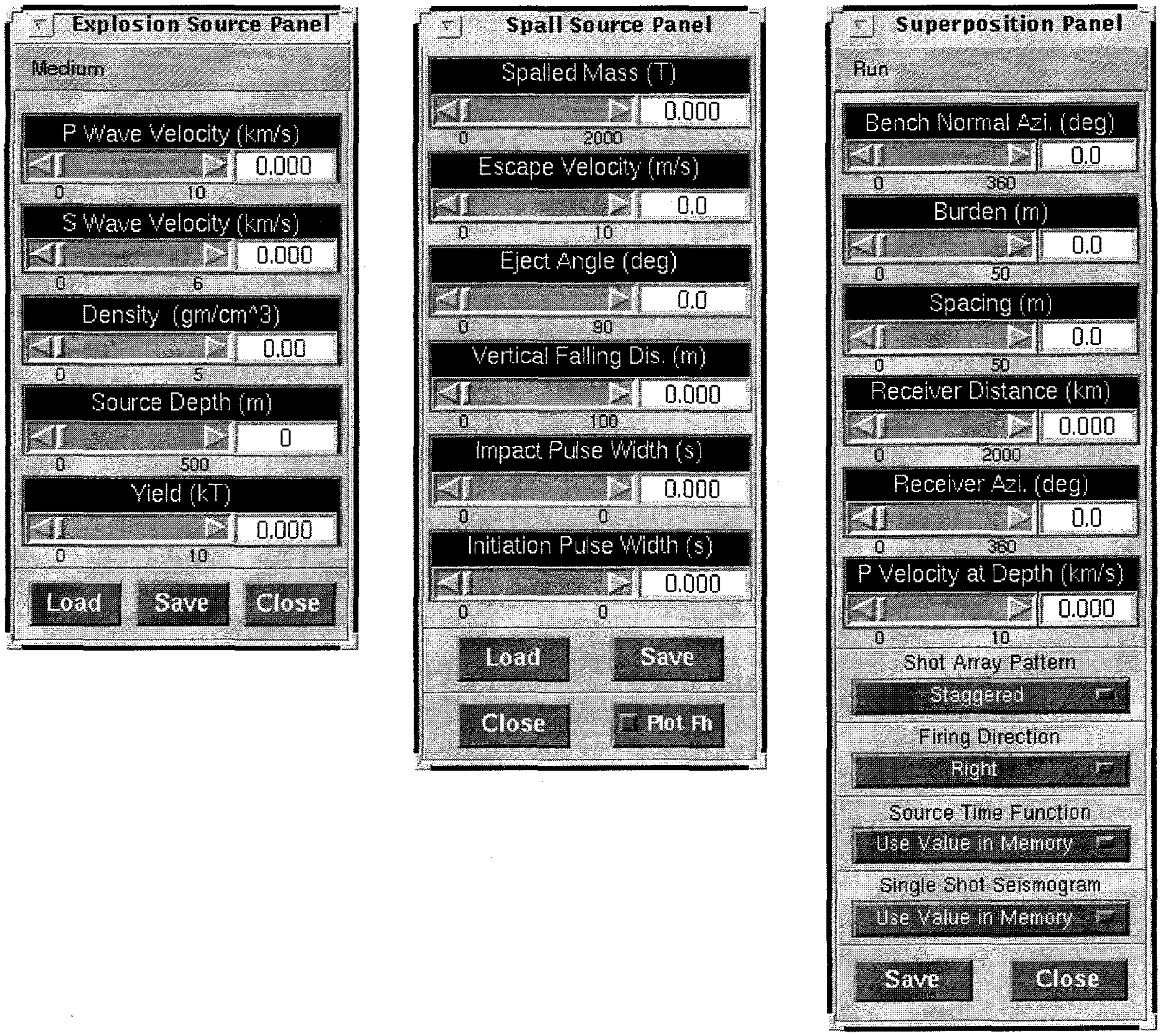

Figure a2

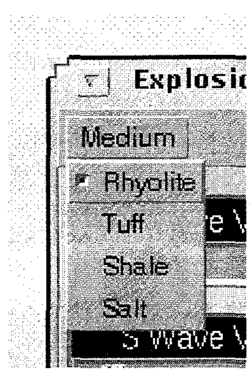

Figure a3

The middle window in Figure a2 is the "Spall Source Panel" window. It is used to calculate the single shot spall source time function. Similar to explosion source time function calculation, the user can input the source parameters either by using the sliders or by typing in the numbers. The source parameters include spalled mass, its escape velocity (not its components), eject angle (relative to vertical), vertical falling distance, impact pulse width and rise pulse width of the spall source time function. The maximum allowable values of impact pulse width and rise pulse width are calculated by the program to meet certain constraints discussed in the main text and set automatically. The program calculates both vertical and horizontal forces each time any source parameter is changed and plots the vertical force and its spectrum by default. The user can choose to plot the horizontal force by checking the "Plot Fh" check box. Again the source time function is stored in memory and can be saved to or loaded from disk.

The major part of the program is to calculate the single shot synthetic seismograms, the impulse superposition and the superimposed synthetic seismograms. The third window in Figure a2, "Superposition Panel", facilitates this calculation. In addition to the parameters indicated in the window, the program requires a Green's function file to calculate single shot synthetic seismograms. A firing sequence file and a yield sequence file are also required to calculate the impulse superposition. These files are MATLAB binary data files. There is one variable in each of these three files. The variable in the Green's function file is named *grn*. It is a MATLAB matrix with each column representing each component of the Green's function except for the first line that contains the time of the first data point, the source-receiver distance and the sampling interval. The Green's function file can be constructed by converting the output from any synthetic seismogram calculation code to MATLAB format. A MATLAB *script named buildgrn.m is included in the UNIX version of the program package that* converts the output from the FORTRAN reflectivity code REFSEIS to the required Green's function file. The script can be used as a template to write conversion scripts for other synthetic seismogram codes. The data format of the variable in the required Green's function can be obtained from the script. The variable in the firing sequence file is named *ts* and the variable in the yield sequence file is named *yd*. They are MATLAB matrices reflecting the firing pattern with element (1,1) being the first shot, rows being the rows of the shot array and columns being the columns of the shot array. Data in the firing sequence variable are in the unit of seconds and data in the yield sequence variable are in the unit of kilograms. The firing sequence and yield sequence files need to be constructed manually. The names of these variables, *grn, ts and yd*, are required and should not be changed by the user.

As with the previous windows, the "Superposition Panel" window provides sliders and input boxes to facilitate parameter input. Generally the user needs to input all the parameters before the calculation unless previously saved results or observed seismograms are used. These parameters include the azimuth of the normal of the vertical bench face, burden of the single shots, spacing between shots, receiver distance, receiver azimuth and *P*-wave velocity at depth. Some of these parameters are used in the single shot synthetic calculation while others are used in calculating the impulse superposition. Under the parameter input sliders are several pop-up menus. The upper two pop-up menus determine the characteristics of the shot array pattern. The user can choose whether the pattern is rectangular or staggered and whether the detonation direction is to the right or to the left when the observer is facing the bench face. These parameters are used to calculate time delays due to spatial distribution of the single shots. The "Source Time Function" pop-up menu is used to tell the program whether to use the source time functions in memory, or to load source time functions from files. Similarly, the "Single Shot Seismogram" pop-up menu is used to determine whether to use the single shot seismograms in memory or to load them from a file for superposition. When the single shot seismograms are loaded from a file, they can be observed seismograms. The observed seismograms should be in radial, transverse and vertical components and stored in column variables R, T and Z respectively. The file should be in MATLAB data format. (Note that there is a bug in MATLAB 5.0 (and below?) for UNIX. You need to "do something else beforehand" in order for the pop-up menu to work. A easy method is to move the window a little before changing the pop-up menu settings. The bug has been fixed in MATLAB 5.1.)

For this third window, the program does not conduct the calculation when the parameters are changed. The user needs to choose what to calculate from the pull-down menu "Run" on the menu bar. Figure a4 shows what calculations are available from the pull-down menu. Once a sub-menu is chosen, the program makes the

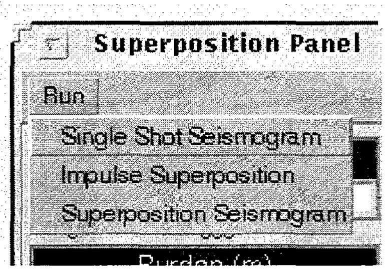

Figure a4

corresponding calculations and plots the results. The results can be saved to disk by clicking the "Save" button.

When calculating the single shot seismograms, the program prompts the user to input the angle between the bench normal and the horizontal spall direction discussed previously. The angle is measured clockwise from the bench normal to the horizontal spall direction. So if the azimuth of the bench normal is smaller, the angle is positive. Otherwise, it should be negative. The calculated single shot seismograms are scaled to one kiloton source strength. Note that the scaling of the single shot explosion source time function — that depends on the original yield the user inputs from the "Explosion Source Panel" window — does not change , except for the long period level.

When calculating the impulse superposition, the user has the option to display the shot array pattern in a separate window shown in Figure a5 with an example shot array pattern displayed. The program then waits for the user to give further instruction to continue the calculation. The user can resume the calculation by clicking the "Continue" button on a pop-up window.

When the "Superposition Seismogram" sub-menu on the "Superposition Panel" window is chosen, the program uses the most recently updated single shot seismograms and impulse superposition time series in memory to calculate the superposition. If any

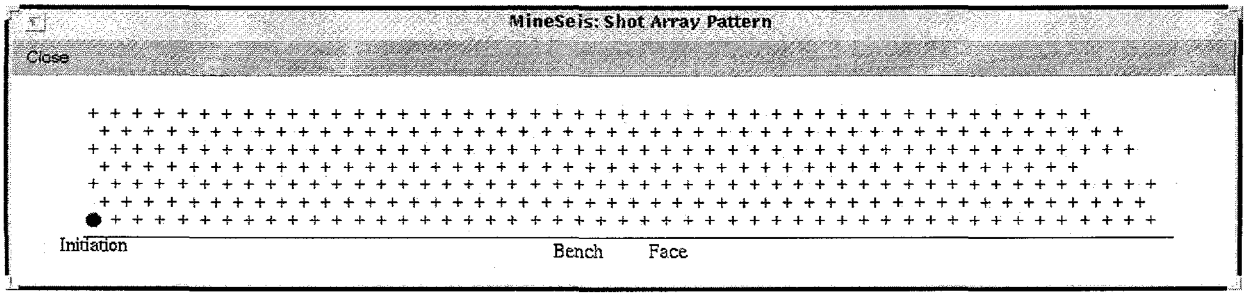

Figure a5

input parameter has been changed, the program will re-calculate or load — depending on the user's choice, the single shot seismograms and impulse superposition whenever necessary before calculating the superposition seismograms. The program also checks the consistency of parameters such as sampling rate, source-receiver distance and shot array pattern parameters (burden and spacing) loaded from files and input from the "Superposition Panel" window. After the time series or the seismograms are calculated and displayed in the "Plot Panel" window, the user can then manipulate them by filtering, changing the axis scaling method and zooming.

For most input parameters, their units are obvious from the windows. The units of the output can be obtained from the labels of the corresponding plots. Care should be taken when constructing Green's function, firing sequence, yield sequence and observed seismogram files. Green's functions should be in nanometers; firing sequence in seconds; yield sequence in kilograms and observed data in nm/sec. The observed data should be scaled to unit kiloton yield source assuming that source yield is proportional to the amplitude.