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PANDA: A SIMPLE, PORTABLE SEISMIC ARRAY FOR LOCAL- TO REGIONAL-SCALE SEISMIC EXPERIMENTS

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Abstract

A portable array for numerical data acquisition (PANDA) was designed and built in-house at the Center for Earthquake Research and Information (CERI), Memphis State University. The design goal was a transportable set of instruments that could record high-quality seismic data. By making modifications to traditional seismic network technology and using a super-microcomputer workstation for digital data acquisition, this array provides a set of reliable and cost-effective instruments for the collection and analysis of high-resolution seismic data. The field equipment and central recording system are designed to overcome several major limitations in existing seismic network technologies, such as low dynamic range, single-component recording, lack of a common time base between stations, topographic constraints in radio telemetry, and lack of field processing capabilities. PANDA overcomes these limitations. To increase the dynamic range and record full three-component data, each PANDA station has six channels divided into two three-component sets. One set is operated at high gain and the other at low gain, giving a minimum of 90 dB dynamic range. Modular design of the PANDA station electronics facilitates field maintenance and also permits the stations to be run in several additional modes (e.g., with both sets of three channels operating at high gain) or with different sensors on each set. Each telemetry link to the central recording site carries data from two stations (12 channels) by repeating data from an "outer" seismic station through an "inner" seismic station and repeater combination. In addition, several repeat-only stations were built. This ability to repeat signals increases the aperture of PANDA to more than 150 km and overcomes topographic limitations on station locations. Other design features include low power consumption, solar power operation, and transmission of daily calibration and diagnostic signals. These features enable the stations to operate unattended for long periods and provide verification of station performance from the central recording site. The central recording system is based on a high-performance super-microcomputer workstation with a 256 channel A/D front end, which allows both real time digital recording with a common time base and immediate processing of the data. A 40-station network with 6 channels per station uses 240 channels, leaving 16 channels for auxiliary inputs such as time codes and spares. PANDA was field tested in the Arkansas earthquake swarm region from October 1986 to April 1987. It was then deployed in San Juan, Argentina, from August 1987 to May 1988, and in Jujuy, Argentina, from September 1988 to May 1989. A total of more than 20,000 earthquakes were recorded during the two Argentina experiments.

Introduction

In the attempt to explore the internal structures of the Earth in greater detail, seismologists face two major obstacles in the collection and analysis of seismic data. The first problem is lack of high-resolution data: There is a severe shortage of high-quality, natural source seismic data necessary for high-resolution seismic studies. The second problem is an overabundance of low-resolution data: Seismologists are presently buried by the vast amounts of difficult-to-process, low-resolution data that currently exist. The two problems are also interrelated: An attempt to solve the first problem by collecting more data by traditional methods will not solve the first problem and will worsen the second. Coupled with the requirement for large amounts of new higher-quality data, therefore, is the requirement for automatic processing and advanced data base management techniques to analyze these data. These problems are generally recognized in the seismological community and several projects such as the Portable Array for Numerical Data Acquisition (PANDA) project at Center for Earthquake Research and Information (CERI) and the Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) (IRIS, 1984) under the Incorporation of Research Institutes in Seismology (IRIS) (Smith, 1987) are underway to address them. Other developments such as the SNARE system (Gledhill and Randall, 1986), a small 16-channel data acquisition system, was implemented by the Department of Scientific and Industrial Research of New Zealand to automatically detect and record 16 channels of network data around Wellington, New Zealand. A PC-based broadband digital seismic network with four broadband stations was designed and installed in central California (Bolt *et al.*, 1988). At CERI, PANDA was designed and built in-house to provide an efficient and reliable tool to achieve both spatial resolution and spatial coverage for medium-term (1- to 2-year) high-resolution portable array studies and also for short-term rapid deployment aftershock surveys.

The main difficulties encountered with most of the data acquisition systems presently available for seismologic field work include but are not limited to: (1) lack of three-component data; (2) lack of dynamic range; (3) data retrieval that is not in real time and is time-consuming, requiring many trips to each recording site; (4) clock drift in individual recorders; (5) limited on-site storage capacity resulting in loss of data; (6) recording media and data formats that are difficult to work with; (7) poor reliability due to failure of mechanical systems under adverse environmental field conditions; and (8) no system redundancy.

The PANDA network overcomes these deficiencies by combining available technology for field sensors, electronics, and telemetry with recently available high-performance super-microcomputer workstation technology. The design criteria include: (1) three-component digital recording with at least 90 dB of dynamic range; (2) telemetry (to avoid the expense and inconvenience of retrieving data from widely separated field sites); (3) real-time digital recording at a central location with a common time base; (4) ruggedness and durability (must be able to function reliably in extreme environments without the need for additional shelter for extended periods); (5) system redundancy to achieve greater reliability; (6) portability (capable of being transported to a remote site by two people); (7) simple installation and maintenance procedures; (8) automatic diagnostics to verify system performance; (9) low power consumption to minimize battery requirements and facilitate solar operation; (10) frequency response from 0.1 to 40 Hz to record local, regional, and teleseismic events; (11) ability to do sophisticated data processing with full graphics capabilities in the field; and (12) upgrade capability to take advantage of future technological developments. All the design goals were achieved, except for obtaining good teleseismic response mainly because of limited funds available in seismometer purchasing.

The development of PANDA began in the spring of 1985. By late fall, the specifications were defined and it was clear that funding could be obtained to build the system. The engineering phase, which consisted of adapting, modernizing, and repackaging previously designed and field-tested hardware from CERI's permanent networks, began in January 1986 and was essentially completed by mid-February. The construction was accomplished in-house during May to July 1986. Initial testing and calibration of system components was performed during August and September 1986. Field testing began in October 1986 with the installation of PANDA in the Arkansas earthquake swarm area near Enola, Arkansas. By the end of January 1987, all major problems with the field equipment and telemetry system had been solved and field testing was completed. The equipment remained in Enola until mid-April 1987 for a period of software development and operated without serious problems. PANDA was removed from Enola in late April, refurbished, and shipped to San Juan, Argentina, in late June 1987. The San Juan deployment and later Jujuy deployment in Argentina were cooperative projects between CERI at Memphis State University, Cornell University, the Institut Francais de Recherche Scientifique pour le Development en Cooperation (ORSTOM), the Argentine Instituto Nacional de Prevención Sísmica (INPRES), and the Nacional Universidad de Jujuy. During the San Juan and Jujuy experiments, PANDA performed successfully in harsh environmental conditions and recorded more than 20,000 earthquakes. Currently, the array is deployed in the central segment of the New Madrid seismic zone and is expected to complete the field experiment in late December 1990. In less than 2 years, therefore, PANDA was developed from the conceptual stage to a fully functioning system, and its excellent performance in the field has demonstrated that the design of PANDA has made a major stride toward solving the problems of high-resolution digital seismology in a cost-effective manner.

CONFIGURATION OF THE PANDA ARRAY

The PANDA network consists of 40 three-component stations that telemeter seismic data to a central recording site via FM radio links (Figs. 1 and 2). The network topology consists of 20 "outer-ring" stations and 20 "inner-ring" stations, where each inner-ring station serves as a repeater for 1 outer-ring station (Fig. 3). Seismic signals from each "outer-ring" station can also be transmitted directly to the center recording site. Five additional repeaters are also available for use at any point in the array to overcome otherwise insurmountable topographic limitations.

Each station consists of two three-component sensors, a solar panel, an antenna, and a watertight fiberglass field box containing the radios, a maintenance-free recombinant technology lead acid battery, and a small metal box for the station electronics (Figs. 4 and 5). Repeat stations have an additional receiver and antenna. Each station weights approximately 125 pounds and can be transported to a remote site by two people.

The sensor used in PANDA consists of 80 sets of three Mark Products L-28B 4.5 Hz geophones (one vertical and two horizontal) mounted in a TDC-2 field case. In addition, 10 three-component Kinemetrics FBAs, similar to USGS's General Earthquake-Observation System (GEOS) instrument (Borcherdt *et al.*,

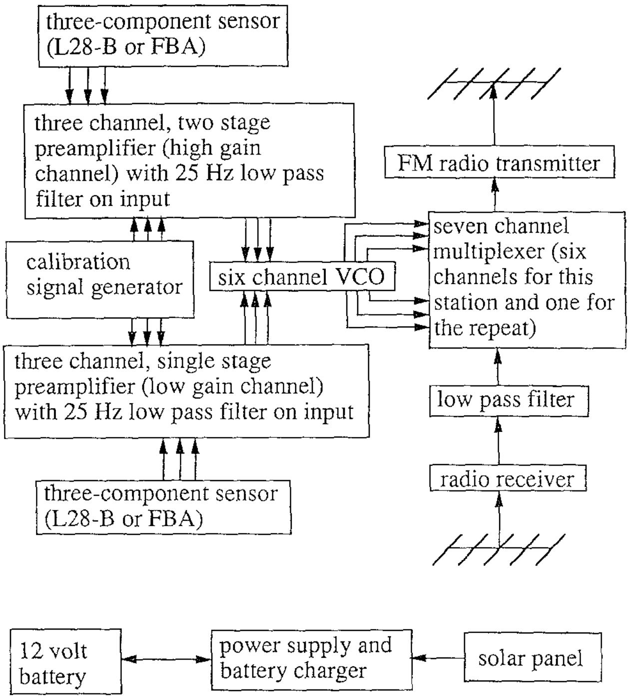


FIG. 1. Block diagram of a PANDA field station. The components illustrated in the dashed box are installed at inner stations only and are for repeating the outer stations signal.

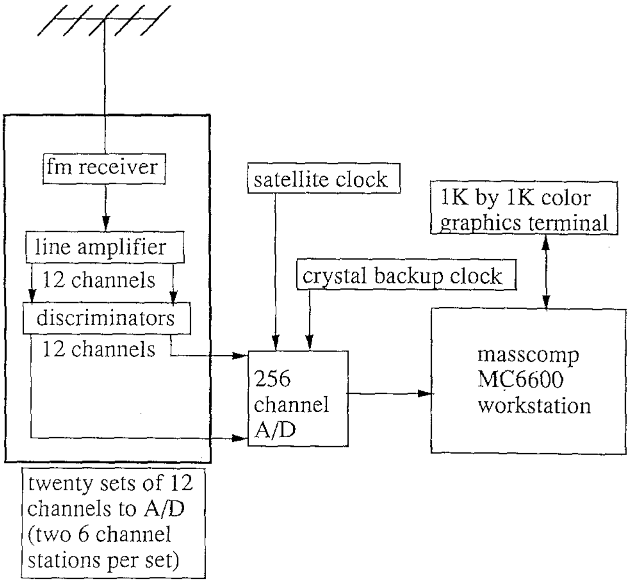


FIG. 2. Block diagram of the central receiver. Only one inner/outer station channel and associated electronics is shown.

1985; Dietel and Borcherdt, 1987), with a full-scale capability of ±2 g, are also available for the low-gain channels of 10 selected stations to guarantee on-scale recordings in the event of large major earthquakes.

Signal conditioning at each station includes amplification, filtering, and conversion to audio FM by a voltage controlled oscillator (VCO) for each

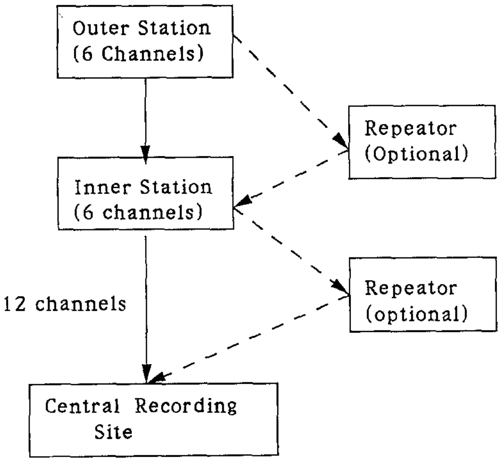


FIG. 3. The standard network topology of inner- and outer-ring stations. Repeat-only stations can be installed anywhere between the outer and inner stations or between the inner station and the central recording site. Multiple repeat is also possible with minor electronics modifications. The ability to repeat signals greatly increases the flexibility of the PANDA network.

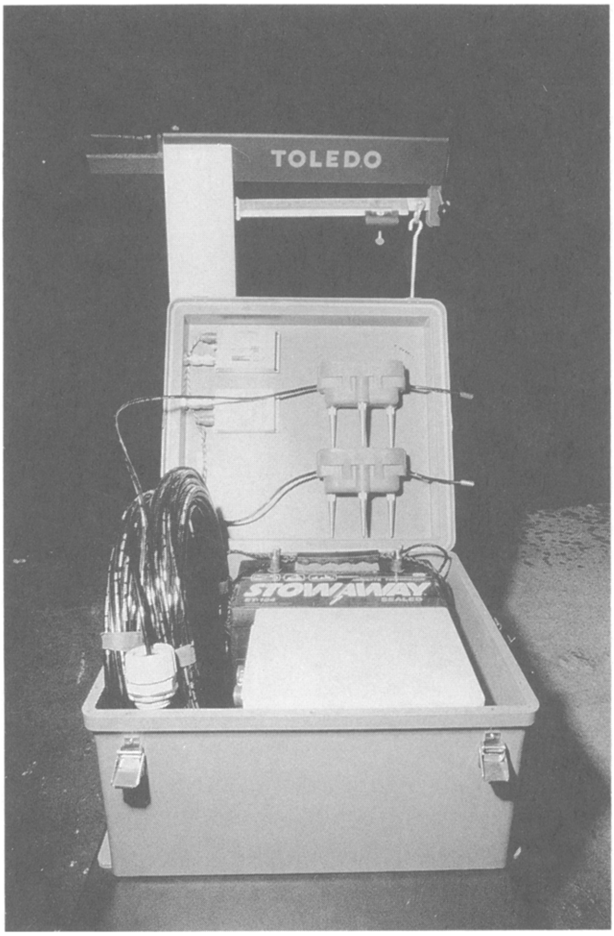


FIG. 4. Waterproof fiberglass field box and two TDC-2 field cases, each with one three-component set of L-28B geophones. Station electronics are contained in the front right metal box. The transmitter and receiver are mounted to the lid of the box.

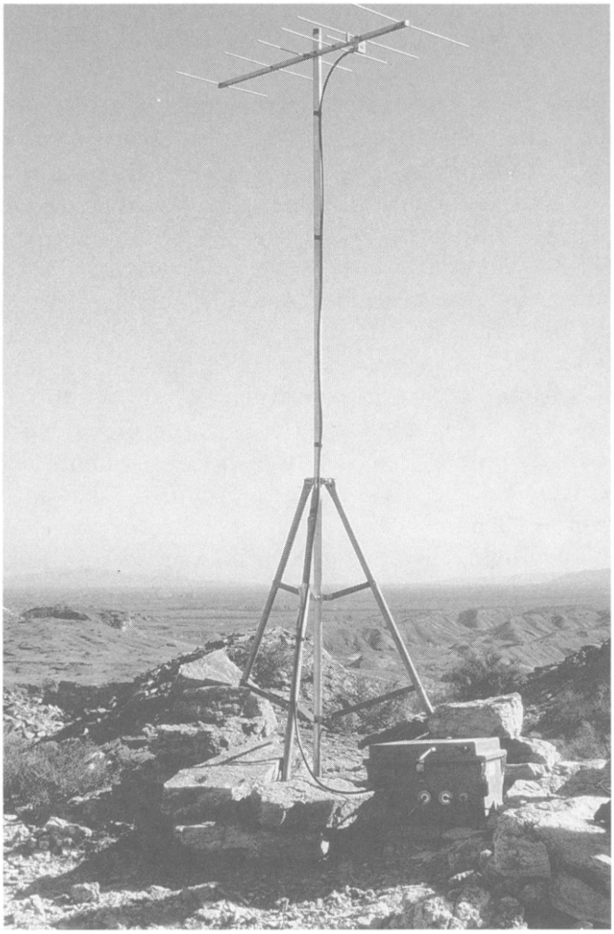


FIG. 5. A PANDA station installed in San Juan (solar panel is not included).

channel. Each preamplifier board contains two independent channels, a two-stage high-gain and a single-stage low-gain preamplifier. The gains may be set in the field and a dynamic range of 90 dB is obtained by setting the high- and low-gain channels to operate with 18 dB of overlap. In addition, a number of preamplifier boards were constructed with the two-stage high-gain preamplifier for both channels. These boards enable an individual site to act as two three-component high-gain stations for small-aperture seismic array experiments. The preamplifier boards also have four-pole Butterworth low-pass filters on their inputs, with a cut-off frequency set by a DIP package plug-in module to 25 Hz. Two single-pole high-pass filters at 0.033 Hz in the preamplifier are used to remove DC offsets.

After amplification, each of the six channels is converted to an audio FM signal by a VCO. The VCO boards are also dual channel, similar to the preamplifier boards, with each board containing a "matched" set of two carrier frequencies. The VCO carriers are spaced at 400 Hz intervals, starting at 800 Hz, with a full scale deviation of ±150 Hz. This allows each radio link to carry 12 channels (6 from the inner-ring station and 6 from the repeated outer-ring station) in a total bandwidth of 650 to 5350 Hz. The VCOs use a phase-locked loop with a crystal reference oscillator to maintain center frequency. This technique limits center frequency drift to less than 0.1 Hz over a temperature range of −20°C to +50°C.

The outputs of the VCOs are then multiplexed to form the signal transmitted from each station. The inner-ring stations also receive the signal from the outer-ring station and multiplex this signal with their own output signals. To minimize the noise and distortion introduced by repeating the signals from the outer-ring stations, the outer-ring VCO carriers occupy the lowest six carrier frequency values. An automatic sine wave calibration signal can be used to verify the frequency response of each channel of station electronics, and along with station identification code and diagnostic information is sent on a 12- or 24-hour basis. Therefore it is easy to verify the performance of individual telemetry channels from the central recording site.

Station locations are determined with a portable global positioning system (GPS) receiver, which enables PANDA to operate in remote areas where good maps are not available. The GPS system provides latitude, longitude, and elevation to within ±10 m. For the small aperture arrays (several meters to kilometer station spacings), the station locations are determined by surveying.

The central recording facility consists of a receiving tower with the antennas and receivers, line amplifiers and discriminator racks, the computer data acquisition hardware, and an uninterruptible power supply capable of powering the full system for up to 30 minutes. The audio outputs of the receivers go to line amplifiers that adjust the carrier amplitudes sent to the discriminators. The line amplifiers also protect the computer and discriminators from lightning and other transients. The output of each of the 20-line amplifier channels is also available from a test jack for diagnostic purposes. The discriminators (switch selectable to AC or DC coupling) demultiplex the signal by means of a bandpass filter and perform the frequency to voltage conversion. This signal is passed to a five-pole Butterworth low-pass filter set by a plug-in package to 25 Hz. This filter, together with the four-pole filter in the preamplifier, forms the antialias filter for the A/D converter.

The discriminator outputs (240 channels) and timing signals from satellite or from other reference clocks are then sent to a 256-channel, 12-bit A/D converter. The sampling is controlled by two clocks: a frame clock that controls the sampling rate and a burst clock that does the actual sampling. On each pulse from the frame clock, the burst clock is used to sequentially sample the 256 channels of the A/D. The frame clock rate is set to 100 samples per second and the burst clock rate is set to 50 KHz (Fig. 6), resulting in almost synchronized sampling for the 256 channels. A higher sampling rate can be achieved for fewer channels by adjusting the frame clock rate.

ON-LINE DIGITAL RECORDING SYSTEM

Previous experience with the collection and processing of digital seismic data helped us to define several goals for the capabilities of the data logging and field processing system. First, given the size of the network and the frequency response desired, the system requires the capability to function as a programmable data logger at a data rate in excess of 50 kilobytes/sec on a continuous basis. A second requirement is the ability to do sophisticated field analysis, including high-resolution graphics, without impacting the collection of data. These conditions can best be met by the use of a micro- or minicomputer

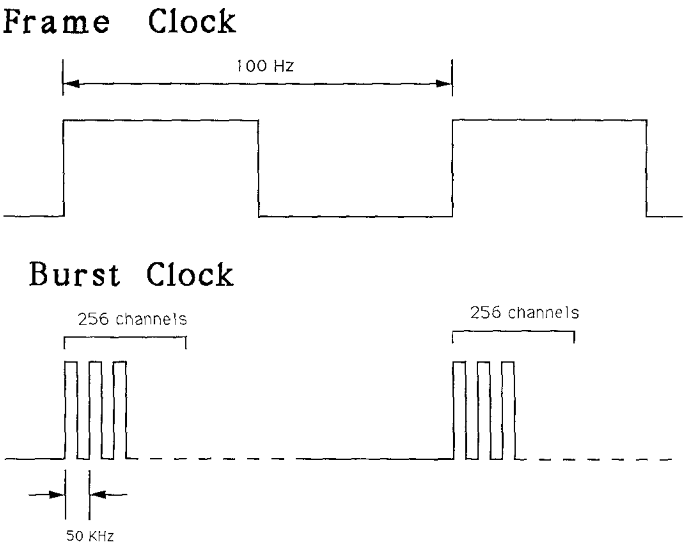


FIG. 6. Timing diagrams for frame and burst clocks used to control the sampling of the seismic data. At each pulse of the frame clock (100 Hz), the burst clock will sample sequentially the 256 input channels at a higher rate (50 KHz).

with a multitasking, multiuser, real-time operating system, a high-speed and high-resolution graphics processor, and an intelligent A/D front end. At the time of development, these requirements ruled out the use of the IBM PC and IBM compatible because of hardware and software inadequacies. Moving up the performance ladder into the workstation or super-mini category gives a large selection of hardware and software capable of meeting these requirements. The existence of real-time versions of the UNIX operating system provides computer systems that meet the requirements and are also compatible with the nationwide base of UNIX machines among the seismological community. The field computer consists of a 32-bit, Motorola 68030 based, MASSCOMP 6600 running MASSCOMP's Real Time Unix (RTU) operating system. In RTU, the method of setting priorities under UNIX is extended to provide real-time priority; i.e., system response to interrupts is guaranteed to be immediate and an unlimited use of system resources is granted. The system has 16 MB of memory, a high-speed color graphics processor with a high-resolution (~ 1 k by 1 k) color monitor, a floating point accelerator, a vector accelerator, two hard disks (320 and 450 MB), a 6250/1600 bpi tape drive, and a MASSCOMP 256 channel A/D and clock subsystem.

Software development started during the Arkansas deployment and continued throughout the San Juan experiment. The software consists of four parts: an event-triggered digital data acquisition program with interactive control, an automatic demultiplexing program running in the background, a set of field analysis programs, and a data archiving program. The data acquisition program contains three basic parts: the A/D interrupt routine, a command line interpreter to permit real-time interactive control of the data collection, and a real-time digital oscilloscope routine. The seismic data are sampled by the A/D and passed to the program in buffers through an interrupt generated by the A/D. The triggering and event detection are then performed by the interrupt routine. The method of short- and long-term average ratios is used to detect triggers. Coincidence conditions between triggers are then used to determine if an event has occurred. Up to five different sets of trigger conditions can be defined and each set can be applied to up to 40 input channels. The channels in each trigger set can also be broken into a maximum of five coincidence groups, each group having its own set of coincidence requirements for detection of an event. When an event is detected, the multiplexed data from all 256 channels, including a pre-event and post-event period, are stored to disk in a file containing 1 minute of data. By fixing the file length it is possible to write the file to a contiguous area of the disk, which makes the transfer rate significantly faster. By making the length 1 minute, it is always possible to decode the IRIG H time codes generated from a satellite clock or a backup clock. If the trigger conditions for an event are still met at the end of 1 minute of recording, additional files of 1-minute length are written until the trigger conditions for event detection are not met.

To maintain real-time interactive response and avoid impacting other users, an interrupt-driven command line interpreter was implemented, using interrupts from the keyboard. The command line interpreter allows practically all parameters controlling the data collection to be modified on-the-fly from within the data acquisition program without interrupting the collection of data. The few parameters that cannot be directly modified from within the program, such as the trigger and coincidence definitions, can be modified without stopping the data collection by editing the respective data definition files and doing a "soft reset" of the data acquisition program. The soft reset reloads the network configuration and trigger definition files without affecting the data collection process.

The final part of the acquisition program is a digital oscilloscope routine that permits real-time viewing of the input data of any channel. The digital oscilloscope is controlled from the command line processor and has variable time base, vertical gain, and a storage scope mode. The ability to see the digital data in real time and at high resolution, especially when combined with voice communication to the field crew, proved to be highly useful for verifying system performance and diagnosing problems in the field in a timely and cost-efficient manner. Currently, three-component data from any station can be viewed in real-time.

After automatic demultiplexing in the background, the data are examined using an interactive graphics program. Under normal conditions during the San Juan experiment, the false alarm rate was under 5 per cent, but it could get as high as 50 per cent during thunderstorms or zondas (regional term for chinook-like winds). During the examination phase, events are classified and graded on quality, the false alarms are removed, and the data are checked for problems concerning the field stations and telemetry. Finally, the data are archived onto magnetic tape.

The archiving program has two modes, manual and automatic. The ideal case is to examine all the data and then archive it. It was not always possible, however, so the program automatically archives the data to tape when the disk is greater than 85 per cent full. With the network fully installed (40 stations) and using a 100 Hz sampling rate, a 12-inch, 6250 bpi, 9-track tape can record approximately 50 minutes of data, and the large hard disk (450 MB) can hold about 120 minutes of data. The typical event rate in the San Juan area filled the disk in about 16 hours, leaving a long period for field analysis before the data had to be archived and erased from disk. During times when the recording center is unattended, a new tape is kept mounted to allow the system to automatically archive the data into the tape if the disk gets near full. During times of very high activity, such as a swarm or aftershock sequence, the system is capable of performing the complete sequence, from data collection to archiving, continuously and automatically, except that new tapes must be mounted approximately once an hour. In addition, during continuous data collection, there is sufficient time and computation power to allow limited field analysis, the limiting factor being the approximately 2-hour residence time of a file on disk. In the worst scenario for beginning a period of continuous recording, 1 hour is available for an operator to arrive and begin mounting tapes. The programs were also developed into a turnkey system, which was successfully run in San Juan and Jujuy by students and technical assistants with no previous computer experience. The software is continuously being developed to include a supervised automatic location capability and features such as filtering and power spectral analysis.

DISCUSSION

The PANDA array has proven to be a reliable and powerful system for collecting large quantities of high-quality digital seismic data. In addition, with its modular construction, PANDA can be upgraded as new technology and funding become available. Digital telemetry and broadband sensors, which are currently too expensive, are two priority areas for future development. The short-period seismometers (4.5 Hz) presently used are portable, inexpensive, very rugged, and well calibrated but are limited in both dynamic range (~ 96 dB) and teleseismic response. The dual gain system of PANDA achieves a minimum dynamic range of ~ 90 dB, which is comparable to that of the seismometer. The present system is therefore best suited for local and regional seismic studies. Figure 7 shows examples of seismograms recorded by PANDA (in the San Juan experiment) during an $M_s = 5.3$ earthquake at a 25 km depth that occurred within the network. The high-gain channels were clipped by this event while the low-gain channels were not.

Amplitude and phase response curves of the PANDA system are shown in Figures 8a and b. The very steep roll-off in sensitivity at low frequencies indicates that the teleseismic response of the system is poor. As a first step to increase the low-frequency sensitivity, a single-pole, 1 Hz, low-pass filter was added to the standard PANDA electronics. This modified preamplifier was installed for testing at the Shelby Forest, Tennessee (SFTN), station of CERI's Memphis area regional seismic network (MARSN). This modification broadens the narrow peak of the unmodified system response, enhancing the relative response to lower frequencies (< 1 Hz) and reducing two orders of system sensitivity especially in high frequencies as shown in Figure 8c. Examples of a teleseism and a local event recorded by MARSN are shown in Figures 9 and 10. These examples demonstrate that the modified PANDA system, installed at SFTN with a 4.5 Hz geophone, can record both teleseismic and local events as well as other MARSN stations that use the S13 1 Hz seismometer. This modification to the preamplifiers is now being installed and tested in the PANDA field stations.

While the installation of a telemetered network may take longer and be more difficult than a traditional network of independent recorders, it offers

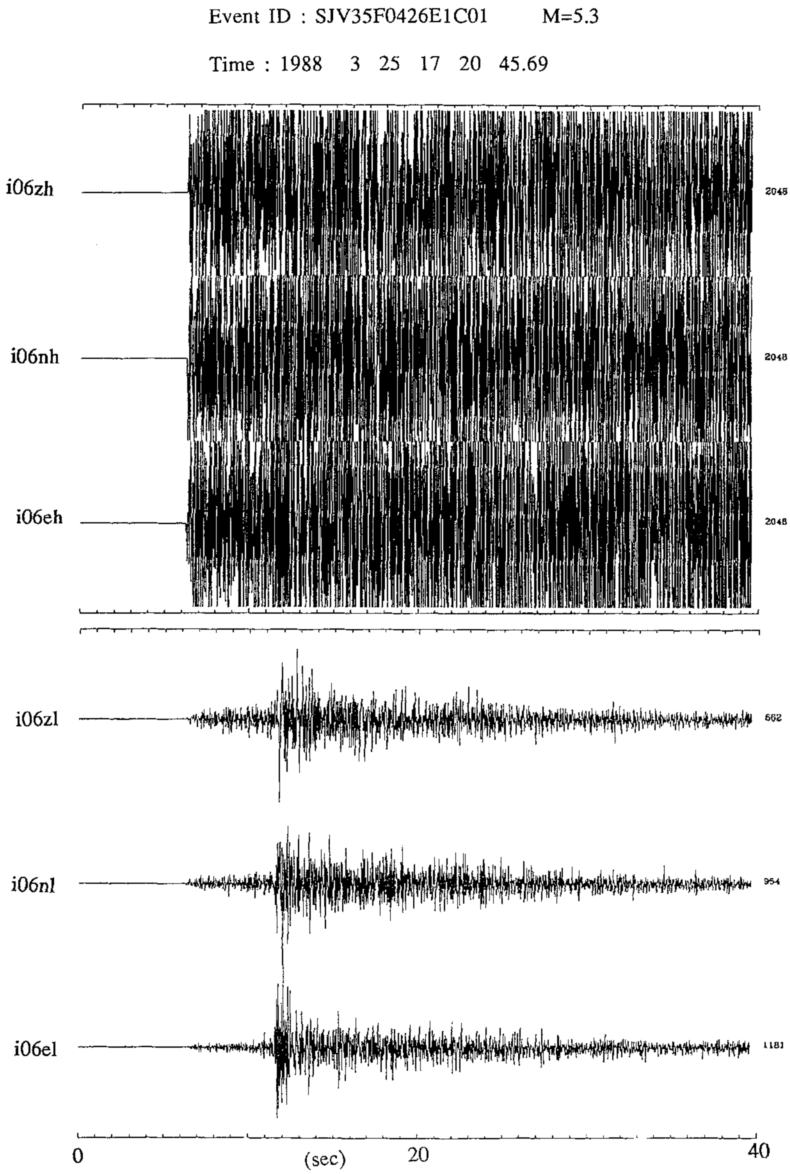
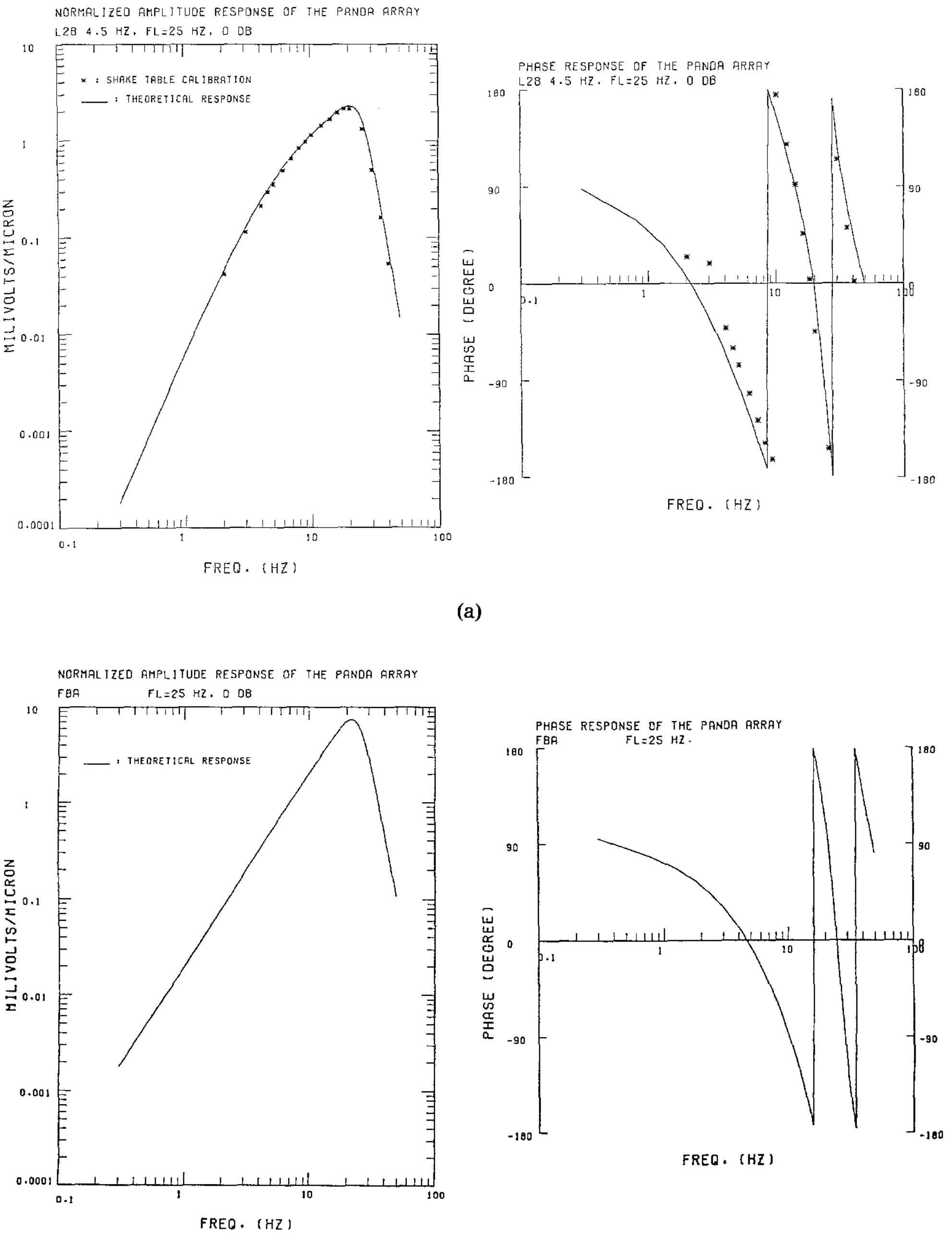


FIG. 7. Examples of three-component seismograms recorded by two randomly selected PANDA stations for an $M_s = 5.3$ event occurring within the network. Station code is shown in the left above each trace. The first one character in the station code represents either an inner station (i) or an outer station (o). The following two characters number the stations from 1 to 20. The fourth character shows the component for vertical (z), north-south (n), and for east-west (e). The last character represents either a high-gain channel (h) or a low-gain channel (l). Maximum amplitude of each trace is shown in volt at the end above each trace. The high-gain channels are completely clipped, while the low-gain channels have recorded the event without clipping.

advantages well worth the time and effort. The PANDA San Juan experiment clearly demonstrates the advantages of a telemetry system. On the average in San Juan, 150 minutes of data (over 100 earthquakes) were recorded per day during the 9-month deployment period. On the average day, therefore, more than 10 megabytes of data (150 events, 60 seconds per event, 100 samples per second, 6 components, 2 bytes each sample) were recorded from each station. It was impossible in San Juan to visit the stations to retrieve data, even on a weekly or biweekly basis. A round-trip to many of the stations required a full day and several stations required 2 days, not because of the distances involved, but rather because of the difficulty of traveling in the remote mountain and



(a)

(b)

FIG. 8. (a) Amplitude and phase responses of the PANDA network using Mark Product L28-B 4.5 Hz geophones. Shake table calibration data are also shown. (b) Amplitude and phase responses of the PANDA network using Kinemetric FBA. (c) Amplitude and phase responses of a test station (SFTN) using L28-B 4.5 Hz geophone with the modified PANDA electronics containing the additional 1 Hz low-pass filter.

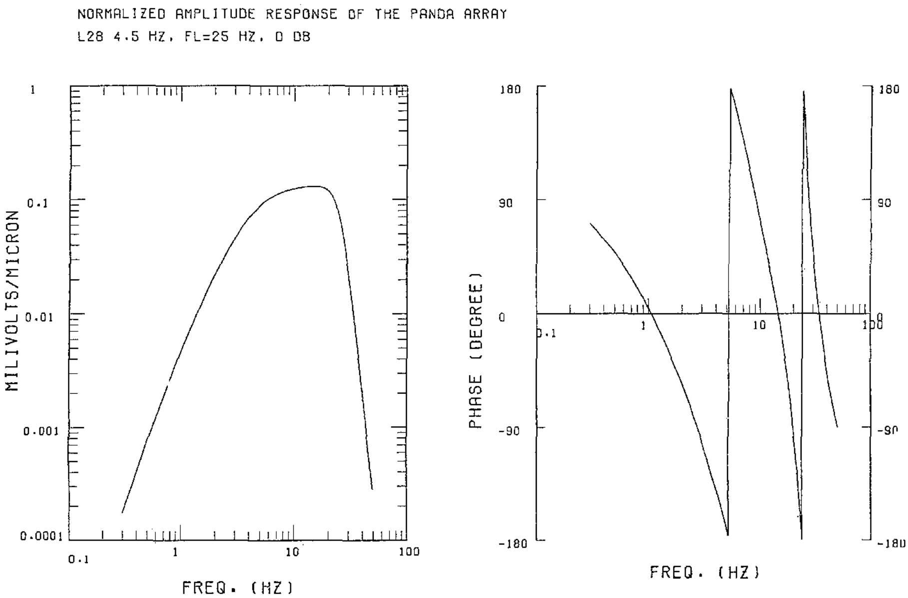


FIG. 8. (*Continued*)

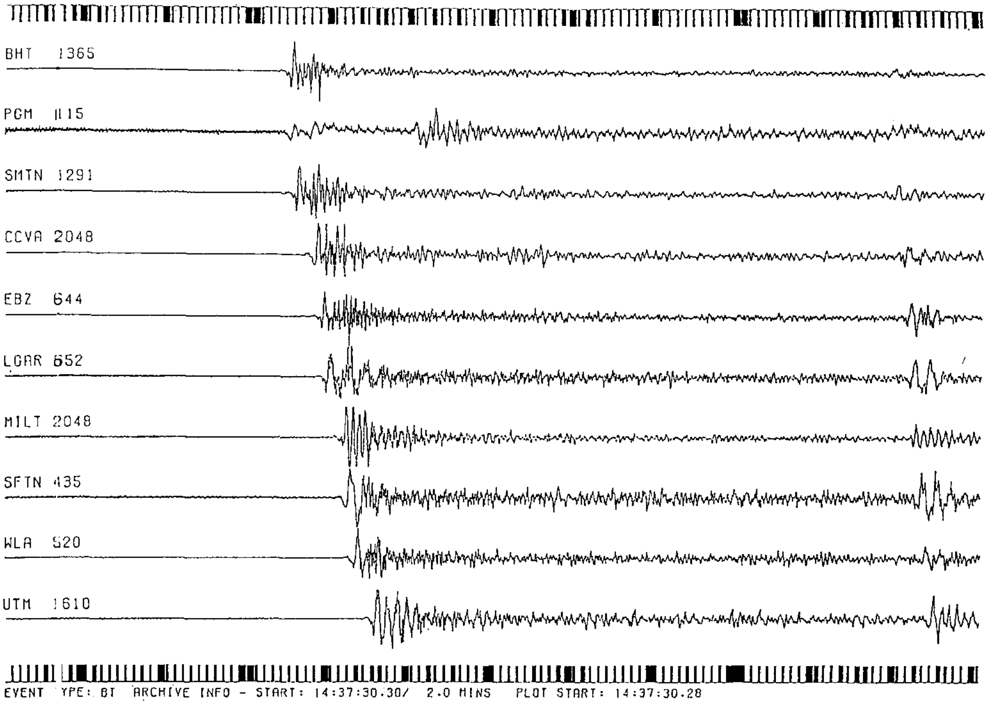


FIG. 9. A teleseism recorded by the Memphis Area Regional Seismic Network (MARSN). Station name and maximum amplitude (in digital counts) for each trace are shown in the left above each trace. Some preliminary phase pickings are also shown with vertical bars along with readings. All the stations shown, except SFTN, have 1 Hz (Kinematrics S-13) seismometers. SFTN is equipped with the PANDA electronics and the L28B 4.5-Hz seismometer, with the addition of 1-Hz low-pass filter. The high-frequency background noise as shown in Figure 10, typical of stations in the Mississippi embayment, has been removed by the application of a lowpass filter.

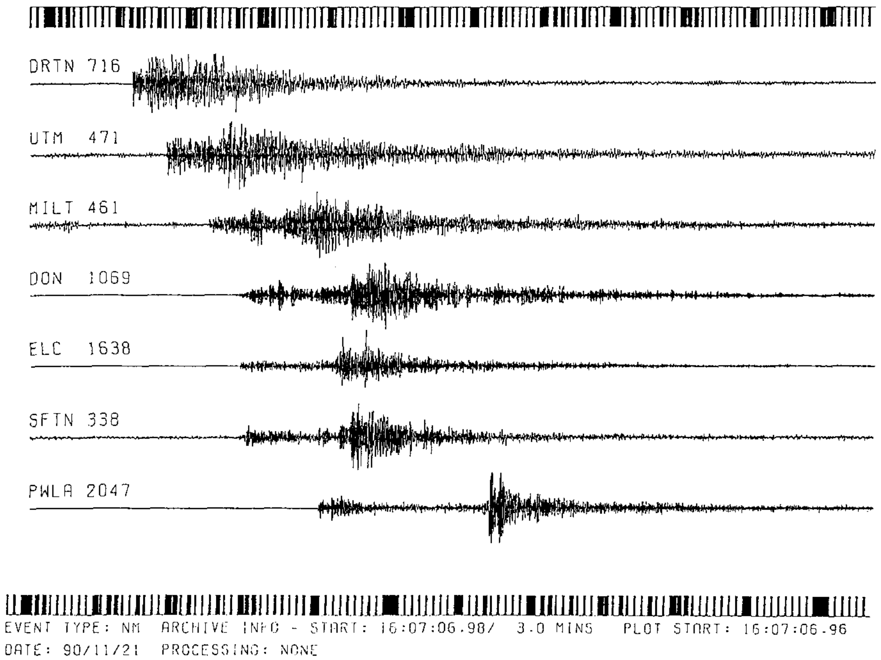


FIG. 10. A local New Madrid earthquake recorded by MARSN. Format is the same as shown in Figure 9. Again, all the stations shown, except SFTN, have 1 Hz (S-13) seismometers.

desert areas of San Juan. A centralized telemetry system is therefore ideal for medium-term (1- to 2-year or longer) seismic network and array experiments in a seismically active but remote area such as San Juan.

With the high data collection rates encountered in San Juan, data storage and data management become very critical. Traditional methods for data storage and data analysis cannot handle such vast amounts of data. Large-capacity storage media, high-resolution and high-speed graphics capability, and automatic preliminary processing become major concerns. When the original data tapes are received at CERI from the field site, a tape system using helical-scan VHS technology is used for both archiving and further processing. With this system, a normal VHS tape can store up to 2.5 gigabytes of data. Several other alternatives are under investigation including an EXBYTE 8-mm tape system and a high capacity rewritable optical disc system.

The basic strategy now used for PANDA deployment calls for installation of a 20- to 25-station network of 150- to 300-km aperture, with the remaining stations used to make several small aperture three-component arrays within the network. The array stations contain the dual high-gain preamplifiers, which doubles the number of sensors in the arrays. As the vast majority of events are not recorded on the low-gain channel, the dual high-gain stations are a compromise to increase the amount of array data at the expense of losing the largest events on the arrays. The station spacings vary from 10 to 50 km for the network stations and a few meters to a few kilometers for the array stations. The flexible station spacings permitted by the telemetry system facilitates optimum spatial coverage of the study region. The small aperture arrays can be moved within the network to provide high-resolution data for correlation, stacking, and filtering analyses. The spatial coverage of the network provides very accurate earthquake locations that establish a "controlled source" environment for the arrays and studies of seismicity, wave attenuation, scattering, source mechanism, structures, and tectonics.

The ongoing and future instrumental development of PANDA will focus on (1) a front-end gain ranging system to replace the high-gain and low-gain setup to improve the system dynamic range to at least 120 dB and to provide the capabilities to upgrade PANDA to a 60-station network, (2) a more flexible telemetry system to allow multiple repeating capabilities of seismic signals from one station via other stations, and (3) a lower-frequency response system by adding a low-pass filter or purchasing three-component 1 Hz, or 2 Hz, or broadband seismometers. A prototype system that includes the mentioned (1) through (3) will be field tested in the New Madrid seismic zone in the late fall of 1990.

In summary, PANDA is a versatile system designed for local- to regional-scale portable seismic network and array studies. Although not "fancy," the PANDA is reliable, produces high-quality digital seismic data in remote areas with extreme environmental conditions, and is affordable at about $2500 for the entire configurations of a single PANDA station. Because PANDA was designed and built in-house, it has a 100 per cent self-maintenance capability and significantly reduces maintenance costs. The design is so flexible that it can be easily upgraded as soon as new technology becomes available. Therefore, PANDA provides an ideal set of seismic instruments designed to achieve both dynamic range and data completeness to overcome the inherent limitations of a traditional seismic network and portable seismic recorders.

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