DEVELOPMENT OF MINE EXPLOSION GROUND TRUTH SMART SENSORS

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Sponsored by the National Nuclear Security Administration

Award No. DE-SC0004230

ABSTRACT

Accurate seismo-acoustic source location is one of the fundamental aspects of nuclear explosion monitoring. Critical to improved location is the compilation of ground truth data sets for which origin time and location are accurately known. Substantial effort by the National Laboratories and seismic monitoring groups have been undertaken to acquire and develop ground truth catalogs that form the basis of location efforts. In Phase I, we have demonstrated the feasibility of constructing an inexpensive, compact deployable Ground Truth Monitoring System (GTMS) for obtaining calibration ground truth information (timing, location, magnitude) autonomously from mining regions. The standoff distance is to be less than 5 km and accuracies of 0.1 second in origin time, 1 km in epicentral location and 0.3 magnitude units without any human intervention are operational goals of the system. Information is to be transmitted for mine explosions that exceed magnitude 2.5.

The prototype GTMS we have developed will accurately determine location, origin time, and magnitude of large explosions in the vicinity of the system, transmitting these parameters to a Ground Truth Processing Center (GTPC). In addition to the source parameters, the three components of the seismic source waveform can also be recorded and transmitted via an inexpensive two-way satellite communication (ORBCOMM) link. The system will allow for configuration choices depending on cost constraints and information needs and employs 24 bit digitizers, a three-component geophone sensor, a three-component MicroeElectroMechanical System (MEMS) sensor, and a pressure sensor. Because we expect the signals may clip the geophone, the MEMS operates in standby mode (thereby saving power) and is activated by a strong ground motion switch when the high-sensitivity (geophone) sensor detects a possible event. The device can be turned to active measurement mode from standby mode in 10 msec. The GTMS is capable of operating continuously for 6-months on a single small battery pack, weighs about 3 lbs and will cost about $1500. If source waveforms are not required, the system cost can be reduced to $1200. The GTPC will enable calibration and ground-truth accuracy to improve over the duration of a deployment using advanced clustering algorithms.

To examine the feasibility of an autonomous ground truth collection device, we developed a prototype software system in Java (for platform independence) to process the data stream from a station in a well-studied, representative mining region. The prototype consists of a detector operating on a continuous stream. The default detector we implemented was a simple power (STA/LTA) plus frequency-shift detector algorithm applied to a three-component data stream. The detector can be configured as a *P* polarization detector as it allows for arbitrary linear combinations of data from the three-component stream. Following detection, the system extracts waveforms around the trigger time and applies a series of measurement algorithms to the waveforms to determine P onset, Rg peak energy and acoustic arrival time and P and Rg backazimuths. The waveforms are archived along with the parameters in a temporary archive. The prototype provides hooks for the Single Station Beyesian Locator (SSBL) that we have developed. We have prior information on the spatial location of the mining region and we treat the group velocities of the *P*, *Rg*, and acoustic waves as random and have some prior distribution that can be either uniform or Gaussian. Bayesian methods are attractive in that prior information can easily be incorporated (e.g., a prior on the mine location based on a satellite observation) and uncertainties are partitioned between data and the priors. Because an autonomous sensor may be deployed in a dense mining district, we have developed clustering algorithms to estimate the number of active sources and characterize their waveforms.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**
4. TITLE AND SUBTITLE **Development of Mine Explosion Ground Truth Smart Sensors**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Rocky Mountain Geophysics,167 Piedra Loop,Los Alamos,NM,87544**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **Published in the Proceedings of the 2011 Monitoring Research Review - Ground-Based Nuclear Explosion Monitoring Technologies, 13-15 September 2011, Tucson, AZ. Volume II. Sponsored by the Air Force Research Laboratory (AFRL) and the National Nuclear Security Administration (NNSA). U.S. Government or Federal Rights License**		

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**11**	

OBJECTIVES

Accurate seismo-acoustic source location is one of the fundamental aspects of nuclear explosion monitoring. Critical to improved location is the compilation of ground truth data sets for which origin time and location are accurately known. Substantial effort by the National Laboratories and seismic monitoring groups have been undertaken to acquire and develop ground truth catalogs that form the basis of location efforts (e.g., Sweeney, 1998; Bergmann et al., 2009; Waldhauser and Richards, 2004). In particular, more GT1 (Ground Truth 1 km) events are required to improve three-dimensional velocity models that are currently under development. Mine seismicity can form the basis of accurate ground truth datasets. Although the location of mining explosions can often be accurately determined using array methods (e.g., Harris, 1991) and from overhead observations (e.g., MacCarthy et al., 2008), accurate origin time estimation can be difficult. Occasionally, mine operators will share shot time, location, explosion size and even shot configuration, but this is rarely done, especially in foreign countries. Additionally, shot times provided by mine operators are often inaccurate. An inexpensive, ground truth event detector that could be mailed to a contact, placed in close proximity (< 5 km) to mining regions or earthquake aftershock regions that automatically transmits back ground-truth parameters, would greatly aid in development of ground truth datasets that could be used to improve nuclear explosion monitoring capabilities.

Although the number of magnitude 2.5 explosions and greater in a given mine region is not expected to be large (e.g., 1 or 2 per week; Richards et al., 1992), events to be processed could be on the order of 10 per day, or a total of 1800 events during the 6-month period of operation. One of the first steps involves automatically detecting events and associating them with a particular mine. A good portion of these events can be identified on the basis of size alone (given adequate magnitude/distance scaling relationships, e.g., Brocher, 2003).

Our SBIR Phase I research has demonstrated the feasibility of developing an inexpensive, compact, lightweight smart sensor unit (or units) that could be used in the development of ground truth datasets for the purpose of improving nuclear explosion monitoring capabilities. The units must be easy to deploy, be able to operate autonomously for a significant period of time (> 6 months) and inexpensive enough to be discarded after useful operations have expired (although this may not be part of our business plan). Key parameters to be automatically determined are event origin time (within 0.1 sec), location (within 1 km) and size (within 0.3 magnitude units) without any human intervention. The key parameter ground truth information from explosions greater than magnitude 2.5 will be transmitted to a recording and transmitting site. Because we have identified a limited bandwidth, inexpensive two-way satellite communication (ORBCOMM), we have devised the concept of an accompanying Ground-Truth Processing Center that would enable calibration and ground-truth accuracy to improve over the duration of a deployment.

RESEARCH ACCOMPLISHED

For our Phase I research, we have developed the concept for a Ground Truth Monitoring System (GTMS; Figure 1) that will be supported by a Ground Truth Processing Center (GTPS; Figure 2). The sensors consist of a three-component (3C) short-period geophones and an acoustic sensor. Because we expect the signals from the locally recorded large mine explosions may clip the geophones, we use them to trigger a set of 3C MEMS accelerometers using a strong ground motion switch that activates in 10 msec (Harben et al., 1995). This also saves power by allowing the MEMS to operate in standby mode. The signals are digitized and processed by a Digital Signal Processor (DSP) where signal picks are made, backazimuths are calculated and locations are made using the SSBL. The GTPS is used to analyze waveforms in order to improve local calibration for improved accuracy over the deployment period. This will be possible because of the OBCOMM two-way communication system that we are proposing for the GTMS so that some waveform data can be transmitted to the GTPC for analysis. Calibration can be improved (e.g., development of group velocity dispersion curves to facilitate a better usage of *Rg*) and transmitted back to the GTMS along with any necessary software patches. This way we can offer calibration as a service providing the ground truth information to contracting organizations. Through collaboration with U.S. nuclear explosion monitoring agencies, employees at the GTPC would handle the mine discovery, development of mine contacts, GTMS shipping, telemetry, data processing and package recovery. The GTPC also can be used to refurbish GTMC units that have been returned for subsequent deployments if it appears that this is a cost-effective approach.

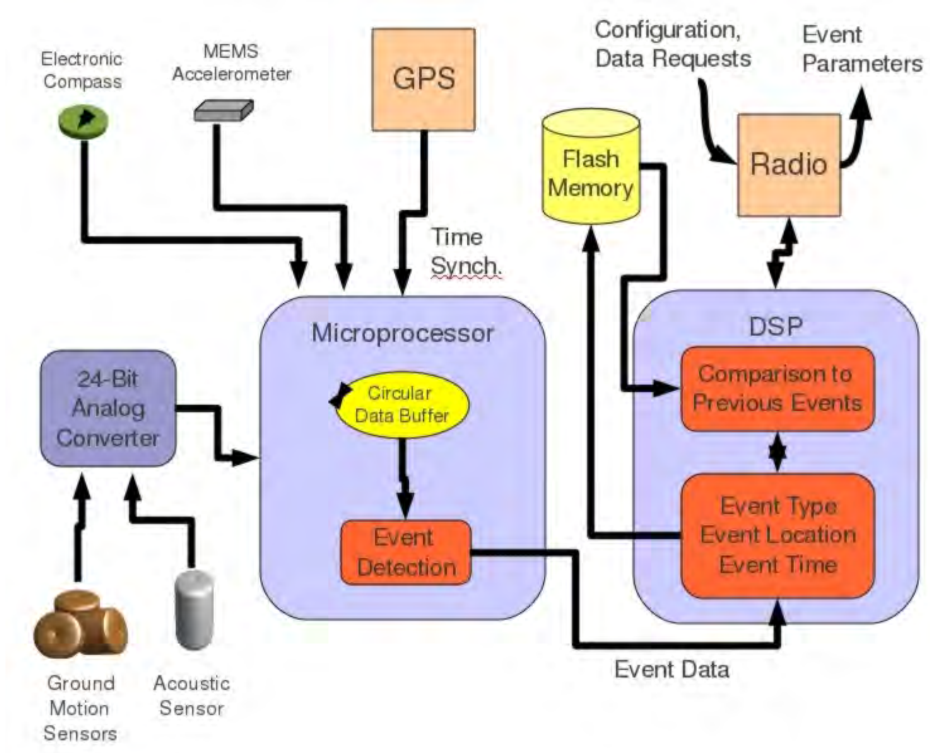

Figure 1. Schematic block diagram of our Ground Truth Monitoring System showing possible configuration of the major and the major paths of communication.

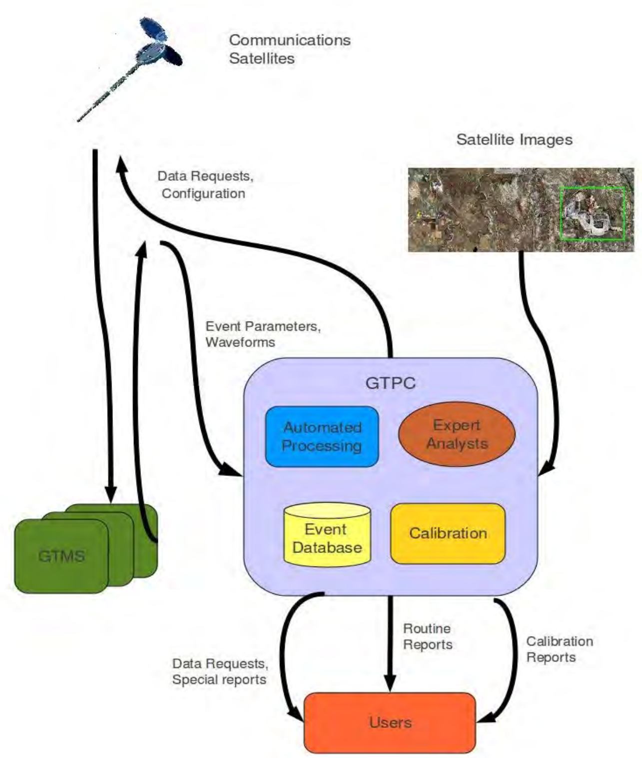

Figure 2. Schematic block diagram of our Ground Truth Processing Center (GTPC).

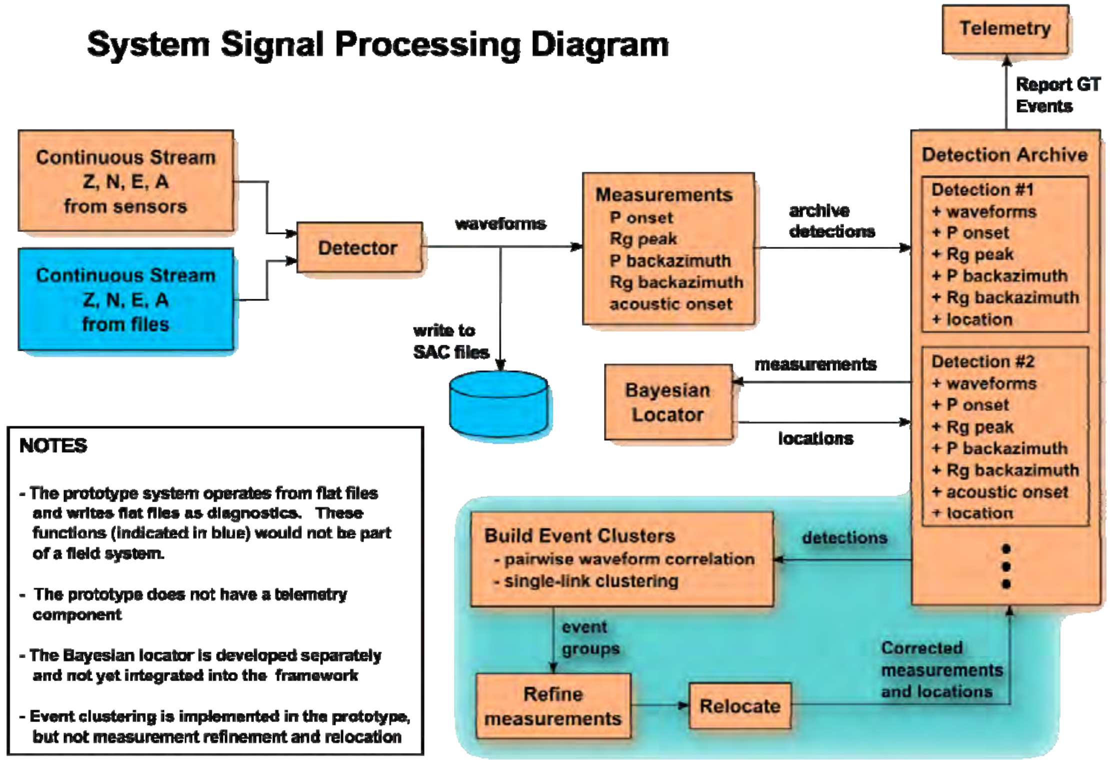

Figure 3. High-level block diagram of a signal processing system prototype under development as part of the GTMS.

Hardware Considerations

The choice of the seismic sensor to utilize is an engineering tradeoff that, at its simplest, is sensor bandwidth and dynamic range versus low power, cost, and size. Since we anticipate large signals, we can tolerate a sensor with relatively low dynamic range provided the sensor does not clip on relatively large ground motions that can be expected near large mining shots. The sensor bandwidth required is also relatively modest, ideally about 1-50 Hz so that an accurate source waveform can be recorded in the local seismic energy band. This frequency band could be as low as 1-25 Hz but the difficulty comes in meeting the low end of the desired bandwidth, not the high end. These sensor performance specifications must be traded off against system requirements that demand low power continuous operation for 6 months on a single battery source, a cost limitation of about $100 per sensor axis, and be part of a small rugged and easily deployed system.

Geophones will provide the basic seismic sensor for the system since they do not require power and therefore help meet the system power limitation constraints. Such sensors, with a bandwidth of 1-50 Hz, would be considered a short-period seismometer if the dynamic range was high. The class of 4.5 Hz geophones offers a reasonable tradeoff of bandwidth at the low end and clipping. With instrument correction for the roll-off, it can record the full source waveform bandwidth of interest. The two candidates are the GS11-D by Oyo Geospace that is used extensively in seismic monitoring of geothermal fields and the Sensor Nederland SM-6 that has similar specifications. The SM-6 (Figure 4a) is preferable for our application because it has twice the physical travel distance of the mass, specifically for the purpose of being less prone to clipping on large signals.

Our approach is to include a strong motion MEMS accelerometer in the system that becomes the active sensor if the SM-6 approaches clipping levels. A new MEMS three component accelerometer by Analog Devices (model ADXL312) is a strong motion sensor well suited to our needs (Figure 4b). The unit cost is less than $10 and the clipping level is user set between 1.5g and 12g. Although the sensor is limited to 12 bits of dynamic range, it would only be utilized at high input levels above the linear range of the geophone sensor. The MEMS accelerometer activates when the geophone detects a possible event. The ADXL312 can be operated in a standby mode utilizing very little power and can be activated from standby mode in 10 msec.

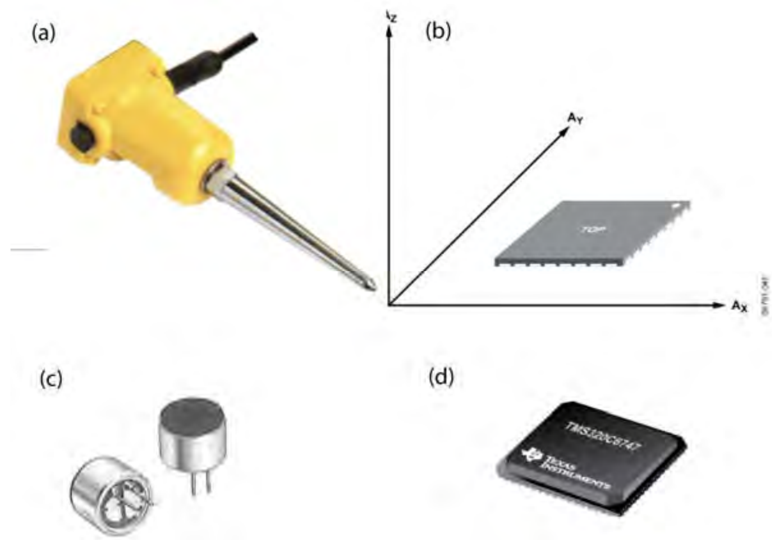

Figure 4. Our preferred sensors and processor for the GTMS. (a) Sensor Nederland SM-6 geophone with emplacement spike. (b) MEMS three component accelerometer by Analog Devices (model ADXL312). (c) Panasonic omnidirectional electret condenser microphone model WM-034BY. (d) Texas Instruments TMS320C6747 low-power floating point processor.

There are an enormous variety of pressure sensors on the market today. All are active devices, consequently power requirements are a major concern. For our system, we desire a low-cost low-power sensor that can record signals below 100 Hz since our sampling rate will limit the acoustic frequencies that can be utilized. Volcano monitoring systems are a good analog for the system we propose because such systems also utilize seismic and pressure sensors. A pressure sensor successfully utilized in many volcano monitoring deployments is the Panasonic omnidirectional electret condenser microphone model WM-034BY (Figure 4c). This very small sensor costs less than $10 and can measure frequencies from 20-16,000 Hz and run continuously for 6 months on two AA alkaline batteries. With a response range in the 20-100 Hz frequency band of our system, it suffices for our purpose.

In our Phase I study, we identified a number of possible communications options, from systems with no communication capabilities to fully networked high-bandwidth real-time communication links. A survey of the methods, consistent with low cost and low power system constraints, eliminates most options. Cell phone and wireless internet communications can be rejected because of spotty coverage. Satellite communications are typically expensive for a continuous link and require significant power. One satellite communication approach is consistent with the system requirements. This approach utilizes a low bandwidth satellite based system (ORBCOMM) that has an affordable cost and is available everywhere. The communications link would only be active for short time periods each day and consequently limit the power requirements. An event of interest can be requested from the GTPC via this link. Only a relatively small data packet can be sent at irregular intervals so the full waveform may require a day or two to send but full source parameters are recoverable.

System Architecture

To meet the objectives of long term operation and small size, and at the same time allow for advanced processing algorithms to be used, it is necessary to use a scheme in which the powerful processor such as a DSP is turned off most of the time, and is only turned on when an event of interest occurs. A low-power microcontroller is used to collect a continuous pre-event buffer, which is scanned for the presence of a possible event using a simple STA/LTA detector. Only when an event occurs is the DSP woken up to apply its advanced processing only to the segment of interest. In addition, the system includes a GPS receiver to provide station location and timing.

The starting point for estimating the cost of the system is to determine the cost of the components. We estimate that the cost of the electronic components and sensors is $700-$800 in small quantities. This is low enough so that after adding the cost of the weatherproof enclosure and manufacturing, a target level of $1500 is achievable. We will leverage non-proprietary hardware interfacing developments produced by Jarpe Data Solutions in development of a specialized microearthquake monitoring system for geothermal reservoirs.

Power Management

The key to meeting the system design goals of many months of unattended operation in a small, lightweight package is to manage the power consumption by taking advantage of the intermittent occurrence of events that need to be processed. Under all options within the basic system design we are considering, the addition of a small 1 watt solar panel to the system extends the operational lifetime of the system indefinitely.

Using the system architecture and components described above, power consumption values from the specifications of those components, and certain operational parameters and system options, we can calculate how long the system can operate on a single battery charge (Figure 5). The operational parameters and system options that we explored are, (a) battery capacity, (b) number of events per day, (c) length of time required to process one event, and (d) number of bytes transmitted via radio per event. From Figure 5, it can be seen that to achieve the 6 month operating time without solar charging, the parameters that decrease system time cannot be greatly increased from the initial values (20 A-h battery pack, 10 events per day, 100 seconds of processing time per event, and 1000 bytes of data transmitted per event). For the number of events per day, 10-20 is a reasonable estimate for a single mine or group of mines, so there should not be an issue concerning that parameter. However, large mining explosions of magnitude greater than 2.5 may only occur once per week at a given mine. The plot of the effect of processing time shows that the processing algorithms have to be carefully constructed to minimize computation time. At a sample rate of 100 samples per second, using compression techniques, transmitting 20 seconds of raw data from 4 channels requires approximately 16000 bytes. It would be possible, however, to transmit data for selected events, for instance 10% of the total detected events. This is consistent with the application since we expect ground truth events, of a size that will be detected regionally and are of interest, will be relatively rare (less than once a month on average) and can be treated specially.

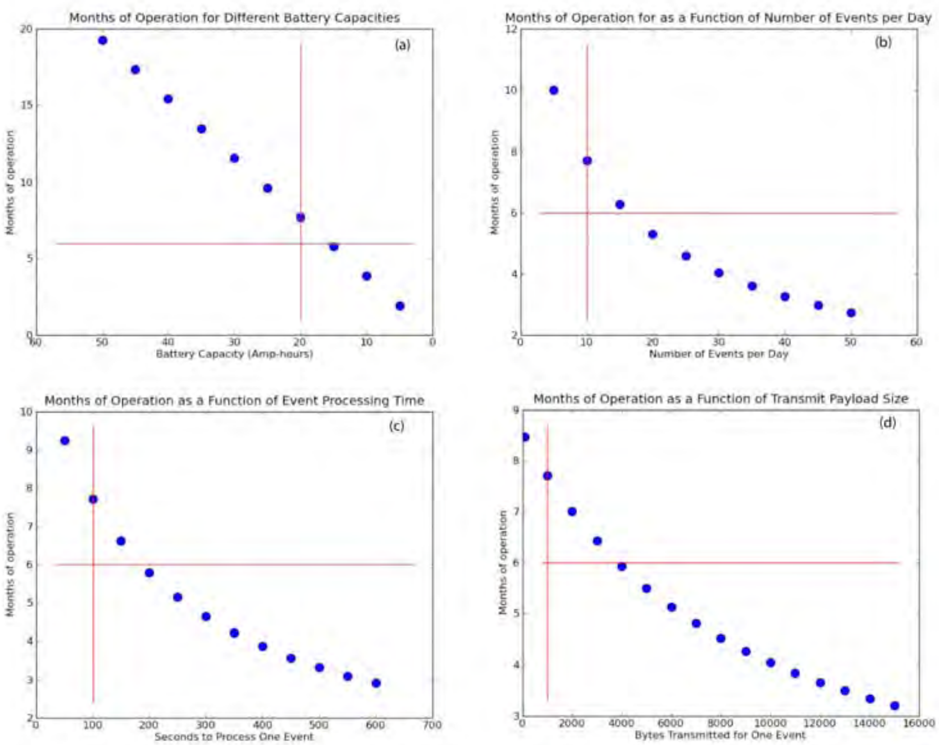

Figure 5. Estimated months of system operation on a single battery pack using different operating parameters. The horizontal red line is drawn at 6 months, the target operational time length. The vertical line in each plot is the default value used for that parameter to calculate the other 3 plots. (a) battery capacity, (b) number of events per day, (c) length of time required to process one event, and (d) number of bytes transmitted via radio per event.

On Board Processing

The next major undertaking is to develop algorithms to measure the key parameters (origin time, location and size) to be transmitted. This is a formidable task and the algorithms need to be simple yet robust in order to operate on onboard computers having limited processing capability. We consider methods that can be used to adaptively improve parameter estimates over the period of deployment and Bayesian methods to simplify calculations by reducing the size of the solution space and to provide realistic uncertainty estimates. For location and origin time, the obvious tools at our disposal for single-station operation revolve around *P*-acoustic or *P-Rg* wave arrival times, three-component backazimuth (from body and surface waves), surface wave dispersion measurements, correlation and coda wave measurements. The main assumption we make is that we know the spatial limits of the mining region that is being monitored.

Therefore, we will focus on methods combining *P* wave arrivals with short-period Rayleigh wave measurements (*Rg*) as well as whole waveform correlation methods. One aspect of *Rg* waves that makes them particularly appealing for local monitoring of mining explosions besides their large amplitudes is their distinctive retrograde elliptical particle motion. Hilbert transforms of the surface wave train can change the particle motion from retrograde elliptical to linear and well-established techniques can be used to enhance the signals and obtain backazimuth estimates (e.g., Jarpe and Dowla, 1991). *Rg* dispersion can be used to estimate event distance and origin time given some prior information on shallow velocity structure. An advantage of this approach is that the relatively slow phase velocity of *Rg* makes origin time and distance estimates more accurate than from body waves if any prior information regarding dispersion is available. A similar argument can be made for acoustic arrivals. However, Bonner et al., (2003) noted that for cast blasting, the origin time for the main surface wave energy release was due to the mass motion of the material cast into the pit rather than from the direct generation of the explosion itself.

The key prior piece of information is an epicentral region that encompasses the mine to be monitored. This can be performed by examination of satellite photos of the mine at the GTPC (Figure 2) prior to deployment.

Prior information and processing for on-board processing includes
1) station location (should be within 5 km from mining region)
2) location bounds of mining region (green box in Figure 2)
3) prior PDF P-velocity between mining region and station (e.g. uniform or Gaussian)
4) acoustic velocity (~0.340 km/s)
5) high confidence *P* STA/LTA detection for large magnitude explosion starts the process
6) search for acoustic and *Rg* arrival around expected arrival time, detect and pick
7) Compute back azimuth (*P*, *Rg*, acoustic/seismic phase) from 3C
8) Single Station Bayesian Locator (SSBL)
9) clustering of detections

This prototype system (Figure 3) runs an STA/LTA to define a *P* detection, sets about making *P* and *Rg* timing and back-azimuth measurements, then archives the detection and moves on. At the end of 5 days it cross-correlates and clusters all detections. Events in a cluster then can be processed further to refine back-azimuths and onsets. The results on clusters could be more reliable than the individual measurements as well as help reject noise burst triggers.

Detection and Picking

The key assumptions we make to start processing is that we know the approximate spatial extent of the mining region (to within a few kilometers) and that the mine explosions that are important for ground truth are *large* (i.e., can be detected by numerous regional stations of a monitoring network). Therefore, detection is not the main problem to be faced by the system and we use a simple STA/LTA + frequency shift detector for detection as well as picking. To illustrate detection and picking we use data from one of the HUMBLE REDWOOD II experiments (Shot 6, HRII, Foxall et al., 2010) at station W1. The explosion was approximately 1450 lbs TNT detonated at a depth of 1 meter in alluvium. Station W1 is at a distance of 3.873 km from the shot point. In this case, the direct *P* wave is detected as well as a secondary *P* arrival presumably associated with a shallow refraction. The detection at approximately 11 seconds is from the high-frequency acoustic to seismic conversion. Because we use a short duration short-term window of only 0.1 second, we define the arrival time to be at the beginning of the STA window. The next step is finding the acoustic detection. We can use the value of the *P* arrival time and the approximate distance range to zero in on the expected arrival time of secondary phases.

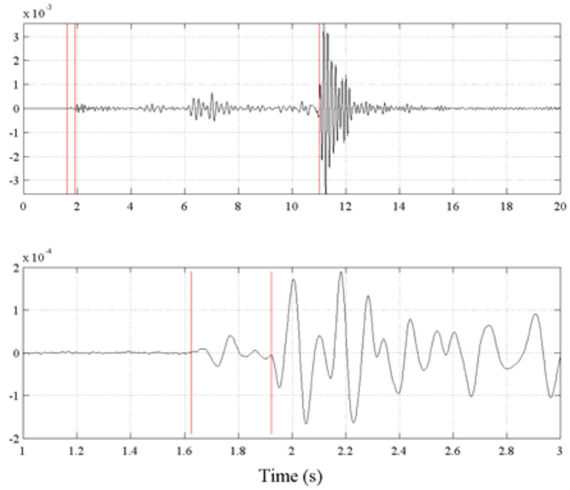

Figure 6. Seismogram from station W1, Shot 6 from HRII experiment. Red vertical line shows automatic detection and pick from P wave using STA/LTA + frequency shift.

Location

Once we have differential arrival times and back azimuth estimates we can combine them into a Single Station Bayesian Location framework (e.g., Fagan et al., 2009; Modrak et al., 2010). In our case, a high-confidence *P* wave detection triggers the processing. We have prior information on the spatial location of the mining region and we treat the group velocities of the *P*, *Rg*, and acoustic waves as random and have some prior distribution that can be either uniform or Gaussian. Bayesian methods are attractive in that prior information can easily be incorporated (e.g., a prior on the mine location based on a satellite observation) and uncertainties are partitioned between data and the priors. Figure 7 shows results using the *P* and acoustic wave arrival times and individual *P* and *Rg* wave backazimuth estimates of 102° and 86° (the actual backazimuth is 95.6°). The estimated epicenter is 160 meters from the true epicenter. The estimated origin time was 0.05 seconds after the actual. Because of the difference in back azimuth estimates for the *P* and *Rg* phases, there is a spread of solutions in the azimuthal direction that fit the data equally well. Note that the epicenter and the origin time are both within the 1 km uncertainty (shown as the black circle in Figure 7) and 0.1 second uncertainty specified in the requirements.

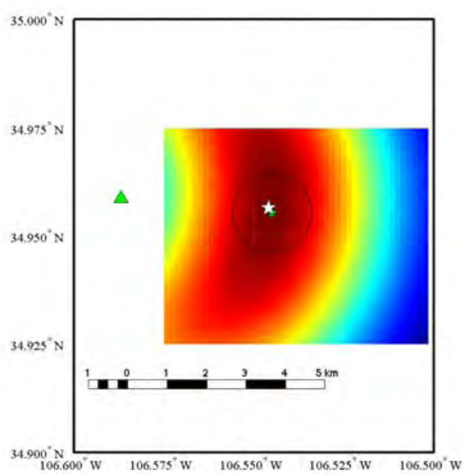

Figure 7. Likelihood contours for HRII Shot 6 (green star) recorded at station W1 (green triangle). The acoustic wave – *P* wave arrival time has been used for distance along with the *P* wave and *Rg* back azimuth for direction. The black circle is of 1 km radius centered on the epicenter of Shot 6.

To examine the feasibility of an autonomous ground truth collection device, we developed a prototype software system in Java (for platform independence) to process the data stream from a station in a well-studied, representative mining region. This software prototype, illustrated by a high-level system diagram in Figure 3, implements a substantial subset of the signal processing functions that GTMS would require to perform event detection, waveform measurement, event location, origin time and magnitude. Following detection, the system extracts waveforms around the STA/LTA trigger time and applies a series of measurement algorithms to the waveforms to determine *P* onset, *Rg* peak energy arrival time and *P* and *Rg* backazimuths.

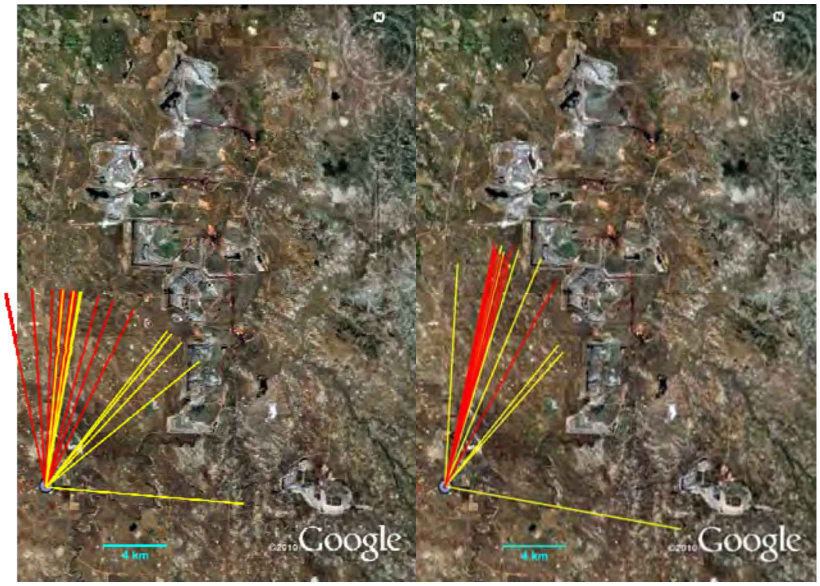

Figure 8. (Left) Automatically determined P backazimuths for the cluster events (red) and the unclustered events (yellow) from station TAI23A. (Right) Rough location estimates made from Love wave (red) and higher mode Rayleigh wave (yellow) backazimuths and relative arrival times.

The most advanced function of the prototype is an event clustering operation, intended to be invoked periodically as a sufficient number of detections accumulate to permit joint event analysis (e.g. Harris and Dodge, 2011). For testing, the prototype was used to process 20 days of continuous data from an Earthscope Transportable Array station (TA.I23A) in the Powder River Basin (PRB) of Wyoming. Since the PRB is a very active mining district, with 22 open pit mines, three weeks of continuous data from this station provided a substantial test of detection and measurement algorithms. Among the likely difficulties that must be surmounted is the problem of distinguishing the explosions at adjacent, mines (say within 20 kilometers) from those of the intended ground truth target. If this station were deployed principally to provide ground truth on the closest (Cordero-Rojo) mine, it also would need to interpret explosions from the many adjacent mines, if only to screen them from consideration as GT events. Back azimuth data from *P* waves and surface waves (Figure 8; left) superimposed on the satellite photo of the middle group of PRB mines. Figure 8 (right) shows that Rayleigh back azimuths are somewhat less consistent than the Love back azimuths, but still better than the P back azimuths. The Rayleigh wave particle motions are indicated in yellow and form a bundle pointing in the general direction of the northern Cordero-Rojo mine. The Love particle motions are indicated in red and form a tight bundle. A rough estimate of location for the 25 events can be formed by back-projecting the range estimate formed from the surface wave minus *P* differential arrival time along the Rayleigh back azimuth or the Love back azimuth (corrected by subtracting 90 degrees). For purposes of exposition, the cluster was associated with the northern Cordero-Rojo pit, with the resulting locations (again indicated as rays) in Figure 8. Note that the events mostly fall somewhat to the west of the actual mine locations, which may be an artifact of the fact that the images in this region were acquired in 2006, while the events occurred in 2010. It is apparent that the mine faces are working to the west, which is in the direction of the rough event locations.

CONCLUSIONS AND RECOMMENDATIONS

In Phase I, we have demonstrated the feasibility of constructing an inexpensive, compact deployable Ground Truth Monitoring System (GTMS) for obtaining calibration ground truth information (timing, location, magnitude) autonomously from mining regions.

ACKNOWLEDGEMENTS

The Humble Redwood seismograms were kindly provided by Artie Rodgers and Bill Foxall of Lawrence Livermore National Laboratory. The facilities of the Incorporated Research Institutions for Seismology (IRIS) Data Management System and the IRIS Data Management Center, were used for access to waveform, metadata or products required in this study and is funded by the GEO Directorate through the Instrumentation and Facilities Program of the National Science Foundation under Cooperative Agreement EAR-0552316. Some activities of are supported by the National Science Foundation EarthScope Program under Cooperative Agreement EAR-0733069.

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