

**BLACK THUNDER COAL MINE AND LOS ALAMOS NATIONAL LABORATORY
EXPERIMENTAL STUDY OF SEISMIC ENERGY GENERATED BY LARGE SCALE MINE
BLASTING**

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In an attempt to better understand the impact that large mining shots will have on verifying compliance with the international, worldwide, Comprehensive Test Ban Treaty (CTBT, no nuclear explosion tests), a series of seismic and videographic experiments has been conducted during the past two years at the Black Thunder Coal Mine. Personnel from the mine and Los Alamos National Laboratory have cooperated closely to design and perform experiments to produce results with mutual benefit to both organizations. This paper will summarize our activities, highlighting the unique results of each. Topics which were covered in these experiments include:

- 1) Synthesis of seismic, videographic, acoustic, and computer modeling data to improve understanding of shot performance and phenomenology;
- 2) Development of computer generated visualizations of observed blasting techniques;
- 3) Documentation of azimuthal variations in radiation of seismic energy from overburden casting shots (See companion paper by Pearson *et al* this issue);
- 4) Identification of, as yet unexplained, out of sequence, simultaneous detonation in some shots using seismic and videographic techniques;
- 5) Comparison of local (0.1 to 15 kilometer range) and regional (100 to 2000 kilometer range) seismic measurements leading to determination of the relationship between local and regional seismic amplitude to explosive yield for overburden cast, coal bulking and single fired explosions (See companion paper by Stump *et al* this issue); and
- 6) Determination of the types of mining shots triggering the prototype International Monitoring System for the CTBT (See companion paper by Stump *et al* this issue).

1. Experimental Purpose The purpose of the experiments that were conducted cooperatively by the Black Thunder Coal Mine and Los Alamos National Laboratory were to understand the generation and propagation of seismic and acoustic energy from different types of mining explosions. The experiments were designed to constrain the physical processes generating these wavefields. Particular attention was paid to the relationship between close-in (100m to 15 km) and regional distance (100-1000 km) seismic and acoustic observations. The synergy of these different data sets was intended to provide information on explosive performance that might prove useful in future blast designs for purposes of optimization.

Additionally, the experiments were to provide data which could be used in the development of three-dimensional models of the blasting process. These models are interpretative tools as well as providing a mechanism for comparison of effects from different types of blasting practices. These relatively simple models provide a visualization aid in understanding the blasts and possibly improving blasting practices.

2. Experimental Design and Approach A number of different types of measurements were made some of which are illustrated in Figure 1. These diagnostics are common to many blasting operations and include seismic, acoustic and video as well as three dimensional topographic models of the mine. The unique aspect of this experiment is the way the data is collected in an integrated way where all data sets are time tagged so that they can be correlated with one another for interpretation purposes. GPS receivers were used for both timing and location of the wavefield instruments. Collocation of the seismic, acoustic and video data acquisition systems provided the opportunity for correlation of processes identified in the video with the ground motion and acoustic signals. Time tags also provided the opportunity for correlation of signals from sensors at disparate spatial locations. For example, video images of the explosions taken from within the pit of the mine could be correlated with seismic records several kilometers from the explosion.

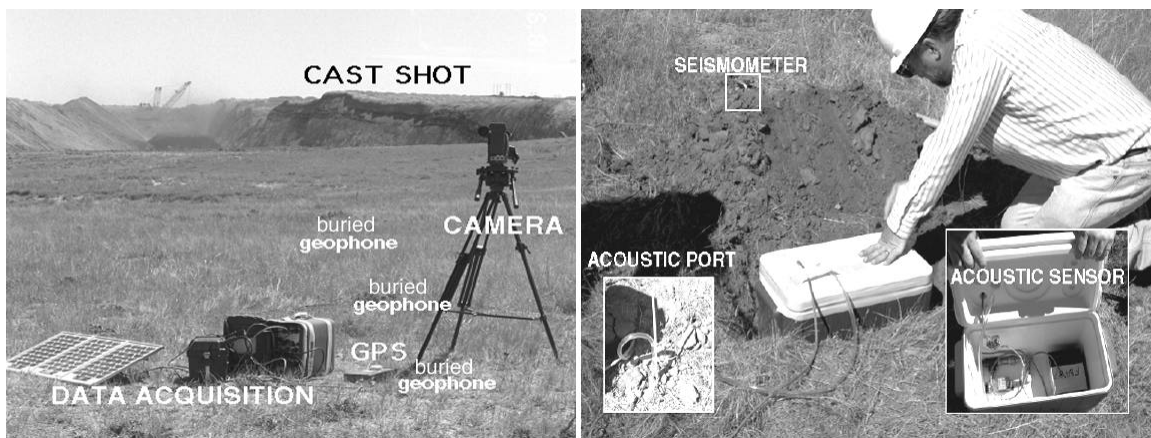


Figure 1: Equipment used in deployment.

Critical to the processing, integration and interpretation of the different types of data collected in this study is the acquisition of or conversion to digital form. In the case of the wavefield data (seismic and acoustic) sensor output is converted to 24 bit digital format and stored on hard disk utilizing a Refraction Technology 72A-08. This acquisition system provides a variety of time sampling options with sampling as high as 1000 samples per second for each data channel. GPS receivers supply time and location information that are automatically included in each data stream. A number of different types of ground motion sensors were deployed in order to span the range of motions experienced in the mine. At the closest distances, piezoelectric accelerometers (Endevco) were deployed providing quantification of peak motions into the hundreds to thousands of g's. Intermediate motions in the range of tenths to a few g's were documented with force feedback accelerometers. At the lowest motion levels, <math>< \text{cm/s}</math>, velocity transducers were deployed.

Digital topography is developed from overhead aerial photography. This information is used to assess the blast induced permanent displacements by comparison of data taken before and after the explosions. Time varying images of the explosion process are developed from Hi-8 video of the explosion. This data is sampled at 30 frames/s or 60 fields/s. The processing of the video data including the conversion to digital form is described in Stump *et al.*, 1996. The data is converted to digital format utilizing a Galileo data acquisition system on a Silicon Graphics Indigo 2. The individual frames are de-interlaced and then

interpolated to provide 120 digital images of the explosion per second. One advantage of this system is that it utilizes relatively inexpensive consumer grade video equipment. Although not providing the high sampling rates of film cameras, these systems provide moderate sampling while offering the opportunity for unattended operation for as much as 2 hours. Thus, they can be placed in locations impractical for other types of equipment. The low cost of consumer grade video equipment opens up opportunities for multiple camera deployments for explosion documentation which can be quite important for large blasting operations such as that at the Black Thunder Coal Mine.

The instrumentation types utilized in these integrated studies and estimated digital data volumes are summarized in Table 1. Video data when it is converted to digital format has the largest volume although this can be reduced significantly by a number of data compression algorithms.

Table 1: Instrumentation Summary

Measurement Type	Instrument	Range of Measurement	Sample Rate	Data Storage Requirement
ground motion	piezoelectric accelerometer	10 - 1000's g's	1000 samples/sec	3 Kbytes/s
ground motion	force-balance accelerometer	.1 - 10 g's	250-1000 samples/s	.75 - 3 Kbytes/s
ground motion	velocity	.001 - 1 cm/s	40 - 250 samples/s	.12 - .75 Kbytes/s
acoustic	diaphragm	100-100,000 μ bars	100-1000	.3-3 Kbytes/s
video	Hi-8	visible spectrum	30-120 samples/s	30-120 Mbytes/s, no compression

The spatial sampling of these different data sets is also quite important. A typical instrumentation layout at the Black Thunder Coal Mine is illustrated in Figure 2. In this case, a number of ground motion instruments were distributed around the mine to quantify changes in the wavefield with azimuth as well as range. Based upon the range of recordable motions documented in Table 1, the closest instruments are accelerometers while the more distant locations have velocity transducers or seismometers. A variety of scale lengths in station spacing from tens of meters to kilometers are employed in order to quantify the spatial coherence of the wavefield. Multiple camera locations are employed to assure full coverage of the explosions, especially the cast shots which can be as large as a kilometer or more in total length. Seismometers and acoustic gages are typically deployed at distances from tens to hundreds of kilometers to document the transition of the wavefields to regional distances.

3. Types of Explosions Documented A number of different types of explosions were documented during these experiments and will be illustrated. The largest of the explosions are those associated with cast blasting (Martin and King, 1995) where explosives are used to remove the overburden with thickness as great as 175 feet. These explosions have burdens between 22 to 38 feet and spacing of 32 feet including up to 9 rows with as many as 100 explosions in a row. A cast blast can include between 2 and 8 million lb. of explosives and total time durations of several seconds.

Additional explosives are used to fracture the coal after exposure. These types of sources are smaller in total size (3,000- 300,000 lb.), shorter in duration and reduced in powder factor since they are not designed to cast material.

Finally, in order to provide a simple quantification of propagation path effects within the mine and to regional distances, a single fired explosion was conducted. Data from this explosion provides the ability

to experimentally assess propagation path effects which can then be used in the physical interpretation of the wavefields from the other two types of sources.

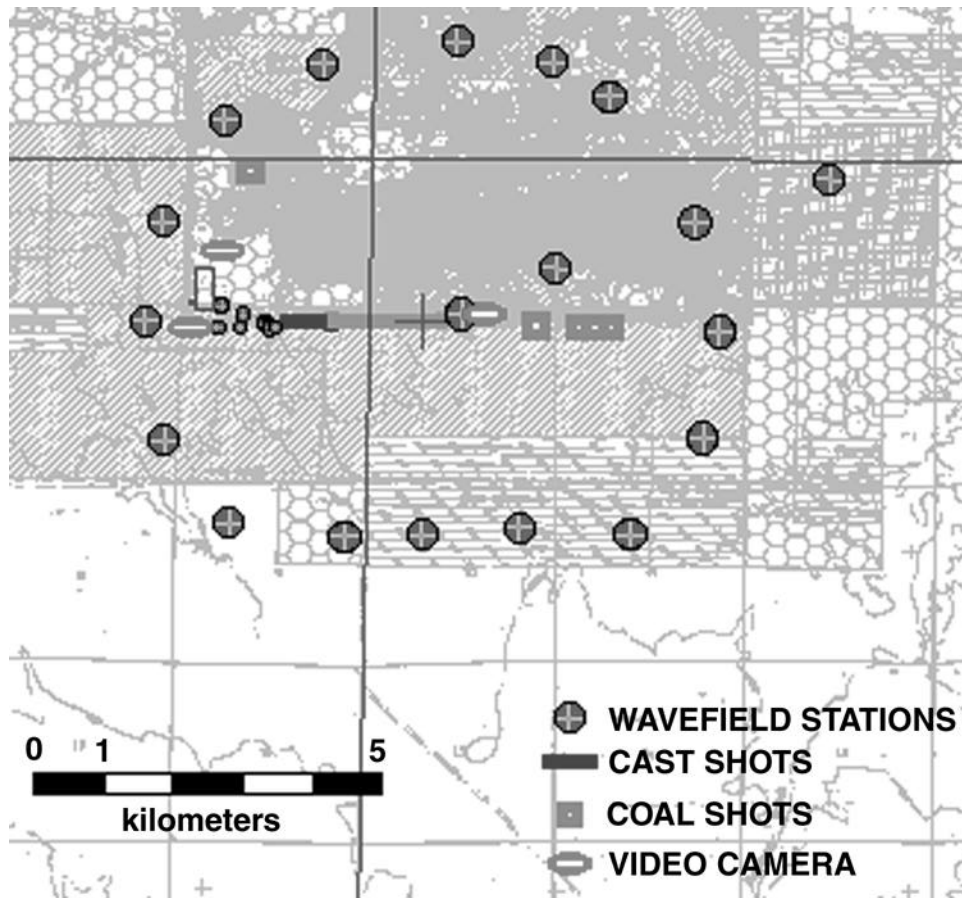


Figure 2: Typical Instrumentation Layout

4. Data Synthesis and Two-Dimensional Visualization Techniques A key factor in the experimental design and utilization of a variety of different sensor was the desire to integrate these different data sets for the purpose of developing a physical understanding of blast phenomenology and a methodology for blast diagnostics. The fact that all the data sets can be converted to digital form and that they each have their own time information provides the opportunity for their integration into a single digital product for interpretation purposes.

An example of this data integration is given in Figure 3. Video images from a large-scale cast blast have been captured and put into digital form. The camera in this case was installed in the pit to provide documentation of cast material. This camera location illustrates the fact that the video camera can be deployed in an unattended location sometime before the explosion thus recovering unique blast diagnostics. Once the video is converted to digital form, the observed ground motion records (in this case velocity record from approximately 15 km range) can be mapped onto these images and time correlated (the vertical bar passing through the three-component ground motions represents the time in the video image). The design blast and instrumentation layout are mapped onto the video image in addition to time and date. The rectangle in the lower center of the image represents the multi-hole blast design with each individual borehole (represented by a rectangle) turning from translucent white to gray at the design detonation time. Thus one can assess progress through the explosive array in each frame of Figure 3 by monitoring this rectangular area. Finally, the ground motion is represented in three-dimensional form in

the lower right of each image by a small ball and accompanying tail illustrating in three space the motion of a particle at the location of the seismometer.



Figure 3: Multiple Frames of Good Cast (See text for description(=))

Images such as those just described can be formed for each video field captured by the data acquisition system. After de-interlacing the video data (Stump *et al.*, 1996), this results in an image every 16.67 msec and with interpolation between video fields an image every 8.83 msec (120 images/s). Four of these images from the cast blast are given in Figure 3 illustrating the very regular nature of the wavefield and the documentation of a well controlled, delay-fired cast blast. Supplementary to displays such as Figure 3 is the construction of movies of the blast including all the fields with the data and models. Experience has shown that the best utilization of these integrated data sets is in this movie format where the engineers and blasters can move through the data set at a variety of different speeds to assess blast performance.

5. Development of Three-Dimensional Visualization Techniques and Models One of the unique aspects of this experimental study has been access to three-dimensional data sets which can be used to quantify physical processes accompanying the explosions as well as in construction of models designed to give insight into these processes. Aerial photography was taken before and after one of the large cast blasts at the Black Thunder Coal Mine and used to develop three-dimensional models of a

section of the mine quantifying the material cast during the blasting. This can also be used to assess secondary sources of seismic waves such as the material cast into the pit.

Utilization of this data can be enhanced with modern ray tracing and imagery techniques. These approaches allow the data set to be viewed from any perspective. The three-dimensional topography before and after the cast shot at the Black Thunder Mine was rendered and is reproduced in Figure 4. The location of the observer is positioned along the axis and slightly above the pit in order to provide a good

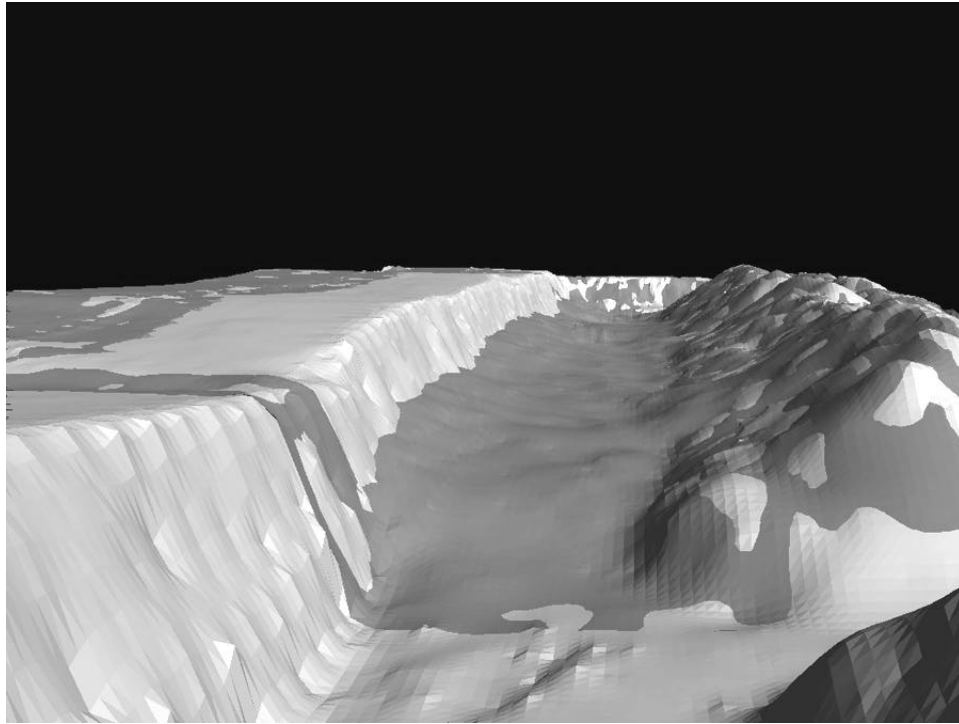


Figure 4: South Pit 3D model before (light gray) and after (dark gray) cast

perspective for assessing the consistency of material cast along the entire length of the explosion. The pit topography prior to the cast blast is rendered in light gray and the pit after the cast blast in dark gray. The material cast is evenly distributed along the axis of the pit. The blast that produced this cast is the one for which video and ground motion data were combined in Figure 3, illustrating that the blast itself performed well. The spatial resolution of this data is on the order of one foot and the limitations of this resolution are illustrated by the alternating light and dark gray pattern both on the bench behind the shot and on the muck pile in front of the cast. No actual change in topography was observed in either place but the 1 foot data resolution results in the before shot survey being randomly higher in some locations and lower in other locations when compared to the post shot survey.

Just as a single three-dimensional data set was mapped onto another in Figure 4, multiple data sets can be combined in three dimensions. Some preliminary work has investigated the possibility of mapping video images of the blasts on top of the three-dimensional models. Carefully documents the camera location and orientation in the mine has produced the necessary information for successful This operation provides the opportunity to develop three-dimensional scales that can be used to interpret particle trajectories and velocities. It also opens the opportunity for the utilization of multiple cameras in the creation of three-dimensional characterizations of the blasting process.

The topographic models in conjunction with information about the blasting process such as the number of explosive holes, their spatial locations, detonation sequence and material property characterization can be used to create simplified models of the blasting process for interpretation of physical observables such as the radiated seismic or acoustic data. We took the three-dimensional topographic model of the mine before the cast shot along with the design hole array (cylinder for each explosive hole) to produce a model of the detonation sequence (white sphere appears at each hole at detonation time) and subsequent generation of compressional seismic waves (expanding rings). This process produced a series of time varying images that replicates the progression of the explosions and the resulting generation and propagation of the compressional seismic energy. It models the finite spatial nature of the source, the temporal effects of delay firing, the compressive energy generated by the direct shock of the explosion and the resulting propagation of this energy away from the source region. Four images with time in the lower right hand corner are reproduced in Figure 5. A complete representation of this process is best viewed as a movie. These are very simplified models that do not include all the physical processes such as the material cast into the pit, the generation of shear energy or the effect of material heterogeneity on the wave propagation. Despite these shortcomings, they illustrate some of the important processes accompanying the explosion such as its finiteness and the effects of the delay firing. This point is emphasized in Figure 6 in which the

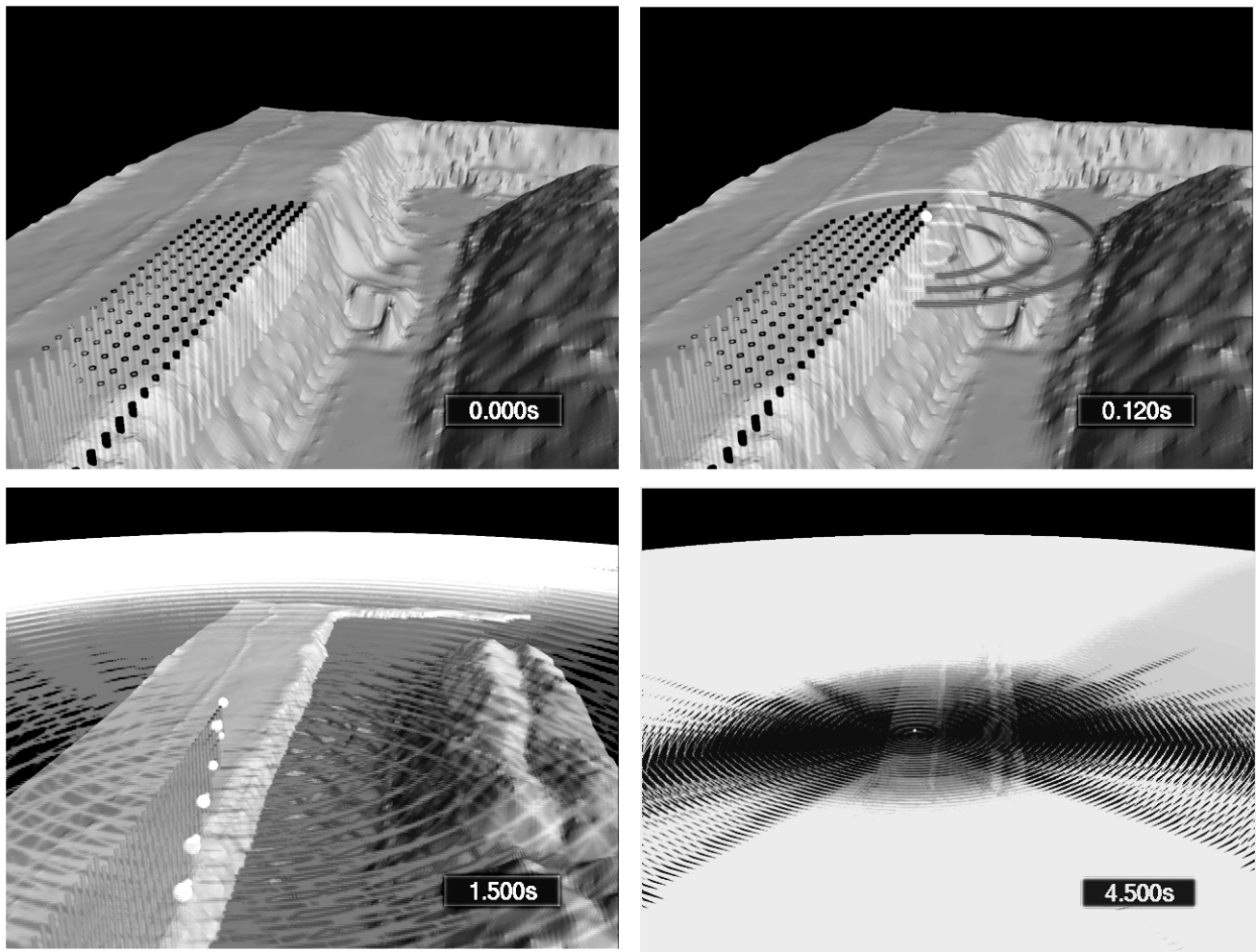


Figure 5: Cast Blast Model (See description in text).

model for the Black Thunder Cast Blast (right hand side of the figure) is compared to a similar model for a moderate size rock fragmentation explosion in a molybdenum mine in Southern Russia (left hand side). The blasting practice at Black Thunder produces a continuous flux of seismic energy where the process of delay firing each row of explosives in the hard rock mine produces a very impulsive train of seismic pulses. The models allow one to see and understand how the blasting practices affects the generation of compressional seismic energy in these two cases.

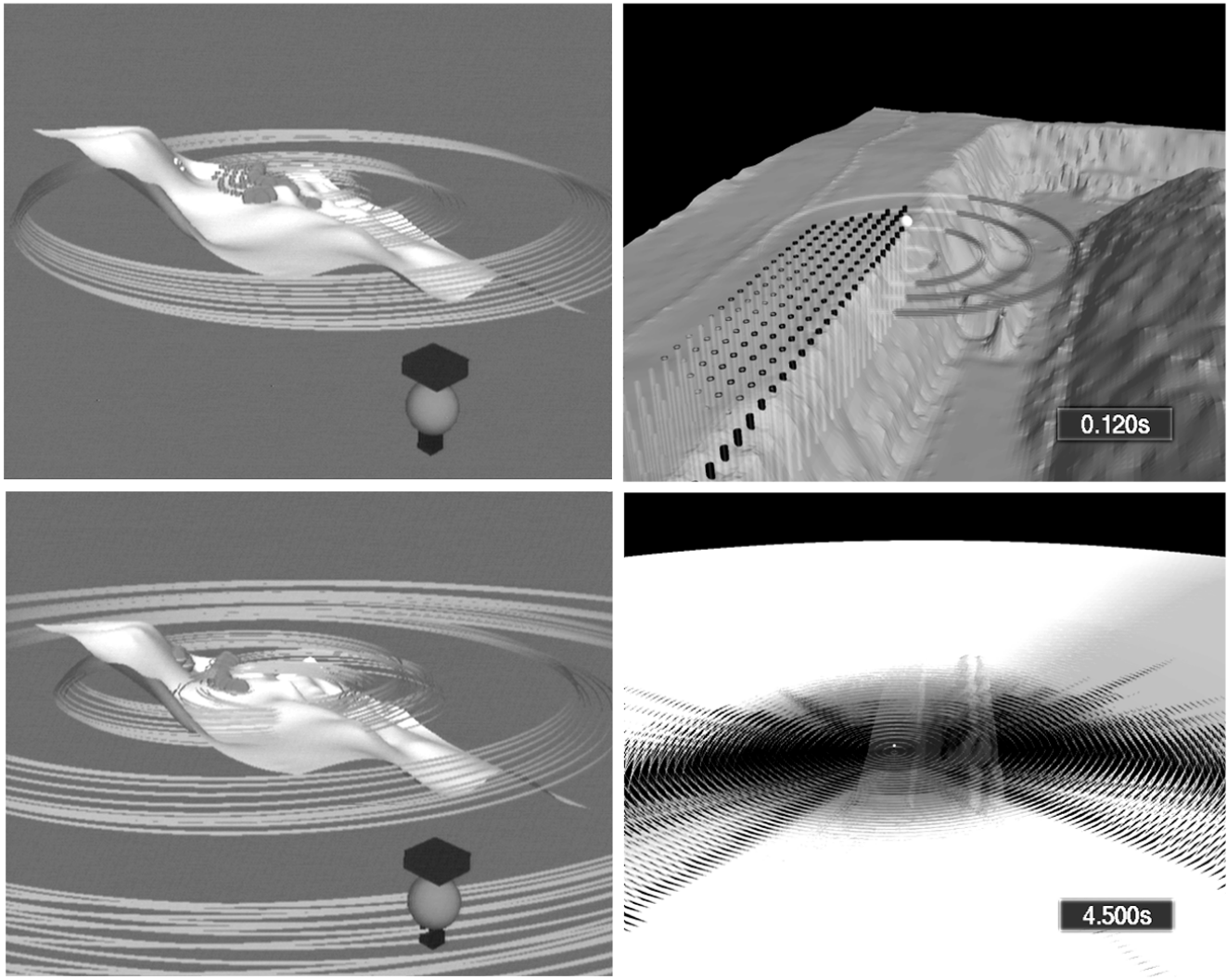


Figure 6: Comparison of Fragmentation (left) Cast Blast (right) Models

6. Documentation of Abnormal Blasts with New Techniques The instrumentation, imaging and modeling tools that have been illustrated can be used as simple diagnostic tools for quantification of explosive performance. This last illustration demonstrates how these tools were used to isolate and identify abnormal performance during a large cast blast. The first step was the synergy of seismic, acoustic and video data from the explosion. The explosion was documented from a number of perspectives but the camera from within the pit was found most useful in quantifying the unusual blast. The video data were combined with seismic (Z-vertical, E- east/west, N - north/south) and acoustic data, Figure 7. A movie was created of the blast from which a single field is reproduced in Figure 7. As this

figure illustrates, the early seismic amplitudes are relatively homogeneous much like those for the other cast shot documented in Figure 3. The amplitudes have been scaled by the large amplitude arrival (circled in Figure 7). This large, impulsive seismic arrival is a factor of five bigger than any other from this blast or any of the arrivals from the other cast blast (Figure 3). It is a result of the simultaneous detonation of a number of boreholes at the end of this shot and is illustrated in the video by the simultaneous movement of the entire free face at the end of the shot (when viewed in movie format). Only through the integration of the video, acoustic and seismic data was this effect identified.

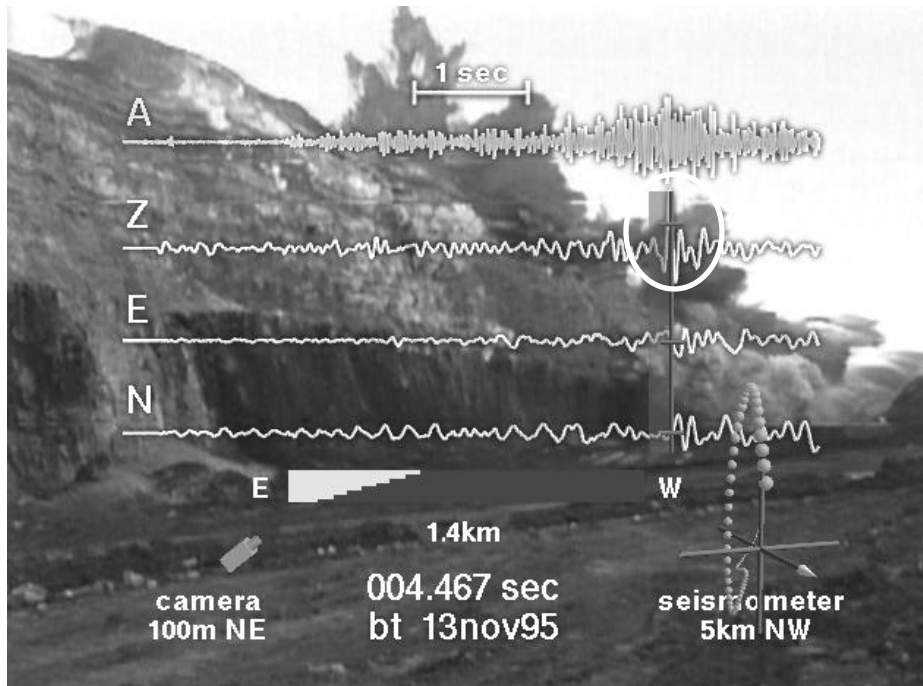


Figure 7: Single Frame of Bad Cast (comparison to Fig 5)

Three-dimensional models can also be used to illustrate what happened at the end of the shot. Figure 8 is a model of this blast focusing on late time around the simultaneous detonation. In the first image at 3.285 seconds, the explosion sequence has progressed normally with the resulting smoothly varying seismic wavefield. At this point in time the holes at the end of the shot detonate simultaneously as indicated by the white rectangular array of holes. The resulting impulsive seismic wave (illustrated in Figure 7) is generated and its propagation through the mine is documented in the remaining time steps in the model in Figure 8 (high lighted by arrows).

Conclusions

The integrated experiment conducted at the Black Thunder Coal Mine has allowed the investigation of the use of multiple types of observations in characterizing blasting processes and performance. The synergy of digital data sets, including video images, has been shown to be useful in characterizing not only the blasts themselves but the resulting seismic and possibly acoustic waves. Careful interaction with these time varying images provides a tool for interpretation as well as suggesting changes to blasting practices. Inclusion of three-dimensional models of the blasting processes provide additional interpretation help in understanding the interrelationships between the blasting practices and the resulting wavefields. Finally, implementation of these procedures on a number of explosions during a blasting program can be used to check for consistency and, in the one case illustrated, identification of anomalous blast performance.

Modern data acquisition techniques, digital data processing, and new image processing tools are beginning to provide unique tools to document, interpret and improve blasting programs and possibly improve productivity. The techniques and tools demonstrated in this paper are only rudimentary and illustrate only a small number of possible applications of these tools.

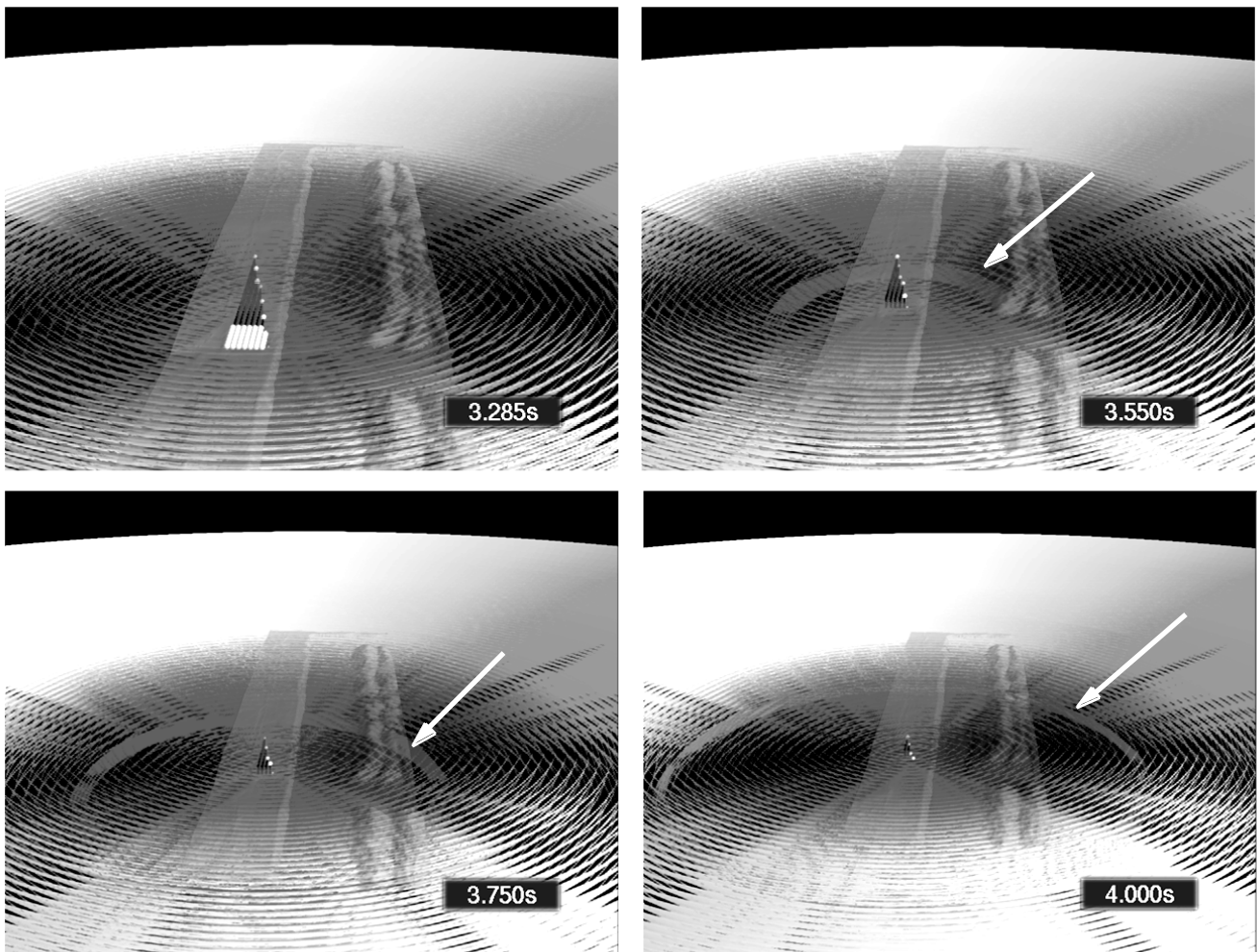


Figure 8: Bad Cast Blast Model (comparison to Fig 7)

References

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