DEVELOPMENT OF MINE EXPLOSION GROUND TRUTH SMART SENSORS

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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 other 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.

In our first year of Phase II, the prototype GTMS_V1.0 was developed and deployed in the Morenci Copper Mine in eastern Arizona in March 2012. GTMS_V1.0 employs a 24 bit digitizer, a three-component geophone sensor, and a pressure sensor. A 32-bit Atmel AVR microprocessor is used for data buffering and processing. It has the capability for high performance computations, is low cost, low-power consumption and has 32 Mb RAM. A circuit board was designed that interfaces to external components such as the 24-bit Analog-to-Digital Converter (ADC), the GPS, serial and flash memory. The AV32 microprocessor is configured to be turned on for short time periods to process detected events using a fully interrupt-based software framework allowing low-power operation. Intermittent GPS operation also saves on power and is only activated during event triggers. Nederland SM-6 4.5 Hz long coil transport three-component geophones are used which appear to be well suited for the GTMS. We have found that the geophones can be operated in close proximity to large mine explosions (e.g. > 200,000 lbs) without clipping. Additionally, the SM-6 geophones have reasonably good low-frequency response so that Rg waves are faithfully recorded. Also in March, a remote site was located approximately 6 km to the north of the mine at our Dead Skunk site (DSK) in the Clifton Ranger district of the Apache National Forest. The DSK site consists of a RefTek 130 digital recorder and marine battery in a weatherproof box. External to the box is a 100 Watt solar panel, a GPS receiver, a microphone and buried SM-6 geophones. Low-bandwidth ORBCOMM satellite is being prepared for GTMS_V2.0 for inexpensive two-way communication between the GTMS and the Ground Truth Processing Center (GTPC).

Most of our processing software work to date has focused on detection algorithms specific to large mining explosions. In this sense, detection is not necessarily a problem, but it is important to minimize the number of false detections in order to conserve power. Processing software is being developed to have the fewest mathematical operations and is focused around 3C Bayesian algorithms to combine detection and picking with location. A GTMS may be deployed in a mining region where just one particular mine may be targeted. Other noise sources can create large signals that can be filtered out using polarization detectors. Also, our work has shown that polarization detectors can be used for reasonably accurate *P* and *S* wave arrival time picks. For the GTMS we use a Bayesian approach because the location of the target mine will be known *a priori*. *A priori* information can be used to reduce false detections and greatly aid with location accuracy and uncertainty estimation.

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 other 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.

We are 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.

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. 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 a Single Station Bayesian Locator (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 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 3 shows a high-level block diagram of our signal processing system prototype.

RESEARCH ACCOMPLISHED

The current configuration of the GTMS_V1.0 is illustrated in the left hand portion of Figure 1. A 32-bit Atmel AVR microprocessor is used for data buffering and processing. It has the capability for high performance computations and is low cost and low-power consumption and has a large amount of memory. GTMS_V1.0 employs a 24 bit digitizer, a three-component geophone sensor, and a pressure sensor (Figure 4). A circuit board was designed that interfaces to external components such as the 24-bit Analog-to-Digital Converter (ADC), the GPS, serial and flash memory. The AV32 microprocessor is configured to be turned on for short time periods to process detected events (using a simple STA/LTA) using a fully interrupt-based software framework allowing low-power operation. Intermittent GPS operation also saves on power and is only activated during event triggers. To meet the objectives of long term operation and small size, and at the same time allow for advanced processing algorithms to be used, the DSP is turned off most of the time, and is only turned on when an event of interest occurs.

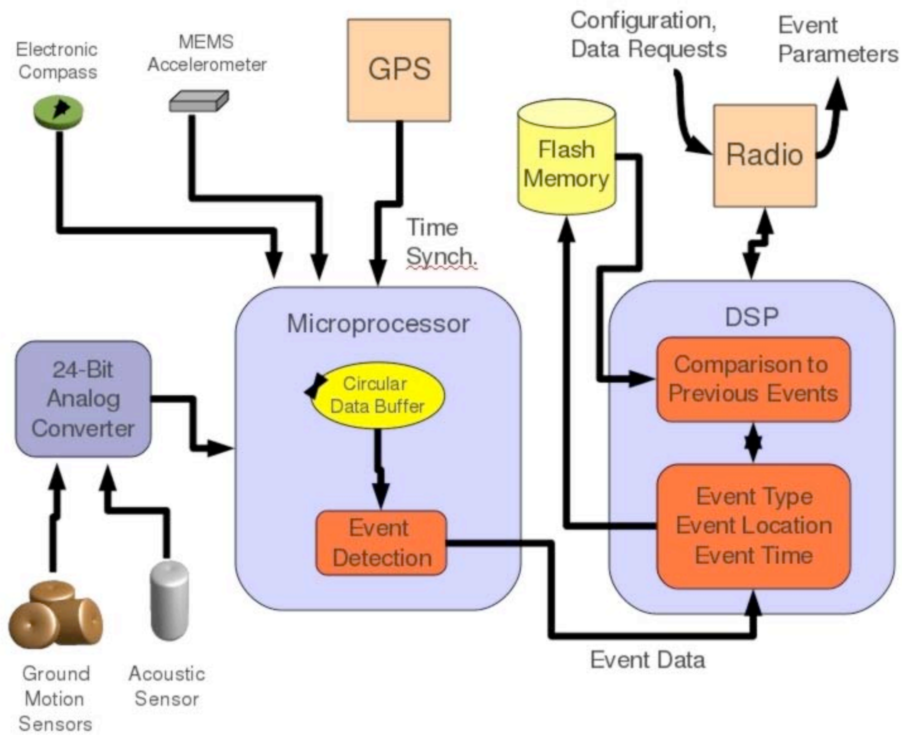

Figure 1. Schematic block diagram of our Ground Truth Monitoring System showing possible configuration of the major and the major paths of communication.

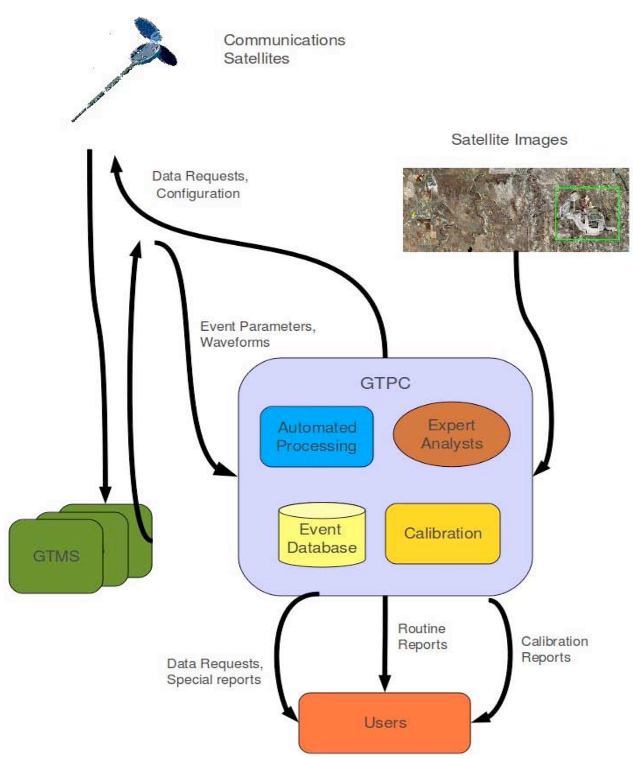

Figure 2. Schematic block diagram of our Ground Truth Processing Center (GTPC).

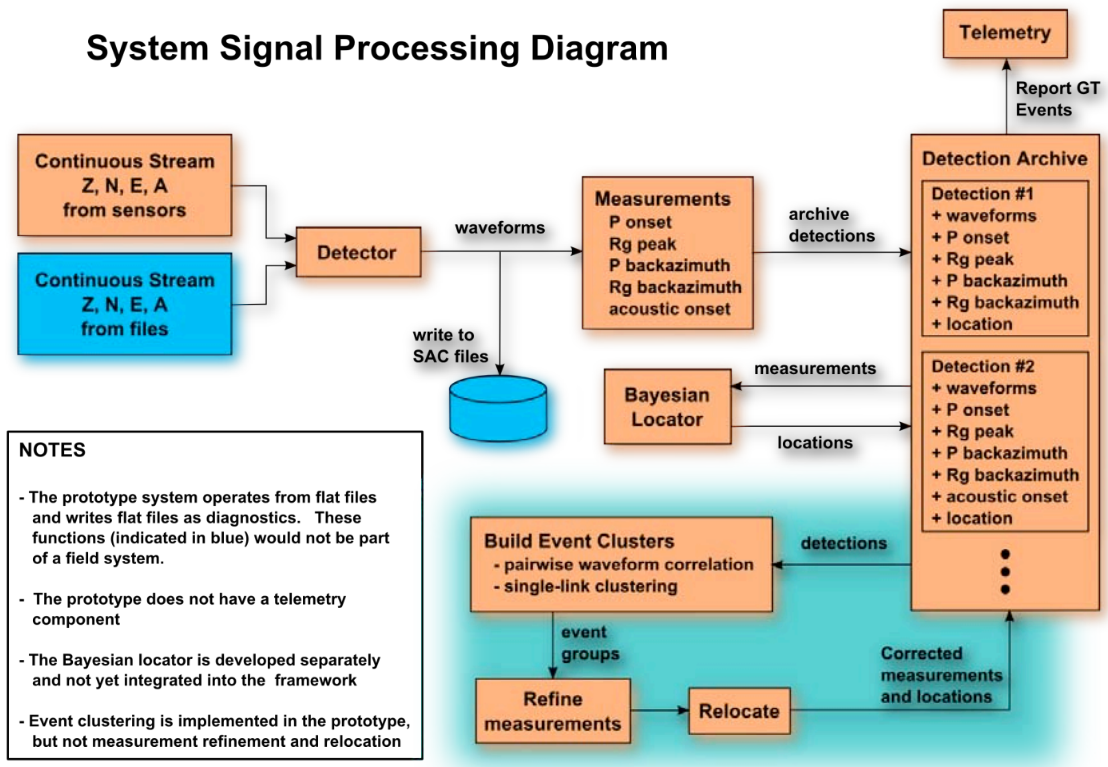

Figure 3. High-level block diagram of a signal processing system prototype under development as part of the GTMS.

Nederland SM-6 4.5 Hz long coil transport three-component geophones are used which appear to be well suited for the GTMS. The 4.5 Hz Nederland SM-6 long coil travel geophones appear to be an excellent choice for the GTMS because they do not clip even at close range of the large mine explosions. We purchased two three component packages one already packaged with emplacement spikes and one with separate sensors for which we built custom-made box. A custom made steel plate was constructed with a leveling bubble and with attachments for both the SM-6 geophones as well as the Kinemetrics Episensor FBA. We have found that the geophones can be operated in close proximity to large mine explosions (e.g. > 200,000 lbs) without clipping. Additionally, the SM-6 geophones have reasonably good low-frequency response so that Rg waves are faithfully recorded. Therefore, it appears that the MEMS backup shown in Figure 1 will not be necessary for the GTMS. Figure 4 shows the GTMS_V1.0 electronics package and enclosure. Figure 5 shows GTMS_V2.0 board that is currently being prepared for deployment.

GTMS_V1.0 is currently operating at the Morenci Copper Mine in eastern Arizona. The Morenci mine is owned by Freeport-McMoRan Copper & Gold, Inc. Through a series of letters and correspondences arrangements were made to deploy a prototype GTMS in the mine and a RefTek recording system in National Forest Service (NFS) approximately 5 km north of the mine (Figure 6). Figures 7 and 8 show the GTMS_V1.0 at the SPJ site in the Morenci Mine. Note that the unit is compact and the external geophones only need orientation and leveling. In future versions, the geophones will be included within the single package. A simple on/off switch is used to begin recording and on-board processing. The solar panel is optional and not planned to be required for 6 months autonomous operation for the final product. The SPJ site overlooks the Garfield pit and is in an excellent location to provide ground truth information on the Morenci shots. At this point the GTMS_V1.0 is providing ground truth for development of processing algorithms for data collected at the DSK site. The Morenci Mine is kindly providing information regarding their shot locations and configuration.

Figure 4. **GTMS_V1.0 electronics and enclosure.**

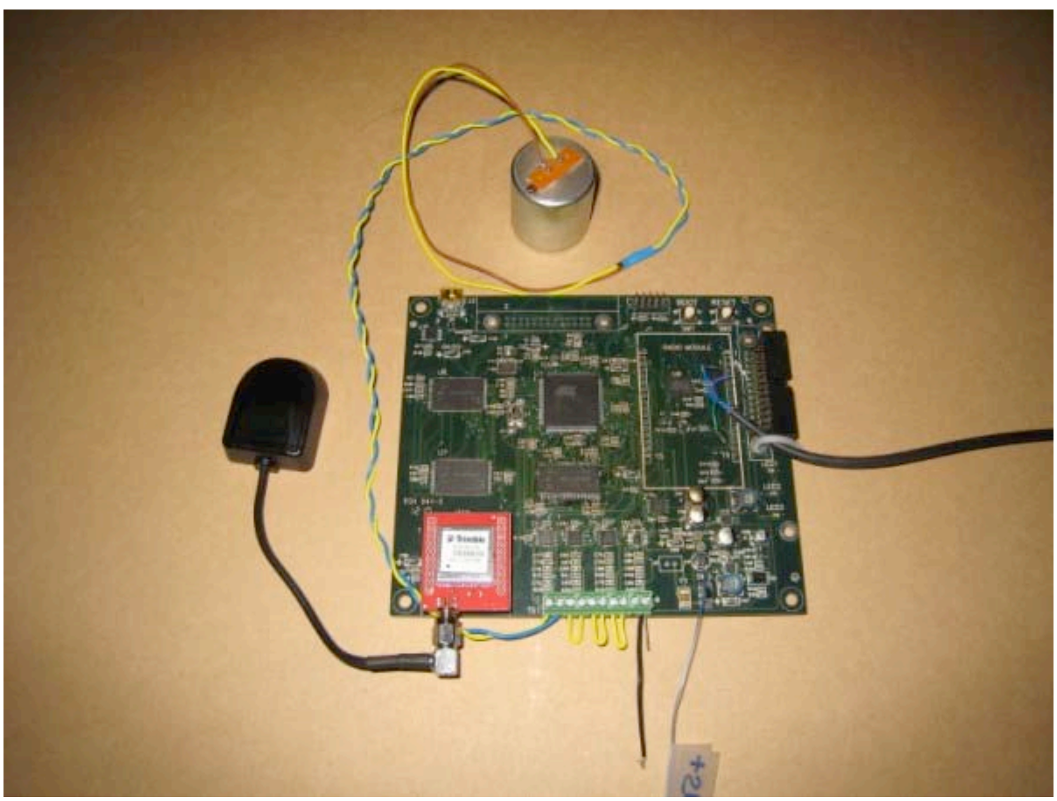

Figure 5. **GTMS_V2.0 electronics showing additional elements of V2.0 relative to V1.0 shown in Figure 4.**

Figure 6. **Google Earth image showing DSK and SPJ sites as yellow thumbtacks**.


Figure 7. Steve Jarpe flips the "on" switch for the GTMS_V1.0 at SPJ site.

Figure 8. Steve Jarpe at SPJ site and the GTMS_V1.0.

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 (e.g. Fagan *et al*., 2009; Modrak *et al*., 2010). 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 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. The 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.

As an example we have developed a horizontal polarization detector and is applied to a small explosion at a distance of 6.1 km filtered between 6 and 15 Hz. To estimate the back azimuth (ϕ) from the station to the source, a grid search is performed between 0 and 180° to find the maximum variance of the radial component. At each back azimuth the variance of the radial component is computed using a 0.5 second window moved down the N and E seismograms with a shift window length of 0.1 seconds. For each time window, the N, E are rotated through angles of 0 to 180° and the radial variance is computed for each angle. The maximum radial variance gives the estimated back azimuth for each time window. The *P* wave train arrives a about 3 seconds, the shear waves at 10 seconds and an acoustic to seismic converted phase at 17 seconds. At this point, the maximum radial variance is referenced to the observed back azimuth, and is controlled by the signal amplitude as well as the degree of polarization. The ratio R_s given by the maximum to minimum radial variance is treated as a random variable and is a measure of the degree of horizontal polarization at an observed back azimuth. R_s is conditioned on a prior back azimuth and is closely related to the commonly used rectilinearity parameter that is related to the ratio of the principal component eigenvalues of the N, E covariance matrix. The rectilinearity (ρ) is simply computed using $1-\sigma_n^2/\sigma_R^2$. Because seismologists are familiar with the meaning of rectilinearity it acts as a specified input parameter and is tied to the non-centrality parameter, λ, used in χ^2 tests discussed below. R_s is the test statistic measuring the degree of polarization at the observed back azimuth. Under a signal hypothesis to be defined below, R_s is assumed to have χ^2 distribution having $2TB$-1 degrees of freedom (*dof*), where T is the window length of each time segment (s) and B is the filter bandwidth (Hz). In particular, under the null hypothesis of a signal, a non-central χ^2 distribution is assumed

$$R_s \sim \chi^2\left(2TB-1,\lambda\right) \tag{1}$$

where the non-centrality parameter is related to the rectilinearity. The rectilinearity parameter is not actually used as a test statistic because of its complicated analytical form.

At this point, the signal is defined as a horizontally polarized phase corresponding to the observed back azimuth. Note that the under the single null hypothesis, the noise distribution (represented by a central χ^2 distribution) is never actually used although it could be for a binary hypothesis test involving likelihood ratios.

The joint probability function of the horizontal polarization R_s and the observed back azimuth for each time window is factored into two independent functions given by

$$\Phi\left(R_s,\hat{\phi}\right)=\Phi_R\left(R_s \mid \hat{\phi}\right)\Phi_p\left(\hat{\phi}\right) \tag{2}$$

where as discussed above, Φ_R is represented by a non-central χ^2 under a signal hypothesis. Φ_p represents a prior on the back azimuth that can be used to filter out polarized signals from unexpected back azimuths (say if a certain region is to be monitored).

The null hypothesis for signal detection is H_0: *P wave from back azimuth* ϕ_0 where ϕ_0 is a prior on the back azimuth. Note that the null hypothesis can be easily modified for shear-wave detection or a Rayleigh wave (e.g. Rg) by incorporating the Hilbert transformed vertical component. Under H_0 the probability of detection (aka *p*-value) is given by the cumulative distribution function (CDF)

$$p_d=P\left(H_0 \mid R_s,\phi_0\right)=\int_0^{R_s}\int_{\phi_0-\Delta\phi}^{\phi_0+\Delta\phi}\Phi\left(R_s,\phi_0\right)d\phi_0 dR_s \tag{3}$$

It can be assumed that the observed back azimuth is either normally or uniformly distributed around a prior back azimuth that might be used to detect polarized signals from a given azimuth range.

Figure 9 shows the detection probability using using λ = 50 (ρ = 0.98) and a Gaussian prior on the backazimuth of ϕ_0 = 99° and σ_ϕ = 5° showing a case that might be used for automatically detecting *P* waves from large, highly polarized events (e.g. explosions) emanating from a given region.

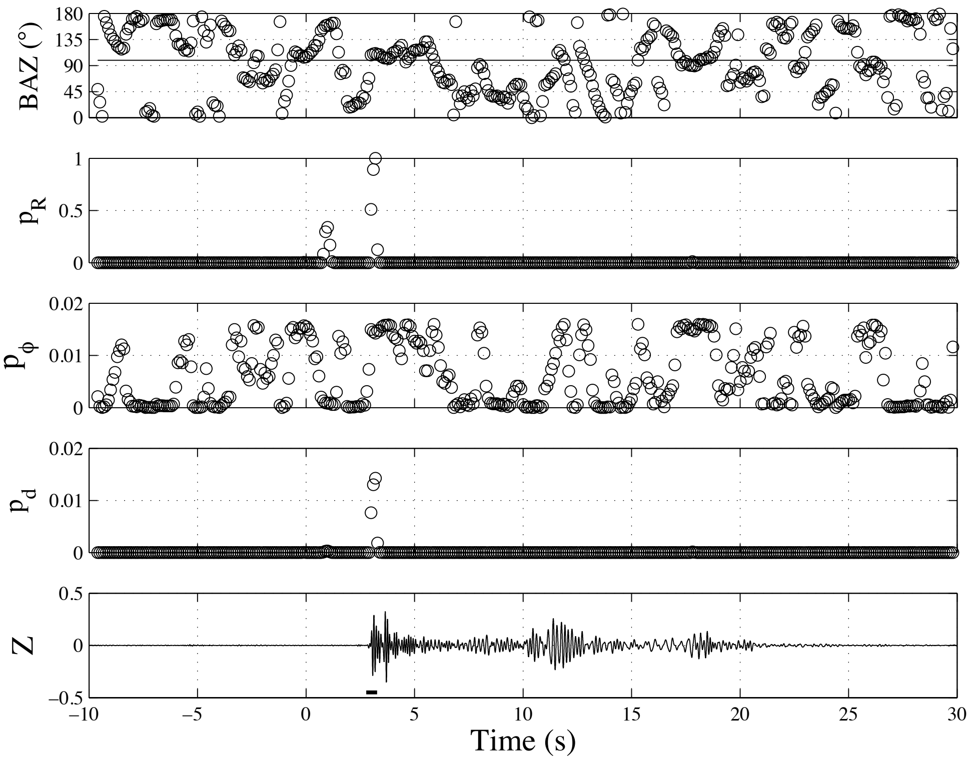

Figure 9. Back azimuth estimate and true backazimuth as horizontal line. P_R is detection *p*-value for each time window under null hypothesis of horizontally polarized signal with ρ = 0.98 having a no prior on back azimuth. P_ϕ is same as P_R but with a prior on the back azimuth. P_d is combined detection probability that is the product of P_ϕ and P_R (see text for details).

We have also been investigating more general Bayesian polarization detectors that involve a binary hypothesis approach on all three components. Polarization detectors have been described widely in the seismological literature, but generally are derived under simple assumptions such as a deterministic polarization vector and noise which is uncorrelated among the channels in the three-component set. The innovations reported here include:

1.) A probabilistic description of the polarization vector and using the Kent distribution as a prior. The Kent distribution allows different uncertainties to be assigned to the azimuth and angle of incidence.
2.) Proper formulation of the problem as a Generalized Likelihood Ratio Test (GLRT) in which unknown parameters are estimated with maximum likelihood estimators, in the process of forming the detection statistic.
3.) Generalization of the detection statistic to account for the polarization structure of ambient noise. When the Bayesian prior on the polarization vector is removed (i.e. the polarization vector is considered to be deterministic, but unknown), the polarization vector is found as the principal eigenvector in a generalized eigenvalue problem, making it a generalization of classical principle components detectors.
4.) A detector formulation, drawn from conventional power detectors, that uses two windows, one to estimate the covariance of the background noise and a second to serve as the signal detection window.
5.) Efficient gradient search for the polarization vector when the vector is subject to a Bayesian prior. The algorithm performs searches along geodesics of the constraint manifold (the unit sphere) for polarization vectors.

CONCLUSIONS AND RECOMMENDATIONS

We are developing a Ground Truth Mine Monitoring System that will be used to improve location capabilities of U.S. nuclear explosion seismic monitoring systems. Most of our work to date has been development and deployment of the GTMS and we are currently preparing datasets upon which to develop our processing algorithms.

ACKNOWLEDGEMENTS

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