DEVELOPMENT OF AN AUTOMATED PC-NETWORK-BASED SEISMIC MONITORING SYSTEM[1]

Peter L. Swanson, geophysicist
National Institute for Occupational Safety and Health
Spokane Research Laboratory
315 E. Montgomery Ave.
Spokane, WA 99207
USA

(voice) 509-354-8072
(fax) 509-354-8099
(email) pswanson@cdc.gov

Synopsis

NIOSH has developed an automated PC-based seismic monitoring system for use in mine ground control studies. The distribution and coordination of data acquisition and processing functions across a local area network (LAN) is a central feature of the system. Design requirements include (1) the use of low-cost, off-the-shelf, data acquisition and computer hardware, (2) the capability of automatically merging waveform data sets from different types of monitoring systems, (3) delivery of raw and processed data underground and on the surface, as well as to remote sites, and (4) automated data collection and processing over long periods of time without the need for human intervention. Current mine-wide installations utilize multiple, autonomous seismic networks located both underground and on the surface and provide 20 to 40 stations within a radius of several kilometers. Event locations, magnitude estimates, and other processed data are distributed for display and analysis on network nodes both underground and in the offices of mine engineers and managers. This paper describes the system's hardware and software components, examples of installations in hard-rock and coal mines, and a few observations from western U.S. longwall coal mines.

Introduction

The U.S. Bureau of Mines (USBM) was eliminated as a federal agency by the U.S. Congress in 1996. The continuing Congressional mandate for health and safety research in mining was then transferred to the National Institute for Occupational Safety and Health (NIOSH) under the Centers for Disease Control and Prevention (CDC). NIOSH's research laboratories in Spokane, Washington, and Pittsburgh, Pennsylvania, conduct much of its mine safety research.

Seismic monitoring capabilities were required in several NIOSH studies in which the reduction of hazards from rock mass instabilities, such as rock bursts, coal bumps, mine collapse, and roof falls, was the primary objective. However, most of the USBM seismic monitoring hardware, software, and expertise did not make the transition to NIOSH. Therefore, an automated seismic monitoring system was developed for use in these ground control studies.

Design philosophy

Several technical and nontechnical issues guided system design. The expense of hardware and software, and expected costs of field installation, maintenance, and operation were of prime concern. Thus, the initial emphasis was in developing several inexpensive automated systems to detect and locate events and estimate magnitudes. Automation of full-waveform inversions and related analyses[1,2] was not part of the original objective, although this functionality can be added. This latter approach was not emphasized in the initial mine-wide monitoring program in part because of the expense of obtaining clear, high-quality signals. Installation of sensors in boreholes is generally required to obtain signals that are not influenced by the fractured halo surrounding mine openings and the surface weathered zone. This is a prohibitively expensive option for the current project work in the deep mines of the western United States. As a result, a certain amount of signal filtering by the rock mass is to be expected in the applications.

Modest-sized arrays of single-axis sensors were selected over networks made up of a smaller number of triaxial stations. This choice was made for the simplicity of automating P-wave arrival picking. Accuracy and consistency in shear-wave arrival picking is much more difficult to achieve using an automated procedure, especially when signals are attenuated because of near-surface effects. While shear-wave arrivals provide strong constraints on locating events, an overriding goal is to establish event locations as accurately as possible with fully automated processing. Errors in shear-wave arrival picks can compromise the accuracy of an event location.

In addition to low cost, reliability and flexibility were important considerations. The expense and downtime associated with timely repair and/or replacement of custom data acquisition and processing hardware, as experienced with some previous USBM systems, was to be avoided. Mass-produced PCs and commercial multichannel analog-to-digital (A/D) converters are very reliable.

A centralized data collection system was also to be avoided to minimize the chance of having a single hardware failure bring about total loss of monitoring coverage. A system of distributed data acquisition modules avoids single-point failures and allows flexibility for network expansions and for configuring systems to monitor complex or difficult-to-access ore bodies. Distributed data sources may include multiple autonomous data acquisition systems operating in different parts of a mine or mining district, surface and underground networks, borehole arrays, portable instruments, etc. The need to deliver summary processed results to mine personnel stationed underground was an additional constraint. These design requirements are most readily satisfied with a PC-network-based system of data acquisition and processing computers (Figure 1).

To take advantage of as much freely available software as possible, the seismic data acquisition and processing software made available through IASPEI (International Association of Seismology and Physics of the Earth's Interior) was selected to serve as the initial basic building block for data acquisition. IASPEI is a nonprofit geophysics organization that produces software modules for low-cost regional and teleseismic earthquake monitoring[3] Several centralized IASPEI PC-based systems were deployed by USBM researchers[4] for data acquisition in the late

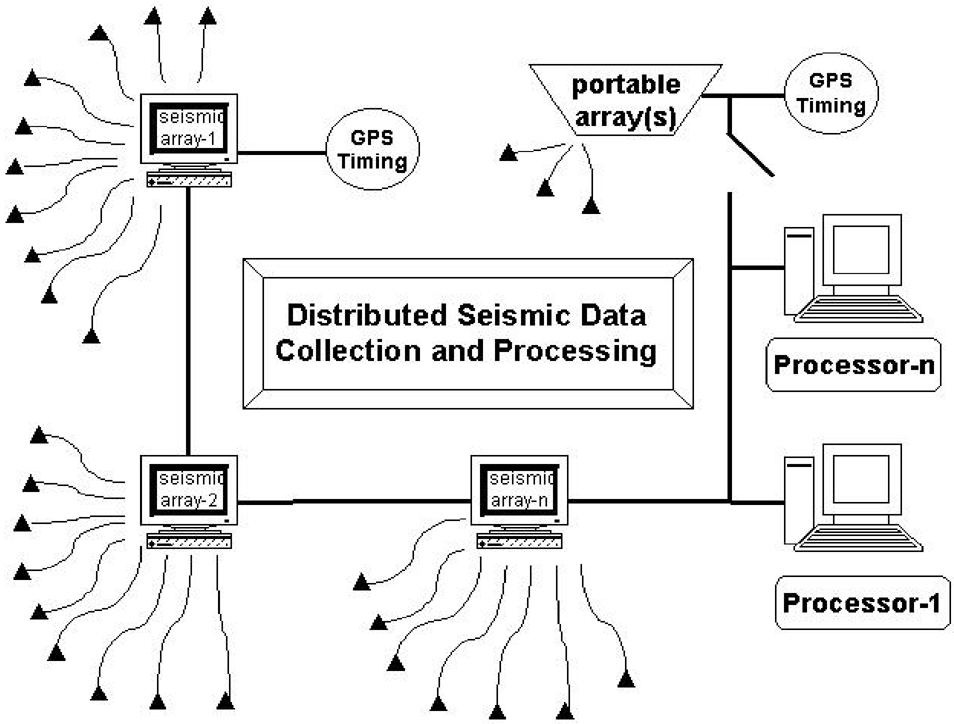

Figure 1. PC-network-based seismic acquisition and processing system

1980s, and updated versions of these systems are still in operation in several western U.S. mines. A common thread to much of the IASPEI software is the use of the PC-SUDS (Seismic Unified Data System) data format based on C language data structures[5,6]. While providing a starting point for collecting mine-wide seismic data, much of the IASPEI processing software is geared toward larger-scale networks and is not directly applicable to smaller-scale arrays.

Hardware

Sensors

Both accelerometers and moving-coil geophones are used in the sensor arrays. Low- noise, high-sensitivity (40 V/g) accelerometers (3 to 3000 Hz) were selected for one hard-rock environment to detect small seismic events occurring within dense localized arrays. In other array deployments, use is made of inexpensive 4.5-Hz geophones mass-produced for the oil industry. The geophone signals are fed into variable gain (1 to 50,000 X) preamplifiers and transmitted on shielded, twisted-pair cables.

Sensors are anchored directly to competent roof or rib surfaces or epoxied to the end of tensioned roof bolts. On the surface above the mine most geophone sensors are placed in waterproof housings in the soil bottom of 30- to 40-cm-deep holes.

Data acquisition

Two different types of digitizing systems are used. With the first kind, seismic signals are transmitted via cable to a commercial off-the-shelf A/D converter attached to a local data acquisition PC. In the second type, seismic signals are digitized near the sensors, and the data are transmitted digitally to a data acquisition PC on the network. In each case, the data acquisition PCs are dedicated solely to collecting waveform files either continuously or in a triggered event-capture mode.

A/D converter attached to network computer

Commercially available PC-based A/D conversion boards used in this development effort are listed in Table I. Typical sampling rates are between 500 and 2500 samples per second per channel for systems having 8 to 64 channels. The maximum sampling rates are not listed as they can depend upon the number of active channels, processor speed, and the selected operating system. Nominal resolution values reported in Table I were given by the manufacturers for a particular sampling rate; actual resolution can be significantly reduced at maximum sampling rates. Antialias filtering is provided by commercial and/or custom programmable filter units.

Table I. A/D converter hardware

Manufacturer and model	Number of channels	Nominal resolution (bits)	Interface
Symmetric Research:			
Par4ch	4	24	Parallel
Par24b	8	24	Parallel
DSPA64	64	16	ISA
Data Translation:			
DT2824	16	12	ISA
DT-EZ	16	11	ISA
DT2821	16	12	ISA

The IASPEI data acquisition software XRTP was developed for Data Translation[2] boards and requires the DOS operating system. The RTPSR (TottCo) software for the Symmetric Research DSPA64 A/D converter is similar. Data files are output directly in PC-SUDS format in both programs. Event detection is based upon an STA/LTA algorithm similar to that reported in Lee and Stewart[7].

The Symmetric Research boards come with data acquisition software that can be used under DOS, in a DOS window under Windows95/NT, and with the Linux operating system. Executable and source code are provided for each operating system so that the user can implement his/her own triggering criteria and make other customizations. Each version has been implemented in different applications of the monitoring system.

Remote A/D conversion and transmission of digital seismic data

Low-power, three-channel 16-bit A/D converters are used to digitize signals at or near remote sensors. Maximum sampling rate is 1000 samples per second per channel. Data are continuously sampled and transmitted back to a data acquisition computer via a cable or wireless telemetry link using the U. S. Geological Survey's RS-232 digital telemetry format[3]. In wireless links, data are telemetered over distances of several kilometers using pairs of 900-MHz and/or 2.4-GHz, frequency-hopping spread-spectrum radio transceivers (license-free operation in the United States). Directional 6-dB Yagi antennas are employed over line-of-sight paths without repeaters. The data are received by a network PC equipped with a 16-channel serial port board using a version of the XRTPDB software[3] that was modified to accept sampling rates of up to 1600 samples per second per channel.

Several commercial seismic and strong-motion data recorders used for earthquake monitoring also provide a compatible RS-232 output stream that can be utilized in this data collection procedure. However, the maximum sampling rates in these units only extend to a few hundred samples per second per channel.

Time-base synchronization

Each data acquisition system records a common timing signal as a data channel. Time signals are subsequently decoded, and each waveform trace is time corrected. The synchronization signal is typically an analog IRIG time code

[2] Mention of specific products or manufacturers does not imply endorsement by the National Institute for Occupational Safety and Health.

output commonly available on timing products manufactured in the U.S. Either IRIG-E or IRIG-B codes with 10- and 1-s frames, respectively, are used. The time codes are derived from global positioning system (GPS) and/or GOES satellite receiver data or are generated as a stand-alone time code in closed systems. Analog time code signals are transmitted to data acquisition systems located underground over copper or fiber-optic cables.

Software

Networking

Several different types of networking and operating system software were examined during system development. As the initial data acquisition systems were restricted to DOS, peer-to-peer networking to the data processing platforms was achieved using the NetBEUI protocol available in Workgroups Add-On for DOS. TCP/IP protocol is used to connect to Linux-based data acquisition PCs. The main processing PCs use either Windows95 or NT operating systems, allowing them to network to all of the data acquisition platforms tested.

Use of mining companies' general-purpose LANs for seismic data acquisition and processing has met with mixed success. If there is no one on site to tend to the monitoring system on a regular basis, a stand-alone, or isolated, LAN is preferred. This avoids problems associated with many diverse users, corporate firewalls, and other security issues. If the corporate system administrator is on-site and attuned to the needs of the seismic monitoring system, problems can be minimized. By isolating the data acquisition nodes onto a separate LAN, these problems can be largely limited to periodic temporary disruption of the automated data processing.

Data processing

A sentinel program watches for the creation of event-triggered and/or continuously recorded data files on the different data acquisition nodes (Figure 2). The program controls the flow of raw and processed data, waveform data file merging, and data processing across the network. Any source of seismic data can be utilized providing it resides on the LAN and can be converted to PC-SUDS format. Upon receipt of a file at a data processing node, a series of batch files is executed to carry out the data processing. Both the data acquisition and processing are controlled through user- settable parameters in ASCII text files. As shown in Figure 2, the initial batch file archives the raw data, decodes the time code and corrects the timebase, makes node-specific timing adjustments, then demultiplexes the data, and performs any other node-specific processing. The data are then brought into a buffer that holds time-stamped data from the other data acquisition nodes. Time-correlated data are then merged into a single SUDS files and sent on to further downstream processing. Typical downstream processing options are shown in the flowchart of Figure 2.

Several different event location methods, which allow some flexibility in dealing with different array installations, velocity structures, and processing requirements, have been used in the automated processing. These include direct, iterative (gradient), and simplex solution methods[8,9]. Event locations are continuously updated on a user-interactive graphical display and exported for additional downstream processing by other user groups. The modular nature of the PC-SUDS utilities and the flexibility inherent in batch processing gives significant user control over the data processing.

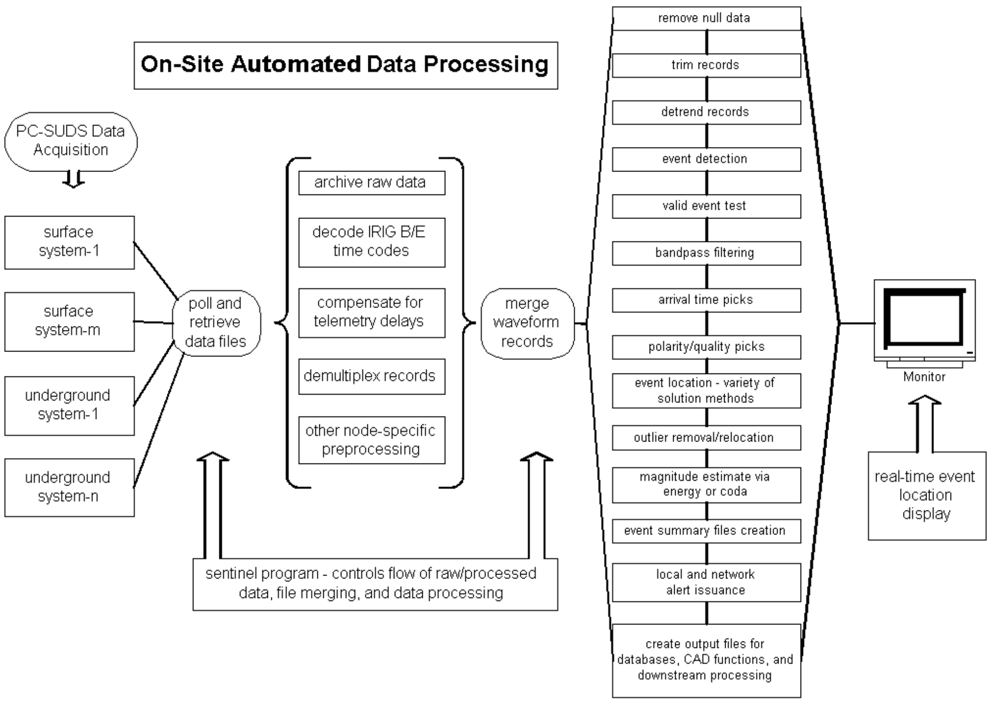

Figure 2. Flow of data acquisition and processing

Example installations

Galena Mine

A prototype of the automated monitoring system was advanced in a joint project with Silver Valley Resources, Inc., at the Galena Mine, Wallace, Idaho. As with most deep mines in the Coeur d'Alene district, rock bursting is prevalent in veins penetrating strong, brittle quartzites. Approximately 70 veins with as many as 25 working stopes are distributed over lateral and vertical distances of 2.5 and 0.8 km, respectively. The design goal was to provide processed seismic data anywhere on the LAN so that (1) supervisory and safety personnel could view seismic activity in the mine while they were still underground and (2) engineering and management personnel on the surface could use the data to facilitate both day-to-day operations and longer-term planning. While the initial design called for three separate data acquisition systems to be centered in three major, widely separated mining areas, the eventual configuration has one mine-wide array and one smaller array that is moved to cover active stope areas of current special interest. A fiber-optic network connects the two data acquisition nodes to each other and to the surface and underground data processing PCs (Figure 3). Processed seismic data are imported into the mine's graphics modeling software and a database program for automatic report generation.

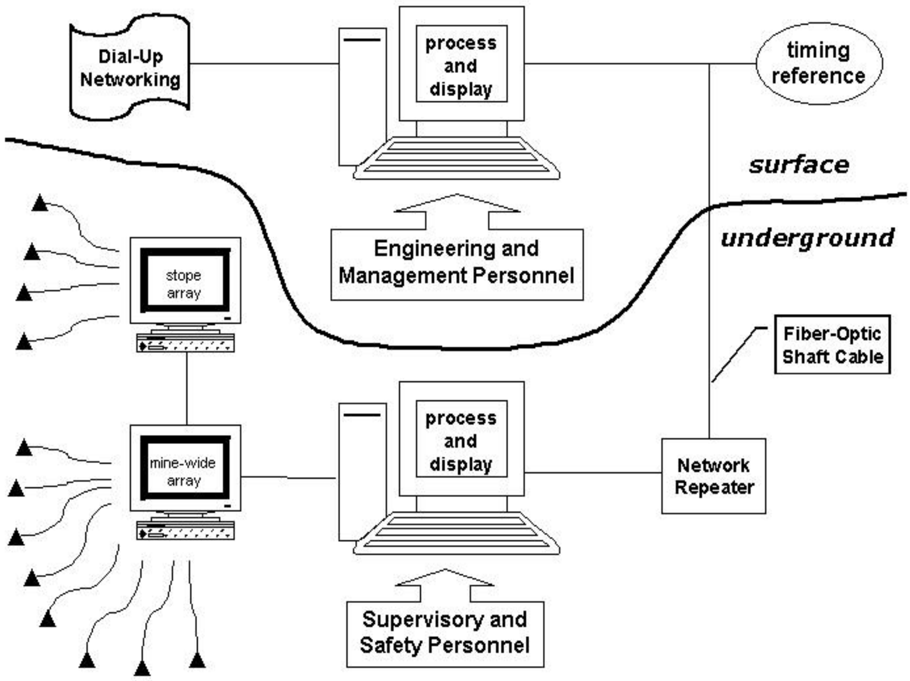

Figure 3. Galena Mine network

Willow Creek Mine

A combined surface and underground monitoring system is deployed at the

Willow Creek mine in Helper, Utah (Figure 4), in an investigation into the mechanics of coal bumps in multipanel longwall sequences[10]. At the level of the mining operation, 12 roof-mounted and two borehole geophones are deployed in the mains and bleeders around the first few panels of a longwall district. Signals are fed by cable to a data acquisition PC housed in an underground trailer. A network connection to the processing workstation in the engineering office is established via fiber-optic cable. Signals from nine surface stations above the longwall panels are sampled continuously with remote digitizers and transmitted to a data acquisition node on the LAN via three 900-MHz, spread-spectrum transceiver pairs. Data from several isolated surface stations are also occasionally merged with data from the main networks in post-collection processing and analysis. A second processing and display workstation is located in the shift bosses' meeting room.

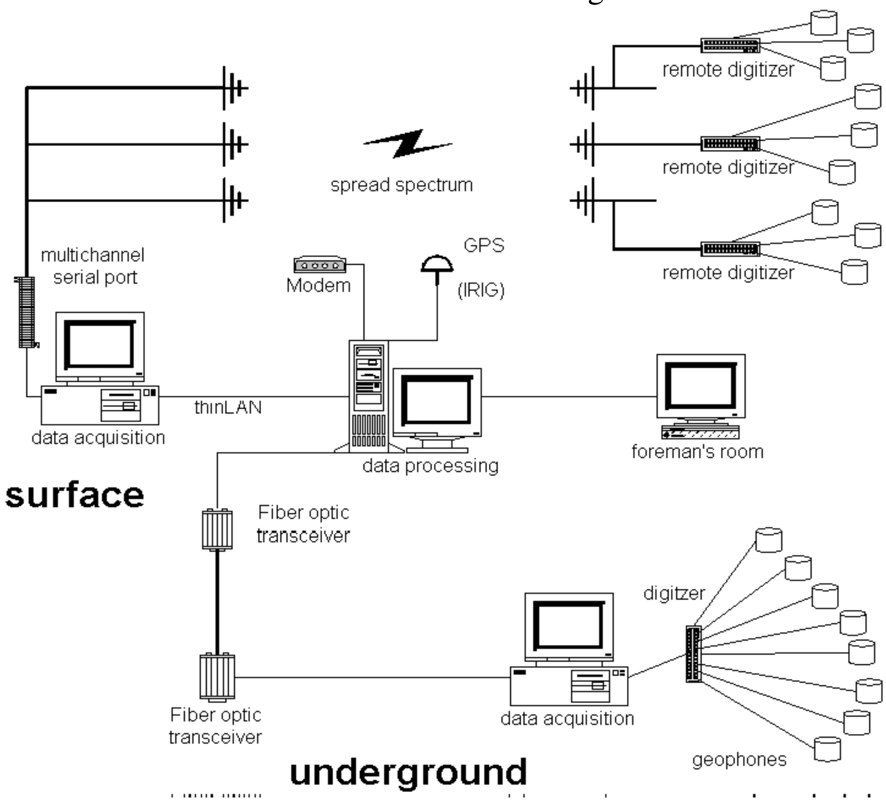

Figure 4. Willow Creek Mine network

Example results

Waveforms typical of those observed with this system in western U.S. longwall coal mines are shown in Figure 5. The large signal-to-noise ratio of the P-wave first arrivals and the overall event-to-event similarity in waveform character allow consistent accurate automatic picks.

Example event locations are shown in Figures 6 and 7. The processing procedures performed for each plot were completely software automated without any human interaction. Data in Figure 6 were acquired from a temporary network of geophones deployed on the surface above a longwall panel at the Foidel Creek Mine near Oak Creek, Colorado. The 600-m-diameter array was 365 m above the coal seam. No underground stations were used in this deployment. Data shown were collected in one 24-hour period as the 262-m-wide face advanced 34 m from right to left (Figure 6). The regularity in fracture and deformation processes associated with each cut of the longwall face is reflected in a similar regularity in the temporal and spatial patterns of seismicity. The cross-panel entries through this 5.5-km long panel had been filled with a lightweight foam cement prior to

Figure 5. Example waveforms from western U.S. longwall coal mine

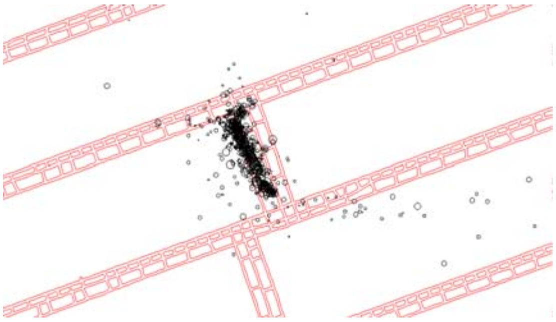

Figure 6. Seismic activity during 34-m longwall face advance at Foidel Creek Mine

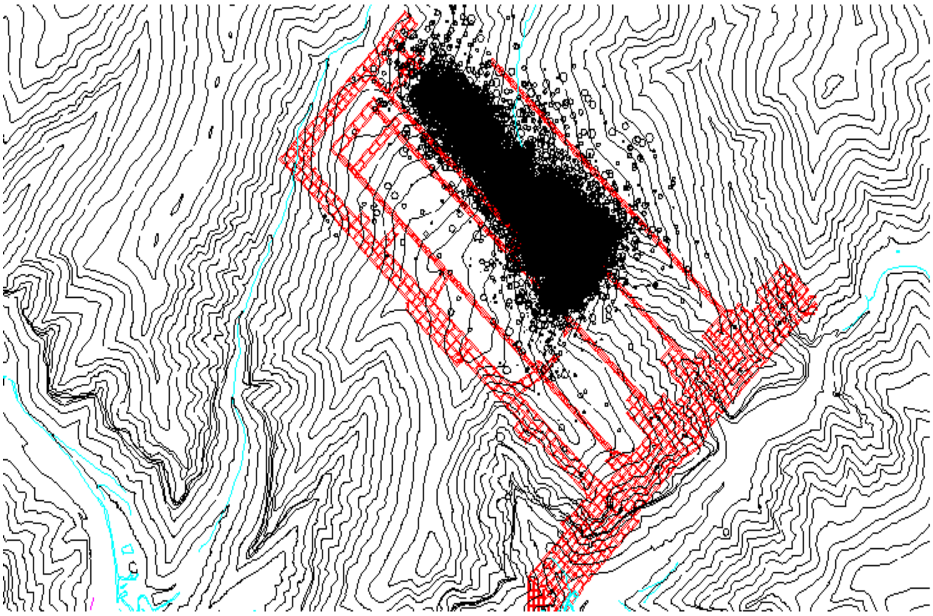

Figure 7. Seismicity observed during extraction of Willow Creek longwall panel

mining through them. Significant changes in the patterns of seismicity were not discernible as the face passed through the backfill, consistent with the uniformity observed in the rock mechanics data. As many as 2000 events per day were detected with this surface array, yielding a detection sensitivity similar to that observed with panel-wide underground networks. The automated processing procedures implemented in the field resulted in 500 to 1000 well-located events per day.

Seismicity associated with the extraction of a 1.2-km long portion of a longwall coal panel at the Willow Creek Mine is shown in Figure 7. Depth of cover over this panel exceeds 800 m and is highly variable because of the rugged canyon-mesa topography. Approximately 13,000 events were detected and located during 8 months of production. Average source to receiver distance is 1.1 km compared to 0.5 km for the data in Figure 6. Despite the larger array dimensions (2.2 by 0.8 km), it is still possible to infer a similar regularity in face deformation processes via the distribution of seismic events.

Summary

An automated PC-network-based seismic data acquisition and processing system has been developed by NIOSH for use in mine safety studies. Several systems have been constructed and deployed in the field for testing and application. Current installations utilize multiple autonomous seismic networks located both underground and on the surface. Event locations, magnitude estimates, and other processed data are distributed for display and analysis on network nodes both underground and in the offices of mine engineers and management. System flexibility is derived from the system's distributed nature, compatibility with multiple analog-to-digital converters and operating systems, and user control over the automated processing. These systems are now being applied in studies designed to reduce hazards associated with roof falls, rock bursts, coal bumps, and mine collapse.

Acknowledgements

This work would not have been possible without the assistance and cooperation of Silver Valley Resources, Twentymile Coal, and Plateau Mining companies. Specific individuals who were particularly generous with their time and assistance include Butch Sines, Rocky Thompson, Andy Schissler, and John Mercier. A number of software modules used in the development of this system were authored and/or modified by R. Banfill, F. Boler, D. Dodge, L. Estey, B. Kenner, and P. Santerre. Tim Geiger developed the remote digitizers. Carl Sunderman developed amplifiers and filter units used in some of the applications. NIOSH employees Brian Kenner, Todd Krahenbuhl, Keith Heasley, John Marshall, Craig Compton, John Ellenberger, and Paul Jeran made critical contributions in the deployment and application of the monitoring systems described herein.

References

1. Mendecki, A. Principles of monitoring seismic rockmass response to mining. *Rockbursts and Seismicity in Mines, Proceedings of the 4th International Symposium on Rockbursts and Seismicity in Mines.* Gibowicz, S.J., and Lasocki, S., eds. Kracow, Poland. Balkema, 1997, pp. 69-80.
2. Urbanic, T.I., Trifu, C.-I., Mercer, R.A., Feustel, A.J., and Alexander, J.A. . Automatic time-domain calculation of source parameters for the analysis of induced seismicity. *Bull. Seis. Soc. Am.*, vol. 86, 1996, pp. 1627-1633.
3. Lee, W.H.K., ed. IASPEI Software Library. Vol. 1: Toolbox of Seismic Data Acquisition, Processing and Analysis. 1989, 1994.
4. Jenkins, F.M., Williams, T.J., and Wideman, C.J. Analysis of four rockbursts in the Lucky Friday Mine, Mullan, Idaho, USA. *International Deep Mining Conference: Technical Challenges in Deep Level Mining*, ed. by Ross-Watt, D.A.J., and Robinson, P.D.K (eds.). Johannesburg, S. Africa. S. Afr. Inst. of Min. and Metall. 1990, pp. 1201-1212.
5. Ward, P. SUDS—Seismic Unified Data System. U.S. Geol. Surv. Open-File Report 89-1888. 1989, 123 pp.
6. Banfill, R. PC-SUDS Utilities. A collection of tools for routine processing of seismic data stored in the Seismic Unified Data System for DOS (PC-SUDS). Version 2.5. 1996.
7. Lee, W.H.K., and Steward, S.W. Principles and applications of microearthquake networks. *Advances in Geophysics*, supplement 2. Academic Press, New York. 1981, 293 pp.
8. Estey, L., Swanson, P., Boler, F., and Billington, S. Microseismic event locations: A test of faith. *Rock Mechanics Contributions and Challenges: Proceedings of the 31st U.S. Symposium.* Hustrulid, W.A., and Johnson, G.A. (eds.). Golden, CO. Balkema, 1990, pp. 939-946.
9. Dodge, D., and Sprenke, K. Improvements in mining-induced microseismic source locations at the Lucky Friday Mine using an automated whole waveform analysis system. *Pure Appl. Geophys.*, vol. 139, pp. 609-626.
10. Ellenberger, J., Heasley, K., Swanson, P., and Mercier, J. Three-dimensional microseismic monitoring of a Utah longwall. *Rock Mechanics in the National Interest. DC Rocks: Proceedings of the 38 th U.S. Rock Mechanics Symposium.* Balkema, 2001, in press.