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DESIGN AND UTILIZATION OF A PORTABLE SEISMIC/ACOUSTIC CALIBRATION SYSTEM

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Empirical results from the current GSETT-3 illustrate the need for source specific information for the purpose of calibrating the monitoring system. With the specified location design goal of 1000 km², preliminary analysis indicates the importance of regional calibration of travel times. This calibration information can be obtained in a passive manner utilizing locations derived from local seismic array arrival times and assumes the resulting locations are accurate. Alternatively, an active approach to the problem can be undertaken, attempting to make near-source observations of seismic sources of opportunity to provide specific information on the time, location and characteristics of the source. Moderate to large mining explosions are one source type that may be amenable to such calibration. This paper describes an active ground truthing procedure for regional calibration. A prototype data acquisition system that includes the primary ground motion component for source time and location determination, and secondary, optional acoustic and video components for improved source phenomenology is discussed. The system costs approximately \$25,000 and can be deployed and operated by one to two people thus providing a cost effective system for calibration and documentation of sources of interest. Practical implementation of the system is illustrated, emphasizing the minimal impact on an active mining operation.

key words: regional seismology, calibration, ground truth, explosion

OBJECTIVE

1. Motivation. The need for calibration of the International Monitoring System (IMS) has been illustrated as locations produced by GSETT-3 have been assessed relative to ground truth information (regional network locations) during the last year (GSE/US/106, GSE/US/108, GSE/FR/22 and GSE/WGE/16). Systematic errors in location can be large and in some instances the actual event location is not contained within the formal error estimates. Bias in locations reflect local and regional variations in the travel time curves for a particular region, inadequate station coverage or problems in depth determination and thus can be location specific. An empirical approach to this problem is the use of events with known location and origin time to develop a set of corrections to the regional propagation model. Once these corrections are established through the analysis of a calibration event, the locations of all other events in the region of interest are improved.

Source information for the purposes of calibration can be provided by locations from local networks although the spatial and temporal characterization in these cases have their own associated errors. A complementary approach to passive calibration is an active one where near-source measurements are made with portable instrumentation at targets of opportunity such as mining explosions. This procedure can provide exact shot time and location for use in improving monitoring system derived locations.

These same calibration procedures (when supplemented with acoustic and video data) can be applied to the characterization of the wavefield generated by the source. Known sources that are documented through this type of extended calibration procedure supply information invaluable in understanding regional seismograms. It is the empirical approach that allows this more rigorous assessment of seismic signals at regional distances.

Mining regions provide an example of the scope of source activity that can benefit from an active calibration exercise that improves the performance of the monitoring network in a specific region. As a result of an experimental program in the last year, an extensive study of mining operations conducted in the Powder River Basin of northeast Wyoming has been undertaken. Within 5000 km² there are 15 active mines each producing over 5 Mtons coal/year. This density of possible sources requires precise locations particularly if this information were to be used for an On Site Inspection.

This region has active surface coal mining where large amounts of explosives are used to remove the overburden above the coal as well as to fracture the coal for recovery. As a result of these processes and the large number of mines in the region, there are many seismic signals generated. During 1995, GSETT-3 located 25 events in the basin and in the first four months of 1996 21 events have been formed in this region as reflected in Figure 1.

These results motivate the need for calibration of arrival times as well as signal character from sources in regions of interest. Table 1 compares a number of REB (Reviewed Event

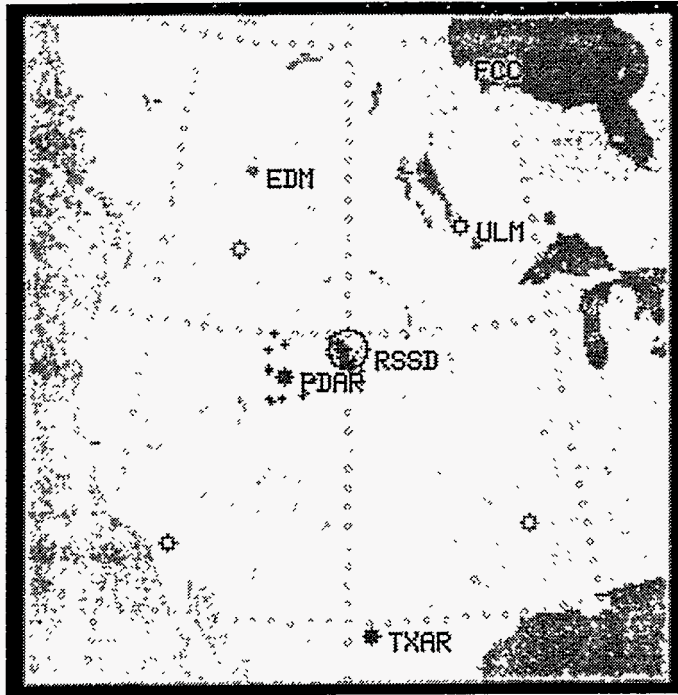


Figure 1: GSETT-3 Events from Wyoming (IDC Home Page). The Cluster of Events in NE Wyoming are in the Powder River Basin

Table 1: Comparison of REB and Mine Locations

Date Time	REB Lat	REB Long	MINE Lat	MINE Long	DIFF km
950126 234342.8	43.64	-105.32	43.68	-105.27	6
950211 201835.4	43.56	-105.23	43.64	-105.26	9*
221238.4	44.27	-105.74			80*
222355.6	43.79	-105.54			28*
950317 203727.3	43.56	-105.13	43.64	-105.26	14
950718 1914742.4	43.58	-104.98	43.69	-105.26	25
960311 201336.9	43.61	-105.22	43.64	-105.26	5
960405 201359.0	43.77	-105.34	43.66	-105.27	14

* The ground truth information provided by mine had an imprecise shot time based on the blaster's log and therefore could be associated with any one of three events in the REB.

Bulletin) locations provided by GSETT-3 with ground truth information gathered from one mine in the region. Assessment of the REB locations is only possible as a result of calibration. In this case, the performance of the network is validated with the calibration information while in other regions the calibration data can be used to reduce bias in locations.

2. Calibration Needs. Some have suggested that blaster's logs typically taken by the mines can be used as a source of information on event time and location for purposes of calibration. These documents provide location to the nearest quarter section (0.65 km²) and time to the nearest 15 or 30 minutes. Many of the largest mining shots have source dimensions that exceed the accuracy of the reported location. Typically, safety issues within the mine, including the clearing of personnel, control the exact shot time and thus the recorded explosion time is the blaster's best estimate, possibly with a reference to his watch. This information, in conjunction with accurate spatial locations within the mine, could be useful for calibration assuming that a recorded signal could be correlated with a particular mine.

Unfortunately, in an active mining region such as the Powder River Basin where individual mines shoot on a daily basis, it may not be possible from the blaster's log to associate a particular regional signal with a single mine unless very precise documentation of the explosion detonation time is undertaken. Table 1 illustrates the problem, where on 11 Feb 95 there were three GSETT-3 events in the Powder River Basin in an approximate 2 hour period and two events within 11 minutes of one another. We were provided with ground truth information from the mine as to precise spatial location of a large cast shot conducted on 11 Feb 95. Typical of blaster's logs (this event was not documented with the calibration instrumentation), the shot time was given as some time around 2200 hours (UTC). With this information, it is difficult, if not impossible, to know with which of the three REB events on the 11th that the ground truth information should be associated. In Table 1 the location difference between each of these three REB events with the ground truthed location is given. Depending on which event is the one generated by the mine, quite different conclusions about the monitoring network performance can be reached. This problem of association can be a problem with blaster's logs but can be avoided with appropriate calibration instrumentation.

The alternative approach to obtaining ground truth information for monitoring system calibration/validation suggested is with a set of simple and easily deployed portable instrumentation. If such a system of equipment could be deployed and operated by one or two people with a minimum of effort then it would provide a cost effective methodology for calibration using sources of opportunity such as those available in an active mining region. This system is described in the next section followed by an illustration of its utilization.

RESEARCH ACCOMPLISHED

3. Example of System The design goals for the calibration system are that it must be deployable by one to two people in approximately one to two hours at a remote site.

The minimum source information it must provide is the origin time and location of the event. Since a supplemental goal of the system is a quantification of the character of the source, in the case of surface explosions, information associated with the design and detonation of the explosions is useful. Video and acoustic measurements that supplement the primary seismometers are included for this purpose. The system should be able to run unattended for hours to days depending on the particular application. The requirement for unattended operation is to accommodate safety issues in the mine at the time of detonation. The ability to record data over the time period of days (excluding video) provides the opportunity to use the system to monitor activity in a mine or mining district for an extended period of time with little or no intrusion on the commercial activities.

The data acquisition system should include six channels, with sample rates as high as 500 samples per second and resolution as high as 24 bits. The high sample rate assures that the system is able to acquire high frequency data which may quantify the detonation times of delay fired mining explosions and the 24 bits assures adequate dynamic range and data with the highest possible bandwidth. An example of a acquisition system that meets these requirements is a Refraction Technology data logger fitted with a large disk to assure long-term stand-alone operation. These data loggers are pictured in Figure 2A and B in two mining operations. Time and location is provided to the data logger by a GPS clock and the entire system is battery powered backed by a solar panel (Figure 2A). This GPS receiver, or possibly an additional handheld GPS, is used to determine the location of the explosion. A single GPS can provide a location accuracy of 20 to 50 m for the explosion and the instrumentation. The location error is much smaller than the size of a typical mining explosion which for some of the larger events can have dimensions in excess of 1 km.

For purposes of recording the near-source, three-component wavefield a 1 to 2 Hz velocity transducer has been found to be adequate. In the demonstration system documented in Figure 2A, a three-component Mark Products L43D velocity transducer is deployed before a large cast blast in the Powder River Basin. Two additional vertical geophones are deployed along a line towards the explosions at 10 to 20 m separation in order to determine the phase velocity of the first arriving P wave for purposes of correcting the arrival time of the first P wave at the observation point back to the explosion. Depending on the spatial separation of these geophones and the explosion, shot times to within one or two tenths of a second of the actual shot time can be obtained. If one wanted to place a geophone on top of the explosion, a very precise detonation time is obtained at the expense of the loss of a geophone.

The sixth channel on the data logger could be assigned to an auxillary acoustic gage. A simple instrument that is capable of recording these source signatures close-in at a modest cost has been proposed by Reinke (1985). These instrument have been found simple to deploy and of adequate dynamic range and bandwidth to make these types of source measurements reliably. This data can provide near-source atmospheric signature information and is used in the supplementary task of source characterization.

Many mining blasts are designed with millisecond delay detonation systems. These designs often lead to complex source signatures which should be documented to allow for removal of the source complexity from the regional seismic observations to improve regional locations. A proven technique for providing this type of information in conjunction with a ground truthing system is deployment of a consumer level Hi-8 video camera which captures 30 frames or 60 fields of data per second. One of these instruments is pictured in Figure 2C ready for a large mining explosion in the Powder River Basin.

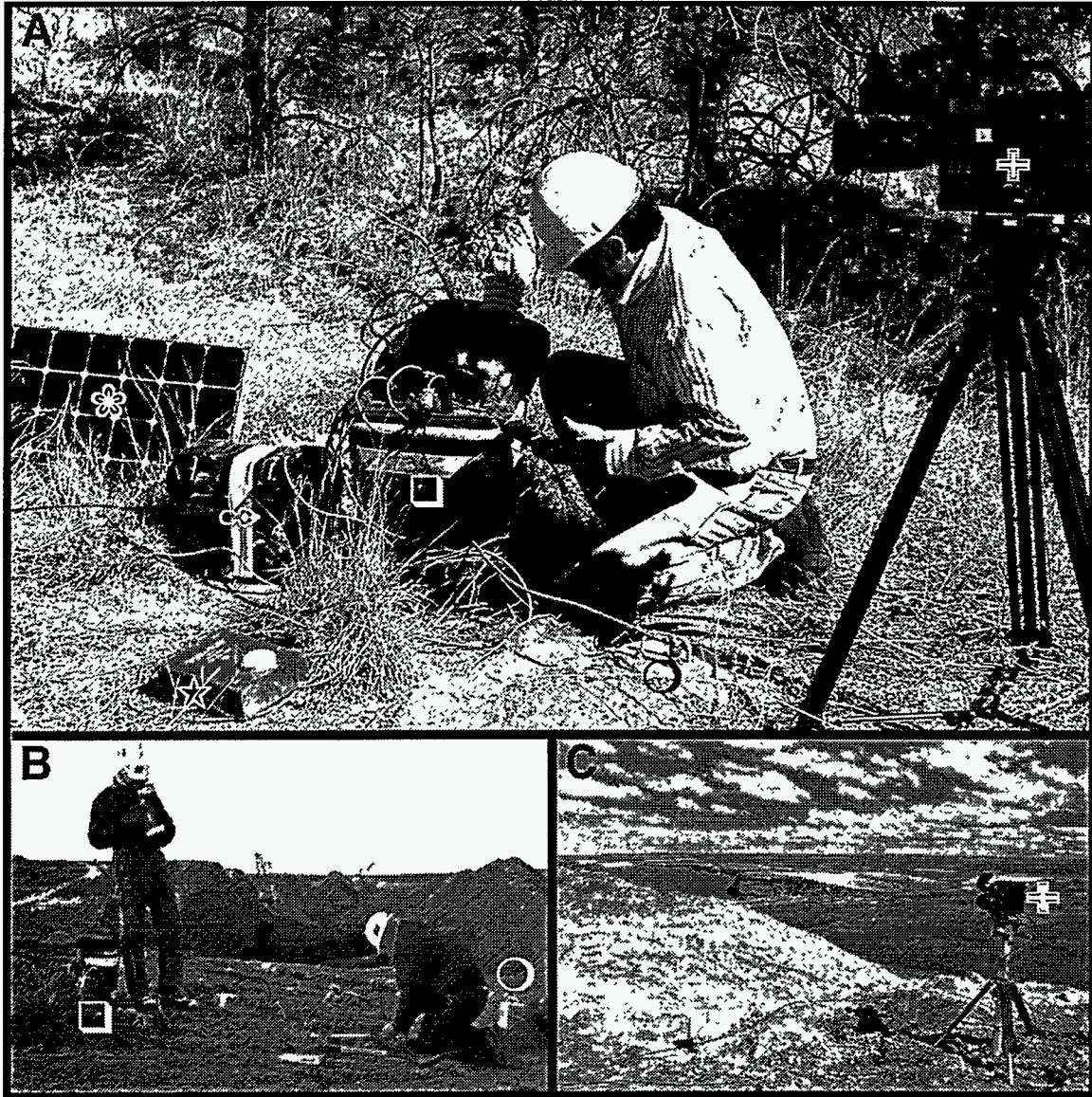


Figure 2 A: The data logger (□) is attached to the velocity transducer (○) and the GPS receiver (☆). The camera (⊕) is to the far right with battery (⎓) and solar panel (☀) to far left. B: Installation of the system in a mine just prior to a large cast blast. D: Hi-8 camera (Sony EVW-300) deployment prior to a large cast explosion.

Normally the camera is deployed in the same location as the seismometer and acoustic gage so that the different source phenomena can be correlated for interpretation purposes. It is possible to deploy the camera at a different site if a special perspective of the blasting processes is needed: A number of different cameras in the price range of \$1000 to \$5000 have been tested such as SONY TR-101 and EVW-300. All are adequate as long as they are Hi-8, which provides improved resolution over standard VHS cameras.

The total cost of this portable system is approximately \$25,000 dollars as configured in Table 2. Careful selection of other options from a number of vendors could bring the cost closer to \$20,000. Thus, a cost effective system that can be used to obtain ground truth information from a number of different sources in widely separated geographical locations with a minimum of impact on the mines and deployable by 1 or 2 people is available.

The system as described is simple to deploy. Practical experience with the installation of this equipment indicates that it can be installed in less than two hours by one to two people. It is completely self contained and thus requires no assistance from the mine in which the measurements are to be made. Even in the case where the equipment is deployed at a location which the mine operators, for safety reasons, would not allow personnel at the time of detonation, the system can operate unattended. In an active region such as the Powder River Basin, the system can be deployed at a number of mines over several days to weeks providing calibration data from a number of spatial locations in a cost effective manner.

Table 2: Portable Ground Truthing Instrumentation Equipment List and Estimated Cost

Component	Possible Manufacturer	Cost
Data Logger, Disk and GPS	Refraction Technology 72A-08	\$16,000
3 Component Seismometer	Mark Products L43D	5,000
2 Vertical Geophones	4 Hz Mark Products	200
Acoustic Gage	Validyne Engineering Corp. P305D	2,000
Hi-8 Video Camera	Sony TR-101	1,500
Cables, batteries, solar panels, hand held GPS	miscellaneous	1,000

4. Utilization of Data from System. The instrumentation described in the previous section has been deployed on a number of mining explosions in the last year for the purposes of providing simple ground truthing information as well as documentation of blasting practices within the mines for comparison to the resulting regional signals. Some of the information given in Table 1 resulted from these deployments and has been used to assess the performance of the GSETT-3 locations and error estimates. This type of information offers the advantage over standard gamma data which results from locations utilizing local networks, in that the exact time and location of the sources that generated

the regional data are experimentally documented and do not suffer from their own set of errors. This active calibration procedure provides precise locations that can be compared to those deduced by the monitoring system.

Data gathered by this calibration system can also be used to assess important source processes that lead to the regional signals that will be captured by the International Monitoring System. The fact that a number of different types of measurements are made by the proposed system (ground motion, acoustic and video) allows for the synergism of these different data types into data products that can be used in source interpretation. This combining of the different data sets is illustrated for two separate large explosions at a mine in the Powder River Basin in Figure 3. In these examples, video of the explosion processes recovered at 60 frames/s is combined and time correlated with three-component ground motion and acoustic signals. In addition, a model of the design blasting pattern is also included and time correlated. The synergy of the different data sets (all recovered from the instrumentation described in this paper) provides a time varying record of the explosive processes correlated with the resulting ground motions and acoustic signals. Single frames, with the time listed in the figure, from two mining blasts are included in Figure 3. A description of how these data sets are processed and combined can be found in Stump *et al.*, 1996. This paper is also available on the world wide web along with the time varying images at the address:

www.geology.smu.edu/~dpa.www/blasts.html

Comparing the single frame images from the two mining explosions demonstrates the utility of the measurements made by this portable instrumentation in documenting unusual source processes. The top image is from a shot that detonated in a very regular pattern as exemplified by the relatively equal amplitude of the complete P wave train. The image reproduced in the figure is 2.833 s into the detonation as represented by the vertical bar through the seismograms. The second explosion documented included the accidental simultaneous detonation of a large amount of explosives late in the detonation sequence. This image is at 3.087 s into the detonation with the simultaneous detonation at approximately 4.25 s into the sequence and represented by the large P signal at that time. This peak amplitude is nearly 5 times larger than the peak from the earlier shot (also observed at regional distances) that detonated in a regular pattern thus illustrating how processes in the mining explosion can dramatically affect the seismic waves.

CONCLUSIONS AND RECOMMENDATIONS

There are a number of ways in which accurate spatial and temporal seismic event locations can be obtained for the purpose of calibrating the International Monitoring System and quantifying its performance. Event locations provided by regional networks are one such approach that has been utilized but suffers from the associated errors. In regions where blasting occurs and is documented by mine operators, source location and time information can be used to compare to regional seismic locations. This second procedure depends on the record keeping in the mine and, as illustrated in Table 1, suffers from inaccurate time information which may preclude association of a particular mine blast with a regional signal, especially in areas of active mining.

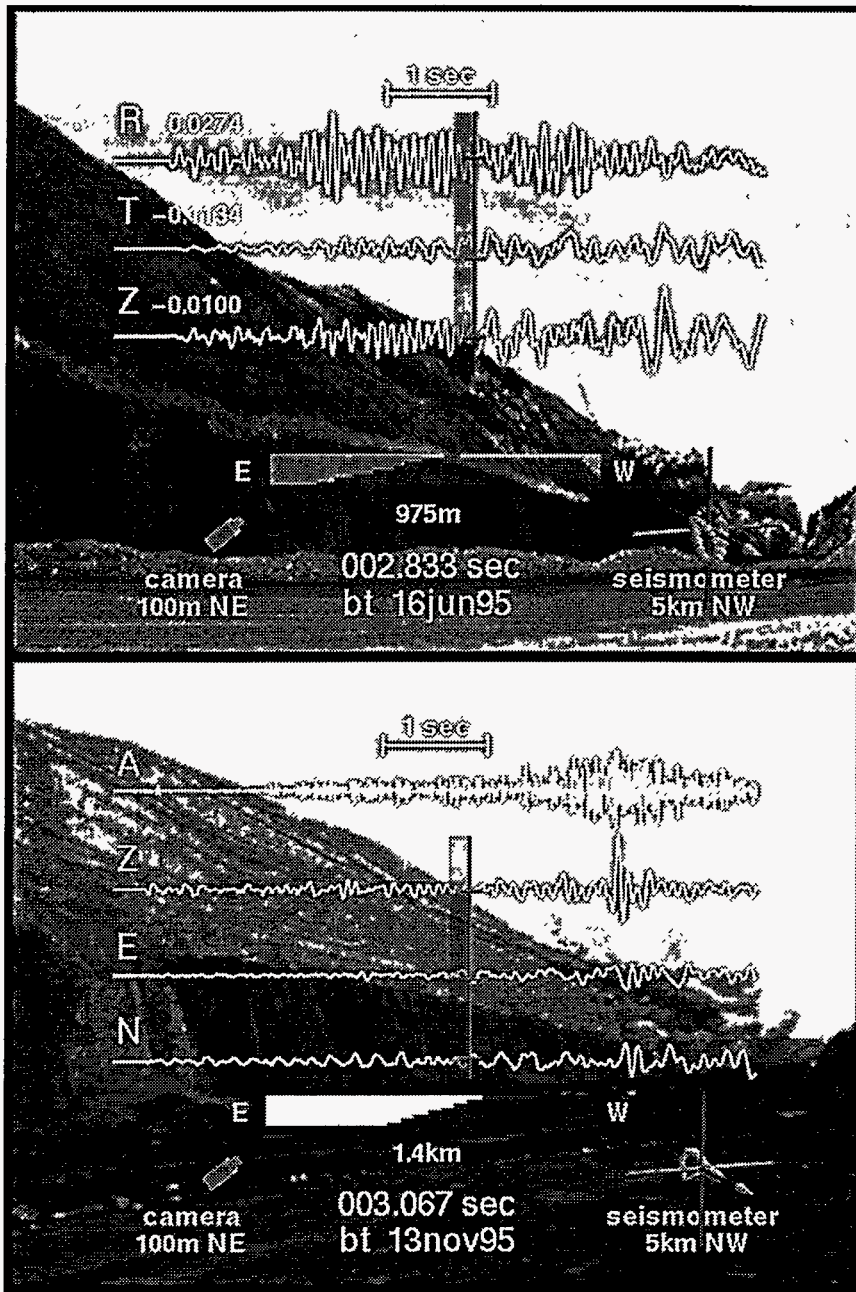


Figure 3: Synergy of ground motion (RTZ or ZNE), acoustic (A), video and models of the design blasting pattern (rectangle in lower center of each figure with individual explosion detonation represented by a change from white to gray). Also included in this figure is the three dimensional particle motion in the lower left hand corner. The two figures are snap shots in time (represented by vertical bar on waveforms) of two large cast blasts. In each case only about one half of the total explosives have detonated at the instant of each image. The 16 June 95 shot detonates in a regular pattern as indicated by the consistent amplitudes in the compressional waves. The 13 November explosion did not detonate evenly but as the data describes a large portion of the explosive array accidentally detonated simultaneously as indicated by the large P wave amplitudes on the vertical velocity record in the lower image.

We propose a third and active approach to the problem of regional calibration. A portable data acquisition system that acquires ground motion for location and shot origin time, and optional acoustic and video data components for phenomenology studies is proposed for temporary deployment in active mines. The system costs about \$25,000 and can be easily fielded in less than two hours by one to two people. Without the optional acoustic and video components the system would cost approximately \$22,500. This system could be used in a mobile mode to obtain calibration information from a number of sources in different geographical locations in a relatively short time period and at modest cost. Typically the spatial location of the event using this system is within 20-50 m of the source initiation point and within 0.1 to 0.2 s of the initiation time. This information can be used either to provide information for improving the seismic monitoring system through reduction of bias in the locations or validating system performance.

In addition to providing source time and location information, the inclusion of an acoustic gauge and a video camera provides documentation of source processes as well. In preliminary trials of the system, this information has proven to be quite useful in interpreting variations in regional signals from mining sources. The mine operators that we have cooperated with have found that this source information is quite useful to them, as it documents blasting performance, and can identify areas of improvement to reduce ground motion and improve their mining efficiency. The fact that the system is self contained and can operate unattended has allowed its deployment to proceed with little or no impact on mine operators which further enhances the cooperation we have received during its testing.

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