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Title: SYNERGY OF SEISMIC, ACOUSTIC AND VIDEO SIGNALS IN BLAST ANALYSIS

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Synergy of Seismic, Acoustic, and Video Signals in Blast Analysis

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Introduction

Mining explosions are designed for a variety of purposes including the fragmentation and movement of materials. The blast design is dependent on the particular application intended and the material properties of the rock. The range of mining applications from hard rock quarrying to coal exposure to mineral recovery leads to a great variety of blasting practices.

A common characteristic of many of the sources is that they are detonated at or near the earth's surface and thus can be recorded by camera or video. Although our primary interest is in the seismic waveforms that these blasts generate, the visual observations of the blasts provide important constraints that can be applied to the physical interpretation of the seismic source function.

In particular, high speed images can provide information on detonation times of individual charges, the timing and amount of mass movement during the blasting process and, in some instances, evidence of wave propagation away from the source. All of these characteristics can be valuable in interpreting the equivalent seismic source function for a set of mine explosions and quantifying the relative importance of the different processes.

This paper documents work done at the Los Alamos National Laboratory and Southern Methodist University to take standard Hi-8 video of mine blasts, recover digital images from them, and combine them with ground motion records for interpretation. The steps in the data acquisition, processing, display, and interpretation are outlined.

We conclude that the combination of video with seismic and acoustic signals can be a powerful diagnostic tool for the study of blasting techniques and seismology. A low cost system for generating similar diagnostics using consumer-grade video cameras and direct-to-disk video hardware is proposed.

I. Data Recording

A. Video Data

Blasts were recorded on Hi-8 video cameras at 30 frames per second with shutter speeds as high as 1/10000 second. These cameras were chosen over standard VHS and 8mm because of their improved resolution while retaining relatively low cost. In order to produce multiple images of the same blasts which can later be correlated, cameras were chosen for some of the experiments that had Genlock capability (locking to an externally generated synchronization signal such that the scan rates of the two cameras represent identical temporal events).

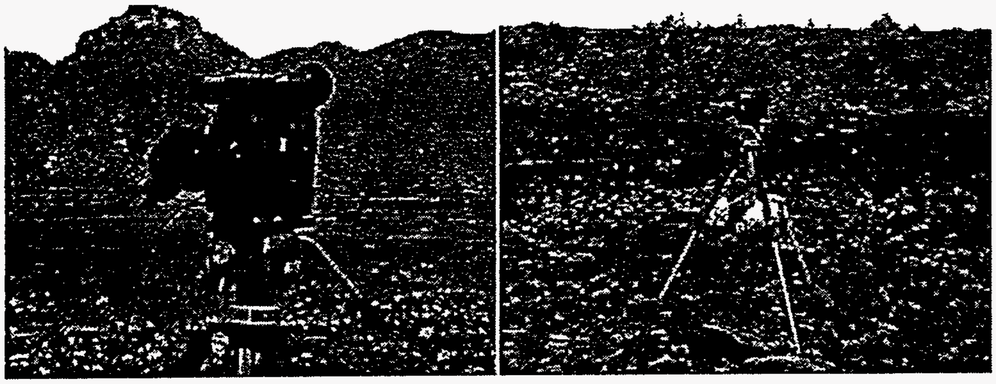

Figure 1. Installation of a Sony EVW-300 Hi-8 video camera overlooking the preparation of a large cast shot. The coax cable is connected to a companion camera so that they are Genlocked (frame-by-frame sync between the two cameras). Note sandbags used to stabilize and dampen the tripod.

An example of a camera deployment in a mining operation is given in Figure 1. Cameras are placed as close as 100 m from a single cylindrical charge, parallel with the free face in front of the charge. Larger millisecond delay-fired explosions necessitate separations between the explosions and the camera as great as a kilometer. It has been found useful to deploy cameras both in front (above the free surface if possible) and in back of the bench on which multiple hole explosions are detonated as well as in the pit where material will be cast.

These different views of the blast provide the data to quantify the performance of the individual explosions in the array as well as constrain the timing of secondary source phenomena such as material cast into the pit. Often there are ground motion sensors installed either near by or directly on the camera tripod for correlation with the video. Battery and video tape limitations permit these cameras to be left unattended for up to an hour before the shot, thus facilitating their deployment in areas not accessible to equipment requiring human attention.

B. Ground Motion Data

Velocity and acceleration waveforms were acquired with a 16-bit Refraction Technology Data Acquisition System, Terra Technology accelerometers and Sprengnether S-6000 2 Hz seismometers. The seismometers were used in the quantification of the near-regional (several to tens of kilometers) wave field while the accelerometers were deployed very close to the blasts (tens to hundreds of meters) providing good azimuthal as well as range coverage of the test bed. Typically the data were sampled at 250 or 500 samples per second in order to characterize the waveforms in as broad a frequency band as possible.

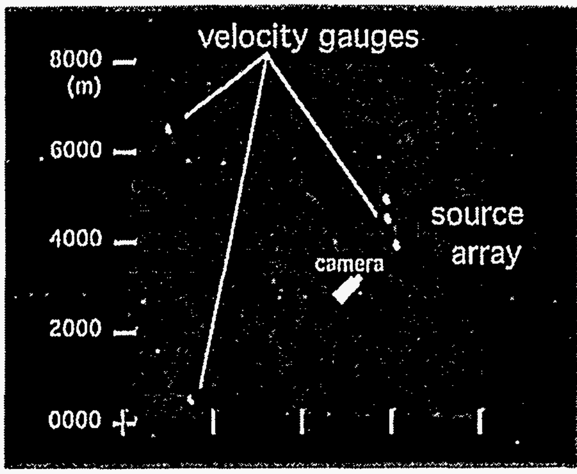

Figure 2.

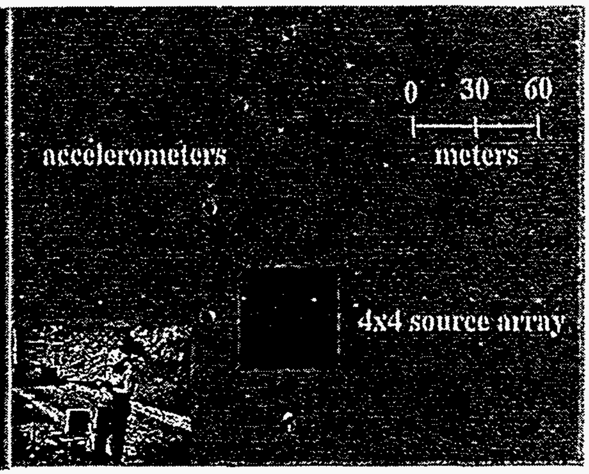

Figure 3.

Figure 2. Near-regional instrumentation plan illustrating the utilization of velocity transducers and cameras to document explosion processes.

Figure 3. Near-source instrumentation plan illustrating the installation of one of the accelerometers and accompanying data acquisition units. The source in this case is a 4x4 array of cylindrical boreholes detonated sequentially.

Accelerometer data were integrated to velocity for interpretation purposes. First arrival time data from the explosions were used in conjunction with the P and S refraction data to build a velocity model for the test site. This model was refined through waveform modeling. Typically at the ranges where observations are made, it is important to model both the body and surface waves as it is the combination of these arrivals that provide the best constraints on the near-surface P and S velocity structure.

Key to combination and analysis of the different data sets is utilization of digital representations of each. The seismic and acoustic data as well as topographic information is typically gathered in digital form. A number of techniques are available to generate digital video as well, both in real time and as a post-processing technique.

II. Digitizing Video

A. Video Bandwidth

The NTSC and PAL video standards were designed to produce visual images by repetitively sweeping an electron beam over a cathode-ray tube. This beam moves horizontally from top to bottom in a fixed number of lines which are modulated in intensity, thus freeing electrons and emitting photons from the phosphor-coated front surface. The vertical resolution of the image is set by the number of scan lines (about 500) and the horizontal resolution is determined by frequency response of the modulation circuitry and the bandwidth of the driving signal (about 700).

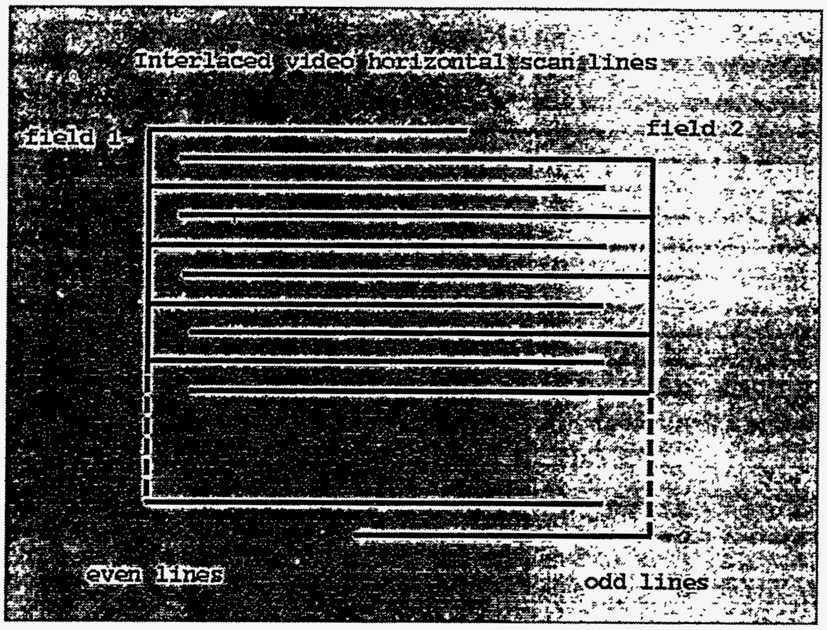

Figure 4. A single video frame is composed of two fields, one for all even numbered scan lines and one for all odd numbered scan lines. The video frame rate is 30 frames per second while the field rate is 60 fields per second.

The NTSC video frame rate is defined as 30 frames per second (although for historical reasons this is actually 29.97 fps) but the video image is actually updated to the screen at 60 Hz to reduce image flicker through a process called "interlacing." Interlaced frames contain two distinct image "fields" which consist of all even and all odd numbered scan lines. The video hardware draws half of the image (every other line) and then the other half 30 times per second.

The two fields that make up a frame produce a single new image every 33 ms (30 Hz). Note, however, that the individual fields are separated in time by 16.66 ms (60 Hz). This timing difference can be exploited digitally to increase the video temporal resolution.

B. Digital Bandwidth

The NTSC video produced by Hi-8 cameras can be digitized into discrete pixel images through video-digitizers or "frame-grabbers" commonly available as computer add-ons. The limitation is the digital bandwidth and throughput of the computer and disk drives. A common digital representation of an NTSC video frame (both fields) is a 640 by 486 pixel image with three color bit- planes of 8 bits each (24 bit color, also called RGB, or component color).

$$640 \times 486 \times 3 = 933120 \text{ bytes per frame.}$$

A useful approximation is 1 megabyte per frame. At 30 fps that is 30 megabytes per second, or 1.8 gigabytes per minute. These are very high sustained data rates by contemporary computing standards, and most hardware cannot maintain the necessary throughput for video playback and recording. Common implementations use either special hardware compressing/decompression techniques to reduce the required bandwidth, or reduce the resolution of the video input by down-sampling or using low-resolution monochrome cameras. The advent of a new generation of low-cost consumer digital video cameras is likely to change this substantially.

C. Hybrid Digitizing Method

At SMU and LANL we are currently using a hybrid process to digitize Hi-8 video using a Sony CVR 5000 laser disk and a Silicon Graphics Indigo2 Workstation with a Galileo video card. The Hi-8 tape is played back and recorded on the Sony CVR 5000 laser disk using the SGI Indigo2 as a "time-base corrector" to compensate for data rate errors inherent in the analog video media and to assure that no frames are duplicated or dropped.

The laser disk is a write-once media that stores 43,500 video frames on each side of a removable media disk making it cost effective for high resolution component video data archival (~$400 per disk). Once the data is stored on laser disk, it is digitized frame-by-frame from the laser disk and transferred to hard disk using the SGI Galileo video card. This process produces digital RGB format color images, each 640x486 pixels with each pixel representing 24 bits of color information.

With typical blasts lasting between 5 to 20 seconds, a single video data volume of the explosion is between 150 and 600 Mbytes. It is important to have large disks and large computer memory for effective processing of these data sets. Compression algorithms such as JPEG or MPEG can be used to reduce the size of these files with some loss of resolution, although fast hardware implementations of these compression schemes are best for rapid data review.

III. Video Data Processing

Four processing steps are applied to the digitized video images before they are combined with the seismic and acoustic waveform data. The images are de-interlaced, the sequence is de-jittered if required, intermediate frames are interpolated, and each resulting frame is given a unique time- stamp.

A. De-interlace

Each digital video frame is separated into even and odd fields. This produces half frames that are 640x243 pixels with every other scan line missing. The missing scan lines are generated by linearly interpolating the pixels on the adjacent lines, and a full frame 640x486 is constructed for each half-frame. This removes the blur associated with the movement of material from one field to the next, and permits field-by-field viewing of the blast. It also imparts x2 slow motion to the images when played back at standard video speed.

B. De-jitter

Cameras at blast sites tend to move around quite a bit as the shock from the P-wave passes the tripod. This can be minimized by tightly coupling the tripod to the ground (we use sandbags and bury the legs) but some residual ringing is still present. This manifests as a periodic oscillation of the image referred to as "jitter." The technique we use to remove camera jitter is to note the location of some fixed point or points in the image and to translate the image such that these points remain stationary. This is accomplished with standard image processing tools for image rotation, translation, and cropping.

C. Interpolation

The de-interlaced and de-jittered images are now passed through a temporal interpolation filter which generates a synthetic image for each pair of input images. This stage smoothes the transitions between frames created from all even or all odd scan lines, and gives a final data rate of 120 frames per second, with a resolution of 8.33 milliseconds per frame. When played at standard video rates this is 4x slow-motion of the original video.

D. Timestamp

Timestamps are especially important when studying the video frame-by-frame. Each final frame is given an individual time stamp by the SGI rendering hardware. These are typically applied to one corner of the image and increment accumulated time from the start of the shot. The start time is variously taken from the end of the count-down on the audio channel, the flash of the ignition system, or the first movement of material.

Some of the new digital video cameras have the ability to record a GPS (Global Positioning System) data stream along with video and audio, which includes time as well as location information. This allows the video to be synchronized precisely with seismic signals which are also locked to GPS.

E. A Single Shot

One of the experimental sources documented in this paper is a single, cylindrical borehole detonated next to the free face of the mine. As Figure 5 illustrates, the bore hole is loaded with explosive (ANFO, emulsion or mixture) and then backfilled to minimize air blast. Although not shown in this figure, the charge is typically spaced 20-30 feet from the free face of the mine. Detonation of the explosion will then fail the material between the free face and the bore hole. The resulting momentum imparted to the rock will move the material into the pit.

Video images of this casting process are captured. Figure 6 illustrates one of the interlaced frames from the single, cylindrical explosion. The camera in this case is oriented parallel to the strike of the free face of the mine.

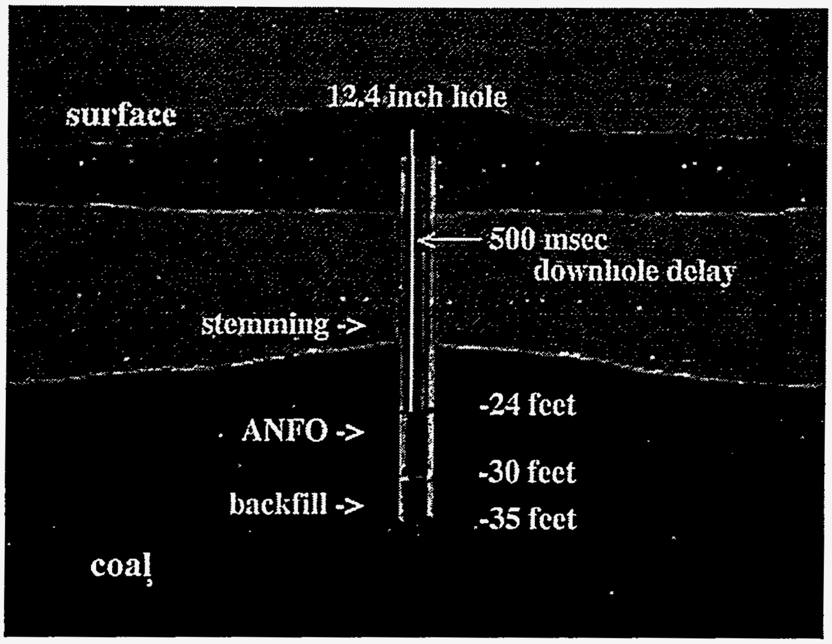

Figure 5. Typical bore hole configuration for a mining explosion. This cylindrical explosion is designed to fracture and possibly cast the overburden which sits on top of the coal (black) in this figure.

Figure 6. Raw, interlaced video frame from the single cylindrical explosion. The frame follows the detonation of the explosive by 900ms.

The fuzzy character of the image is due to the rapid speed at which the material is moving and the interlacing of two fields sampled 1/60s apart to produce a single video frame. The frames are de-interlaced into one even and one odd field and each linearly interpolated into its own frame (640x486) which represent two time points separated by

0.01667s. Additional contrast and image enhancement is performed on the de-interlaced images using common image processing utilities. The marked improvement in the image quality after these steps is illustrated in Figure 7.

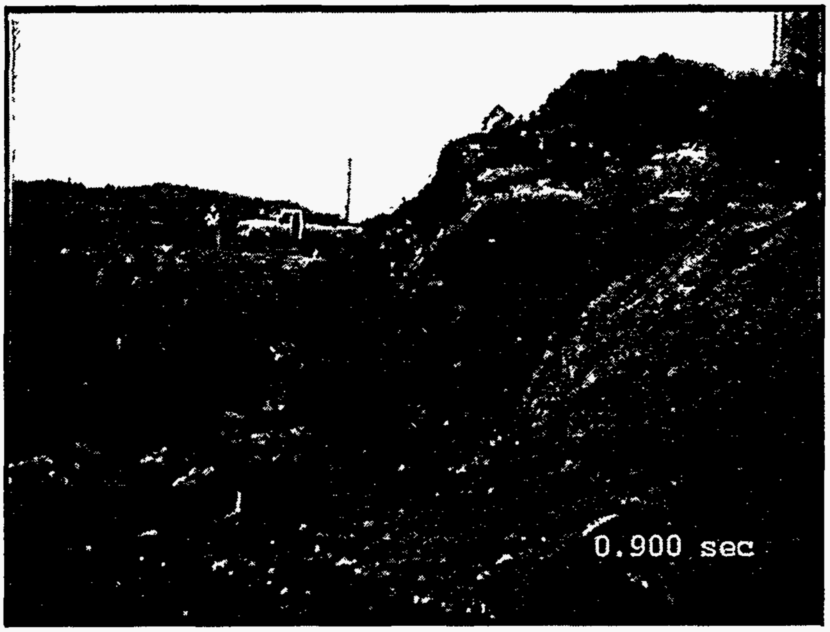

Figure 7. De-interlaced and image enhanced version of the even field from the frame displayed in Figure 6.

Although not obvious in the single frames and fields displayed in this paper, the camera moves as the P wave arrives at the recording site. This motion degrades the interpretation of the blast and so the de-jittering process described in section III.B.3 is applied. The resulting corrections for the frames in the video are combined to produce a representation of the camera motion in the plane of the image. The individual frames are then combined and animated on the SGI to produce a digital record of the blast at 0.01667s resolution.

These images can now be used to determine the timing of source related processes as well as a quantification of size and volume of material affected by the explosion. The final step of the process is to combine the digital video images with the digital ground motions so that one can investigate the relationships between the ground motion and the source processes as recorded by the camera.

IV. Combining Video and Waveform Data

A. Waveforms

A traditional method for displaying seismic and acoustic data is as waveform plots in two dimensional Cartesian space. The vertical or 'y' axis represents the magnitude of each data point, possibly signed, while the horizontal or 'x' axis represents time in some convenient units, increasing to the right.

Various common software utilities such as spread sheets, data bases, and higher math tools include the ability to create these 2D and even 3D waveform representations of arbitrary data sets. These can then be combined with time-aligned digital video images through a process called "compositing."

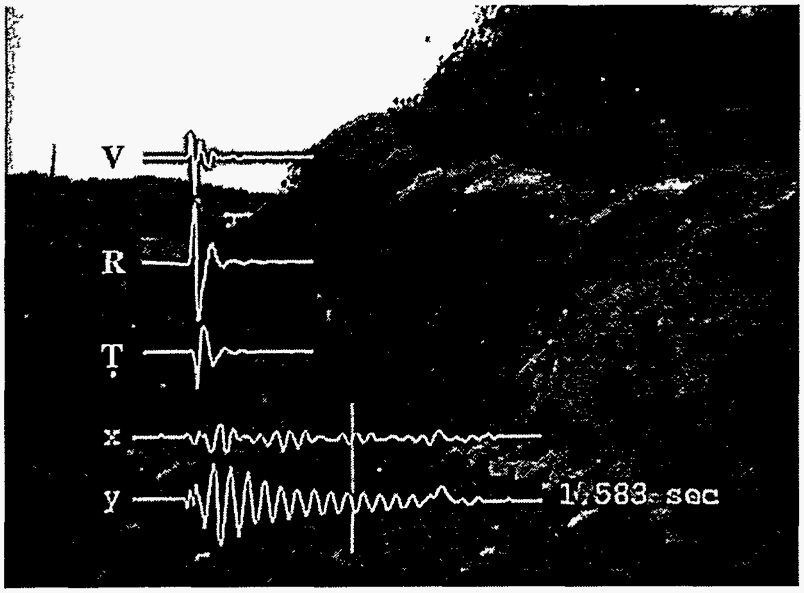

Figure 8. De-interlaced video frame with composited waveforms.

A slightly more complex method for creating the waveform images makes use of generic rendering software and hardware available on the Silicon Graphics Indigo2 Workstation and other computers. The raw seismic data is filtered through the data processing software *mkwaves* , developed in the Geophysical Imaging Laboratory at SMU, the output of which directly drives an OpenGL graphics engine.

This additional complexity allows high quality, anti-aliased waveforms to be rendered which can be seamlessly integrated with the video frames. It also provides the ability to generate other 3D geometric shapes as part of the same image. This is the method used to create a moving cursor bar, blast timing model, and particle motion display.

Figure 8 illustrates a de-interlaced and processed video field with composited waveforms. The upper three are ground velocities (V-vertical, R-radial, T-transverse) derived from accelerometers located near the camera. The lower two waveforms are the camera displacements (x-tangential, y-vertical) used to de-jitter the images.

Comparison of the ground motion record with the camera displacements illustrates the under damped pendulum response of the camera tripod. The near-source ground motions are completed many ms prior to the video image displayed in Figure 8. The image also illustrates that there are still many dynamic processes taking place in the source region despite the small ground motions.

Careful review of the animation reveals the importance of the initial shock from the explosive in generating the near-source ground motions. The P wave as it propagates from the initial shock to the camera can be seen as a reflectance change in the near-surface materials. These two observations indicate that, for the recorded near-source ground motions, late time explosion phenomena, including the material cast out into the pit, do not contribute to these waveforms.

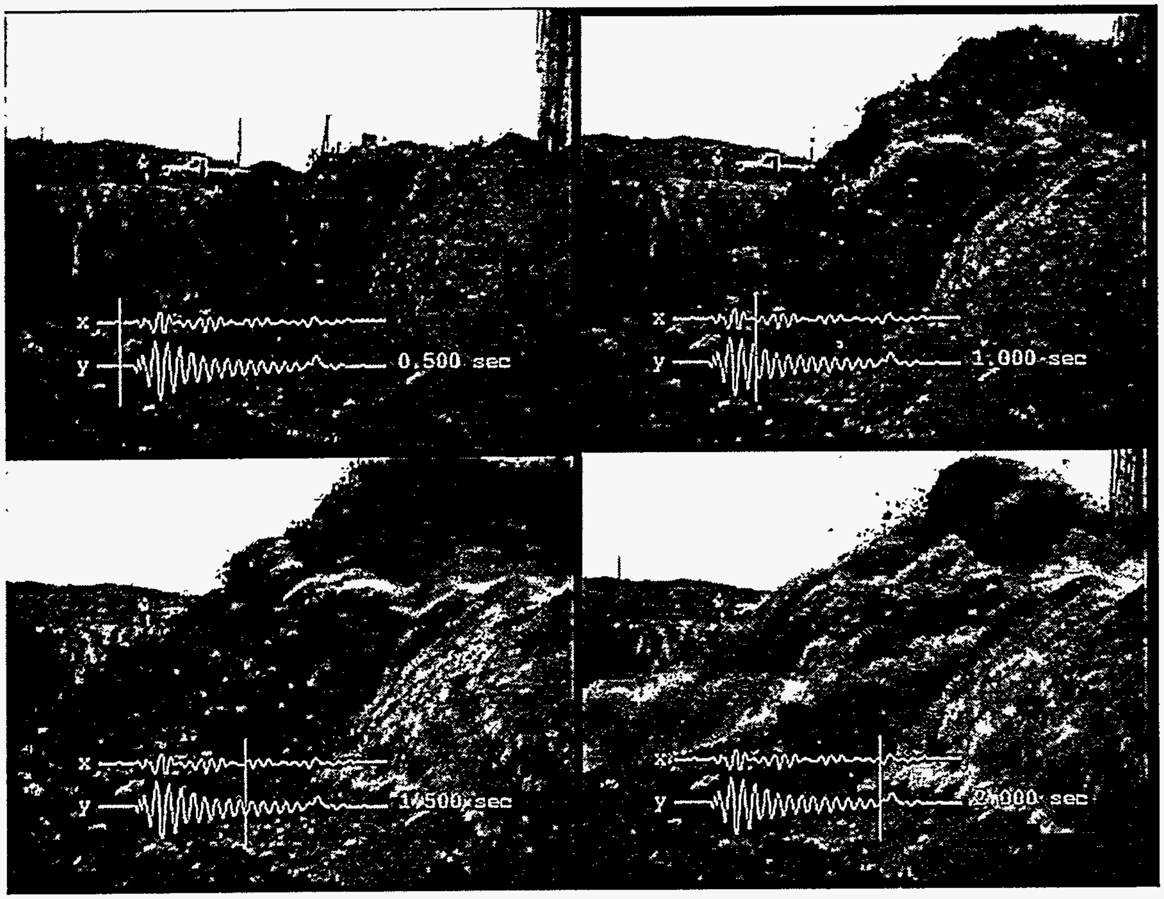

Figure 9. Four frames from a single shot mining blast designed to cast materials. Waveforms represent the ringing of the camera tripod as excited by the impulsive ground motion. The vertical cursor bar sweeps along from left to right indicating the time-alignment of the current video frame with the waveforms.

B. Moving Cursor

The combination of blast video and seismic and acoustic waveforms requires some method of temporal coordination among the various data sets. This is the purpose of the moving cursor bar. The cursor marks the point on the waveform or waveforms that correspond to the current video frame. It is rendered by the graphics engine, along with the waveforms, as a 3D object with a unique location for each frame. Figure 9 illustrates a moving vertical cursor bar at four time intervals.

For longer blasts it is sometimes desirable to render the cursor at a fixed location and scroll the waveforms underneath. In this case, a single cursor is created and a unique sub-section of the waveform is rendered for each frame. Figure 10 illustrates ground velocities and video of a 4x4 array of boreholes similar to the single shot, detonated in a delay-fired explosion. The video frame shows the shot 1.166 seconds after initiation.

Coordination of the seismic and video data is variable. The finite speed of seismic waves constrains the seismic data to be collected later in time than the video of the event which produced the wave; light travels faster than sound. The same is true of the acoustic channel. Accurate alignment of the seismic and video data would show the seismic signals arriving after their visual counterparts, and the acoustic signals thereafter.

A more intuitive arrangement is to subtract the seismic travel times from the data and align the waveform with the source event on the video. The acoustic channel can be handled the same way. This alignment seems preferred by blasting engineers and seismologists analyzing the shot performance.

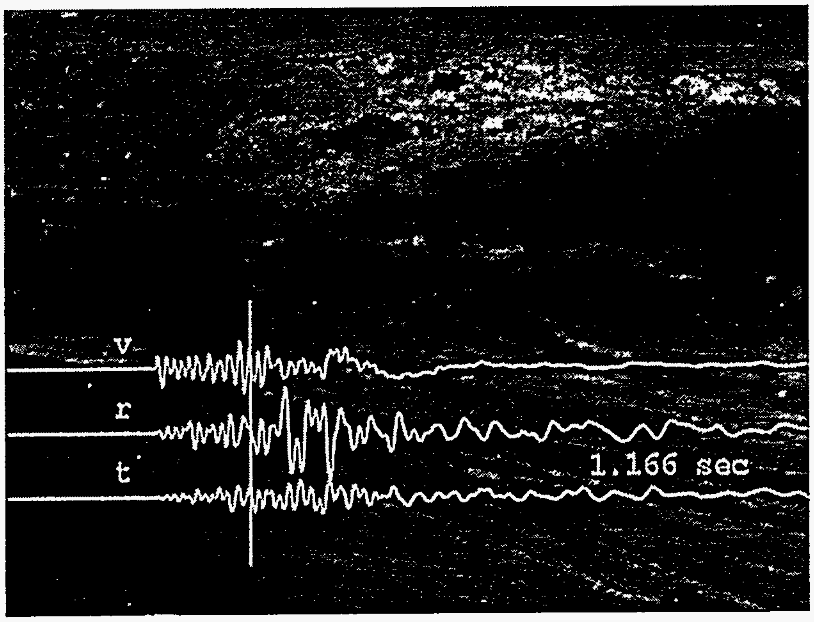

Figure 10. De-interlaced, de-jittered and composited field from a 4x4 array of boreholes detonated in a delay fired explosion. The ground velocities and the camera are at a range of approximately 250 m from the source. The time stamp is in the lower right corner and the vertical cursor bar across the three component waveforms align the video with the equivalent seismic source event.

C. Blast timing model

A simple model of the delayed detonation pattern may be rendered along with the waveforms and cursor objects. These can be generated from blaster's design data or from field measurements. The model has a small transparent colored square for each bore hole in the pattern, and these change color as each detonates in turn. In this way multiple delay fired shots can be seen to propagate along the model from one end to the other. When combined with video of the blast, similarities and differences between designed and actual blast performance may be observed.

D. Particle motion

A three dimensional particle motion model may be rendered along with the other graphics objects. This is essentially a small sphere that moves around in Cartesian 3-space as driven by the three component seismic data. The x, y, and z axes are rendered as small cylinders intersecting at right angles, and the central sphere orbits around the intersection. A "tail" of spheres of decreasing radii give a visual history of the particle's motion through space. This object is a dynamic representation of the motion of a given particle of the earth as it is perturbed by the seismic waves.

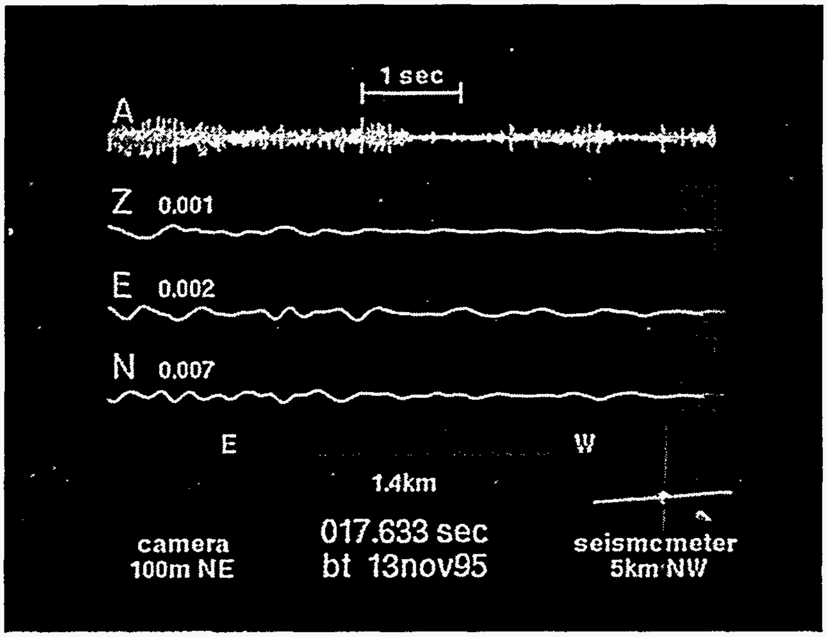

Figure 11. Graphics display generated from seismic and engineering data before compositing with a video frame. An acoustic channel (A) and three seismic channels (Z-vertical, E-east/west, N-north/south) are displayed as scrolling waveforms, along with a blast timing model in the lower center, and particle motion display in the lower right.

E. Graphics Overlay

Figure 11 illustrates a completed graphics overlay generated by the OpenGL hardware and software on the SGI Indigo2, driven by *mkwaves* . The input for this display consists of the three component seismic data, a single channel of digital audio from the HI-8 camera, and the engineering data for the blast design.

The time stamp in the lower center indicates that this frame of data aligns with a video field 17.633 seconds after ignition. The blast timing model above the time stamp illustrates the shot was 1.4 km long running east and west, and all the boreholes have detonated at this time. The seismic traces and particle motion show an amplitude of essentially zero at this late point in the shot. Only the acoustic channel shows an appreciable signal as fly rock continues to rain down near the camera.

Figure 12 shows the same shot earlier in the sequence. The blast timing model below the waveforms indicates about a quarter of the boreholes remain to be detonated. However, at 4.5 seconds into the shot an unusual high amplitude pulse in the seismic and acoustic data corresponds to the simultaneous movement of a large section of the free face.

The P-wave seismic energy falls off quickly thereafter, while the timing model shows that many of the boreholes are still left to be detonated. This taken together with the visual observations of the simultaneous sudden large movement of the free face strongly suggests that a large group of boreholes detonated simultaneously at the end of the shot, creating huge ground motions and air blast and, some thirteen seconds later, showering the camera with fly rock.

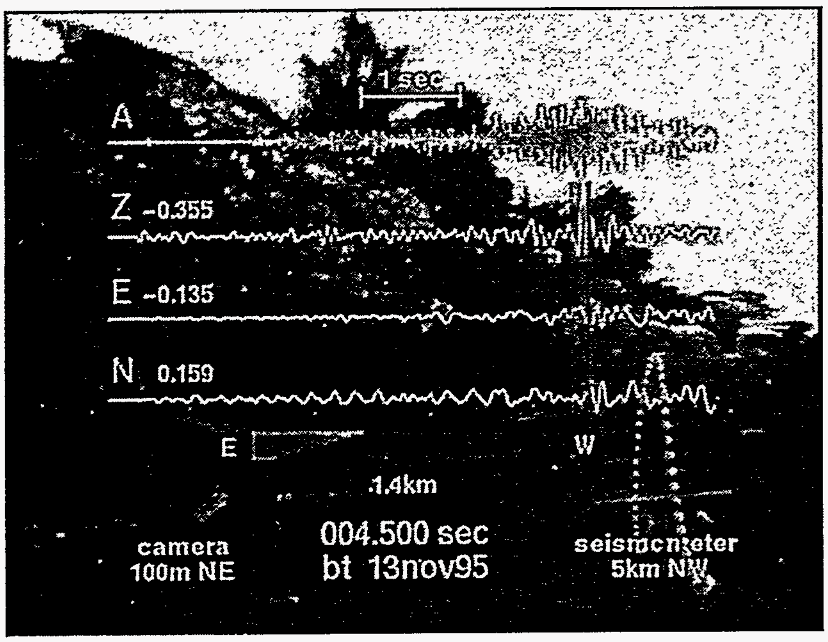

Figure 12. An anomalous event. A high-amplitude spike in mid-blast corresponds to a peak on the audio channel and slings the particle motion display outside of its boundaries.

V. Low Cost Implementation

Techniques developed at the Los Alamos National Laboratory and Southern Methodist University as described in this paper require fairly expensive and sophisticated computers and imaging processing expertise. A simpler approach is proposed.

A. Video cameras

Two approaches are possible here. One is to use conventional video cameras and digitizing techniques, the other is to move toward all digital video. The later has potentially more to offer but is currently not as well developed. Additionally, many mines and companies that deal in blasting already have the Hi-8 or lower resolution VHS cameras used in these experiments.

B. Computing hardware

Most of the image processing and generation described herein does not require special graphics hardware. Any sufficiently fast computer can run the software versions of the custom graphics hardware engine. Certainly the common 150 and 200 MHz Pentium processors, equipped with sufficient memory and disk space, are well capable of the image
generation and video post processing.

C. Video hardware

The video digitizing hardware needed for such a system must be capable of digitizing and compressing video in real-time. A number of schemes are available to accomplish this. The most common and robust offer hardware JPEG (Joint Picture Expert Group) compression and decompression at variable rates. This allows video to be digitized, compressed, and saved on harddisk, all in one step.

D. System integration

The base system as described above is capable of recording and playing back video at variable rates, from single frame to hi-speed, for blasting analysis and design. This capability itself has turned out to be a powerful analytical tool in the hands of an experienced blast designer.

Combination of video and seismic data sets requires the seismic data to be collected and appropriately time aligned. This process is more problematic, given the wide variability of ground motion collection techniques and instruments. The advent of low-cost GPS-equipped digital cameras and seismic gear in the near future will simplify this requirement and move the technology from the hands of the technical consultants to the blast engineers themselves.

CONCLUSIONS

The synergy of video, seismic and acoustic signals can be a powerful diagnostic tool for the study of blasting techniques and seismology. A low cost system for generating similar diagnostics using consumer-grade video cameras and direct-to-disk video hardware is now feasible. Future enhancements including multi-camera 3D analysis of mass material movement and automatic recovery of face velocity parameters can be based on such a system.

ACKNOWLEDGEMENTS

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