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A Computer-Automated Laboratory System in a University Environment

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***Abstract*—A computer-automated laboratory system at the University of Missouri-Rolla, Rolla, which serves a wide variety of instruction and research disciplines including Geophysics, Cloud Physics, and Computer Graphics, is described. The system serves as an example for campuses which are relatively small in geographic area and with budget limitations which dictate a step-by-step evolution. The paper describes 1) the constraints and economics realized in the development of the system, 2) the characteristics of the minicomputer network, and 3) an evaluation of the system philosophy and performance. Also included is a description of diverse laboratory projects supported by the computer-automated system.**

I. INTRODUCTION

AN AUTOMATED laboratory system at the University of Missouri-Rolla (UMR) is described. Laboratory minicomputers are distributed throughout campus laboratories and connected to a large central computer.

Several motivating factors led to the development of the UMR minicomputer network. Initially, there were clear advantages to making the power of the central computer and its peripherals more accessible to the remote laboratories. Furthermore, a minicomputer network had the potential for providing new and improved input media to the central facility, an IBM 360/50. Also, many applications were not being adequately served by the slow response of a batch environment. Some required on-line control and quick response to real-time events. Providing dedicated computers for these applications was impractical in the university environment. As an alternative, the decision was made to provide a relatively inexpensive connection of modest-sized minicomputers to a central facility to provide both increased computing capability and quick response to real-time events.

There is a wealth of papers on computer networks, but most deal with resource sharing among larger systems. The Seventh Annual IEEE Computer Society International Conference [1] was devoted to computer networks. The Purdue University and Northwestern University computer networks are described on pages 125–128 and 191–194 of the *Conference Digest*. One difference between those projects and the one described here is that there was no attempt here to provide generalized remote-job-entry or computational capability. Since the campus is relatively small in physical size, all laboratories are within short walking distance of the computer center. Conventional time-sharing services are available to UMR from an off-campus computer.

II. THE MINICOMPUTER NETWORK

A. Background

The framework of the automated laboratory system at UMR is the homogeneous star-type network of minicomputers shown in Fig. 1. This configuration was arrived at after a period of about 6 years of evolution [2], [3].

The original automated laboratory system consisted of a single 12-bit word minicomputer with 8 channels of A/D and 4 channels of D/A converters. This system was used to control an analog computer in the Electrical Engineering Department and was linked via a 110-Bd dial-up line to the central IBM 360/50. Although useful, this first system was plagued with several serious problems. First, the low data rate over the dial-up line was a severe bottleneck. Second, the use of standard IBM equipment for interfacing the dial-up line to the central computer made expansion of the system an expensive proposition. Third, and finally, all of the data acquisition peripherals were located at the remote site. This meant that users with no real-time analysis requirements still had to acquire data in an on-line real-time environment. This type of user would have preferred to acquire data at his leisure and submit it to the central facility as a normal batch job. Unfortunately, the only method of data entry at the central site was through punched cards or nine track magnetic tape, which was either cumbersome or expensive for most laboratory data.

The experience with this initial system led to the development of the current configuration. The IBM 2702 controller was replaced with a programmable front-end processor, the

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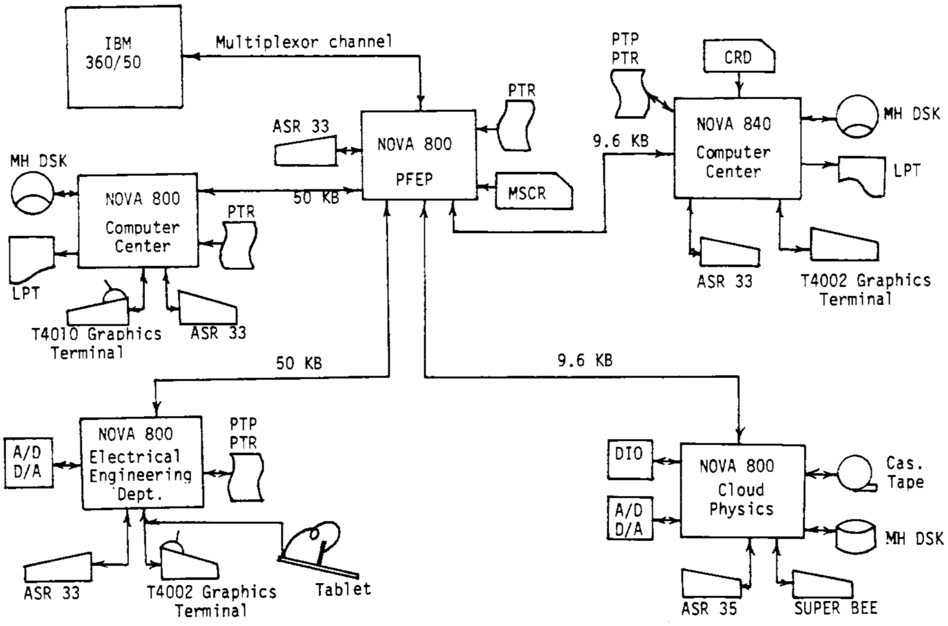


Fig. 1. Mininet hardware configuration.

12-bit word minicomputer was replaced with a newer and more reliable 16-bit NOVA 800, and the dial-up line was replaced with a high-speed asynchronous private communication link. Although probably not required by most applications, the line speed of 50K Bd was chosen as being the upper limit that the NOVA 800 could safely support with its programmed I/O channel. This second system was gradually expanded, as equipment became available, to the current configuration. With the introduction of larger disk-based systems at the remote sites and their accompanying larger operating systems with slower interrupt response times, it became necessary to decrease the communication speed. 9600 Bd appears to be the maximum rate which the real-time disk operating system can service without data over-runs. The link to nondisk-based systems remain at 50K Bd. The star topology and programmable front-end make expansion of the system possible at minimum expense and with the least amount of disturbance to existing users.

B. Communication Protocol

All of the front-end processor peripherals including the high-speed communication links appear as teletypes to the host software. All data are transferred to the host over the multiplexor channel in the byte multiplex mode. Data can be in the form of 7-bit ASCII characters with even parity, or 8-bit binary information. Using the current configuration of hardware and software, data are transferred between the host and front-end CPU's at a rate in excess of 800 bytes/s.

The front-end processor software is an entirely core resident multitask organization under control of a small real-time executive. All devices with the exception of the high-speed communication links are logically separate from each other and are controlled by separate tasks. The communication links are also controlled by separate tasks but do interact somewhat for reasons which will be made apparent.

The data link software module actually consists of 2 physically separate entities. Each "link" consists of the master control module resident in the front-end processor and a slave module resident in the remote. All links connected to the front-end share a single reentrant master module. At 50K Bd, the communication software must process each character within 200 μs. The current hardware/software configuration takes somewhat over 100 μs to process a character, assuming no background activity. Thus the master control module must insure that only one remote link be allowed to transmit at a time. The polling scheme, which is used, results in effectively asynchronously time multiplexing the limited bandwidth of the front-end processor.

The communication control software also handles the problem of error and buffer control. Errors are detected by a single even parity bit attached to each character and corrected by retransmission. Experience has shown, however, that over a path of 1000 ft, random errors are extremely unlikely. In order to conserve the limited address space of the minicomputers, a scheme is used to control the rate at which new data arrive. All data are sent in variable length blocks, each of which must be correctly acknowledged before the next is sent. This eliminates a processor from having to buffer large quantities of data.

C. System Design Choices and Evaluation

Time response and bandwidth characteristics are heavily dependent on software systems both at the host and the remote. Due to the general-purpose nature of the network, these figures of merit tend to vary somewhat. For example, a typical data acquisition application involves collection of data with a fairly simple assembly language program and buffering at a remote site. The data are then sent in a burst to a Fortran program in the host where they are formatted and stored on disk for later retrieval. The response time between end of transmission and a request for another transmission is about 1-1.5 s. If there is no host disk I/O involved, (as would be the case in an interactive simulation program) this host "turn-around" time is reduced to about 0.5 s depending upon the amount of computation involved. Opening of a new host disk file causes the longest noticeable delay (other than actual transmission time) and is on the order of 15 or 20 s.

The choice of serial asynchronous transmission versus synchronous or parallel transmission was dictated more by reason of economy than efficiency. Performance-wise, asynchronous transmission has a higher synchronization overhead than synchronous transmission, but for short blocks of data, the difference is not that great. Parallel transmission between buildings and associated larger cables was deemed impractical and unnecessary. Communication interfaces which could make use of the minicomputer's DMA channel would have improved performance, but it was believed that reduction of software overhead by a factor of about 30 did not justify the factor of 4 or 5 increase in cost. Also, it was expected that a non-DMA interface would be more flexible and easier to use.

Several mininets in existence use unique bus-type communication links. It was decided here to use standard off-the-shelf interfaces and reduce the amount of custom designed hardware in the system. Experience with student-built equipment has shown that although smaller stand-alone equipment can be quite serviceable, larger integrated systems tend to be poorly documented, difficult to maintain, and costly over the long run.

Designing the front-end software so that the front end is effectively asynchronously time-multiplexed has proved to be a wise decision. During the 2 years the system has been in operation, no more than 2 remotes have been active at once. Restricting the operation to 1 remote at a time would have needlessly reduced the usefulness of our front end. On the other hand, using classic time multiplexing would have needlessly reduced the systems bandwidth available to each remote. Most of the time, only 1 remote is active. Therefore, it is desirable to allow it to transmit at the maximum rate and only reduce the allowable rate during the occasional times when more than 1 remote is active.

Finally, the commonality of hardware has proved to be a tremendous advantage in the UMR environment. Maintenance of all 10 NOVA's on campus can be performed by one person. Spare parts are needed for only 1 type of machine, all hardware is interchangeable, and new interface designs are immediately usable on all machines.

Of course, software is also transportable in this environment. While application software is not often traded because of the diversity of applications and laboratory peripherals, operating system software is very similar in all machines and can also be kept up to date and maintained by 1 person.

III. Current Application Areas

This section of the paper consists of a description of application areas which make use of the minicomputer network in somewhat dissimilar ways.

A. Geophysics Research and Instruction

Research and instruction in the geophysics area at UMR concentrates on the use of seismic methods to probe the internal stratification of the earth in an effort to detect and isolate abnormal localized geological structures that may exist near the surface. Such structures might be fault zones, solution cavities, salt domes, buried stream channels, or perhaps simply undulations in the rock layers which might be favorable to the accumulation of oil or mineral deposits. Related engineering problems, such as the response of tall buildings or dams to seismic energy, also fall within the broader scope of these studies. Thus the seismic methods of interest in this program deal with the transmission of elastic waves through the heterogeneous earth and their effects on man-made structures.

The basic experimental process, shown in Fig. 2, consists of setting out a number of seismometers each of which produces an analog signal proportional to orthogonal components of velocity. The ground is set in motion with either an explosive charge or a shaker. The data is then recorded and played back for 1) determination of future seismometer placements and 2) later mapping of underground abnormality or analysis of the man-made structure under test.

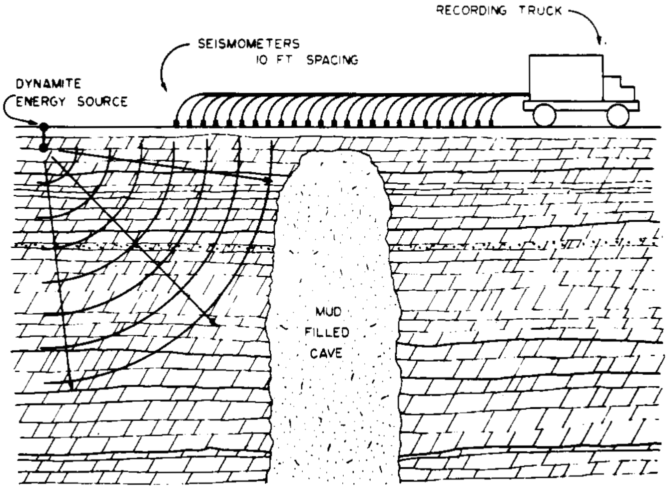


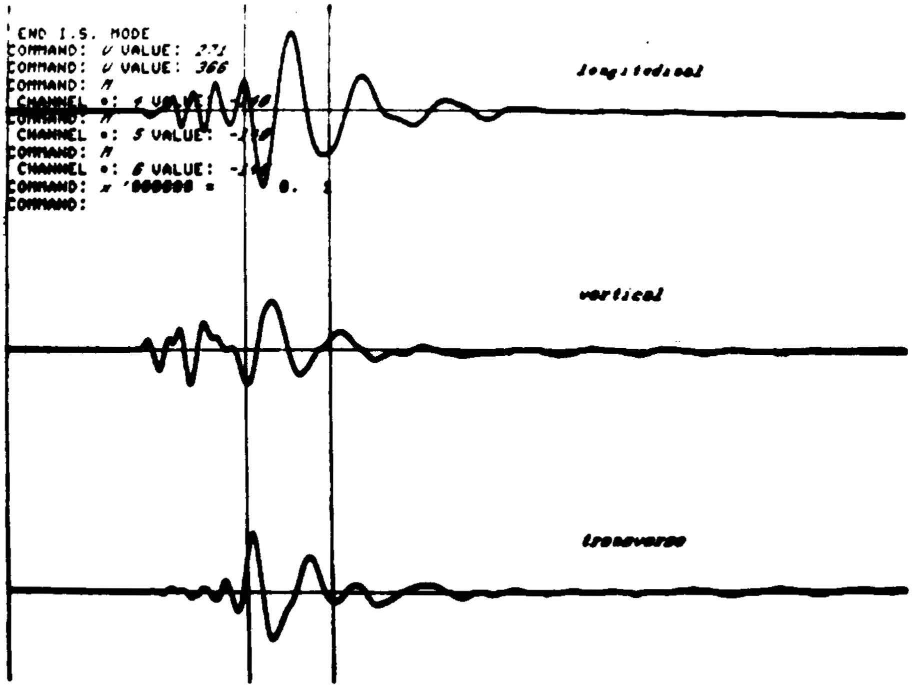
Fig. 2. Experimental configuration.

Fig. 3. Mobile laboratory van.

An early instrumentation system consisted of a Texas Instruments 9000 Series Seismic Amplifier System and a Model 432 Digital Field System (DFS). The DFS system digitized up to 31 channels of analog data from remote seismometers and stored the data on magnetic tape. Later, records were located on the tape and played back to an oscillographic camera to recover the original analog information.

A serious disadvantage of the instrumentation system just described is that it provided no in-field automatic data analysis. The experimentor had to rely on visual pattern recognition techniques to determine the validity of the data and for the planning out of the total experiment. Since the project operated within a university environment, funds did not permit the use of sophisticated, expensive, and dedicated computing equipment.

As the price of minicomputer systems dropped and as the minicomputer network began to materialize, it was decided to have 1 remote minicomputer station serve a dual role. During periods of relatively low student activity, the minicomputer would be disconnected from the network and installed in the mobile laboratory van shown in Fig. 3 to support field projects in the geophysics area [4].



```
END I.S. MODE
COMMAND: V VALUE: [illegible]
COMMAND: V VALUE: 366
COMMAND: M
 CHANNEL •: 4 VALUE: -[illegible]
COMMAND: M
 CHANNEL •: 5 VALUE: -[illegible]
COMMAND: M
 CHANNEL •: 6 VALUE: -[illegible]
COMMAND: X '000000 = [illegible]0.
COMMAND:
```

Fig. 4. Typical three-component seismometer output.

A mobile laboratory has been constructed and consists of a 2.5-ton surplus U.S. Army truck with a completely enclosed rear compartment. The van houses the minicomputer, its peripherals, and associated test equipment. The van is completely air conditioned and capable of being powered from a 220-V utility outlet or from an on-board generator.

The minicomputer is a NOVA 800 Jumbo computer with 16K core and hardware multiply and divide option. A moving head Diablo cartridge disk system with 1.2 million 16-bit word capacity and a Tektronix 4010 storage-tube graphics terminal are peripheral to the NOVA. A high-speed reader is included for initial loading of application software and utility routines.

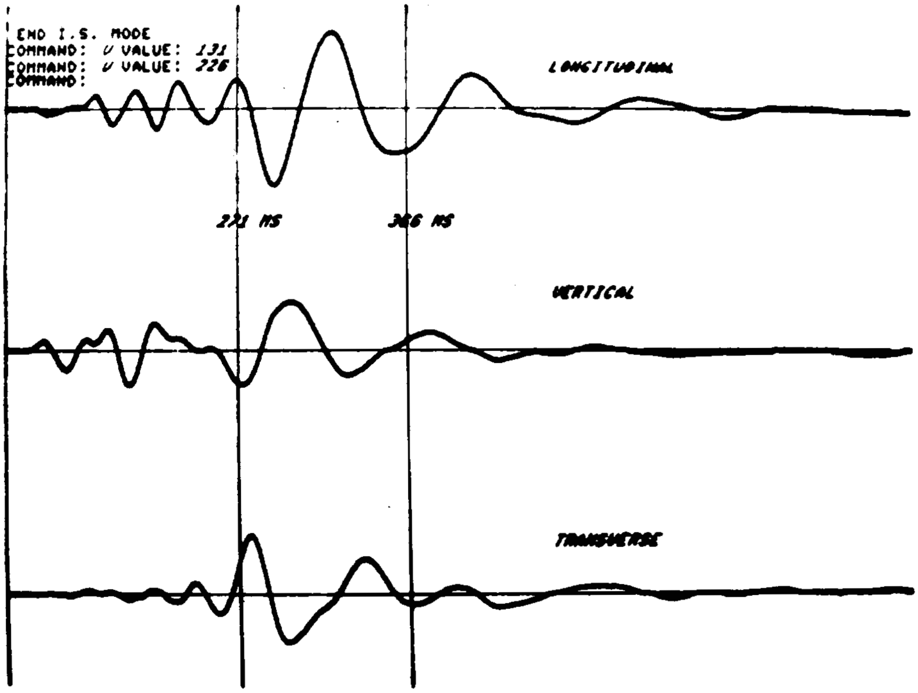
The system is capable of digitizing up to 32 analog channels at accurately timed rates of up to 1 KHz per channel. The data is stored on disk for later recall, manipulation, and analysis. Individual channels of data may have a dc level removed, be shifted in time, and be normalized in amplitude. Channels may be added, subtracted, and multiplied collectively for such operations as signal averaging. Arrays of time samples may be normalized and fast Fourier transformed at 2^{10} samples in about 1.5 s. The spectrum may be modified and an inverse transform obtained. Also, single events of interest in a waveform may be isolated or used as models for wavelets entered from a digitizing tablet.

A variety of displays of the data or functions of the data, without any modification to the data arrays used or storage of the resultant functions, are available. All plots may be scaled by powers of 2 and offset to display any desired window of information. Vertical and horizontal markers are scaled to be consistent with the displays for waveform measurement. Thousand-point plots typically take slightly over 2 s. Single channel time plots of information stored in the sample buffer and of real information stored in the transform array are available. If the information in the transform array is rectangular complex spectral information, magnitude and phase angle functions may be plotted as well as the stored real and imaginary representations of the transform. Several plots involving more than 1 channel of sampled information are available.

Fig. 4 shows the output of a typical 3-component seismometer plotted with respect to time. This figure is a copy of the graphics terminal display. Vertical markers have been added to pinpoint 2 instances of time. Fig. 5 shows the same data magnified by a factor of 2 and shifted 140 ms to the left.

Windowed plots of particle velocity with respect to time may be derived from 3 channels of data. Oblique and projected views from any angle are allowed at selectable speeds up to maximum terminal plotting speed. Particle plots may be interrupted for point number identification and then continued to allow isolation of individual events in the 3-dimensional representation. Fig. 6 shows a typical particle plot. The small x, y, and z axes represent the longitudinal, vertical, and transverse components, respectively. The x axis is shown coming out of the screen. Fig. 7 shows the same data rotated 85° around z and 40° around y. Displays are also available of correlation and convolution functions of any 2 channels of sample data. Fig. 8 shows a display consisting of a single component of the output of 10 seismometers and a second display consisting of a correlation of the raw data with an isolated wavelet.

The command structure of the program allows rapid and convenient use of various analysis methods and hence allows the user to concentrate on innovative techniques for data reduction which might be neglected or missed in a system with slower turnaround. Once a promising sequence of analysis steps has been arrived at, it may be stored and recalled at will for use on other data sets. This feature of the program has proved indispensable for the orderly display and analysis of 3-axis data where the same operations are required for each channel. The command sequences are not intended for use in building basic new functions, which are best implemented in assembler code, but means are available to enter run-time variables, do simple arithmetic, do an arithmetic branch, pause for displays, and set up loops. These command sequences are stored and executed as they are initially entered, so errors are detected immediately, and preparation time is kept to that normally required for command keyboard entry.



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END I.S. MODE
COMMAND: U VALUE: 131
COMMAND: U VALUE: 226
COMMAND:
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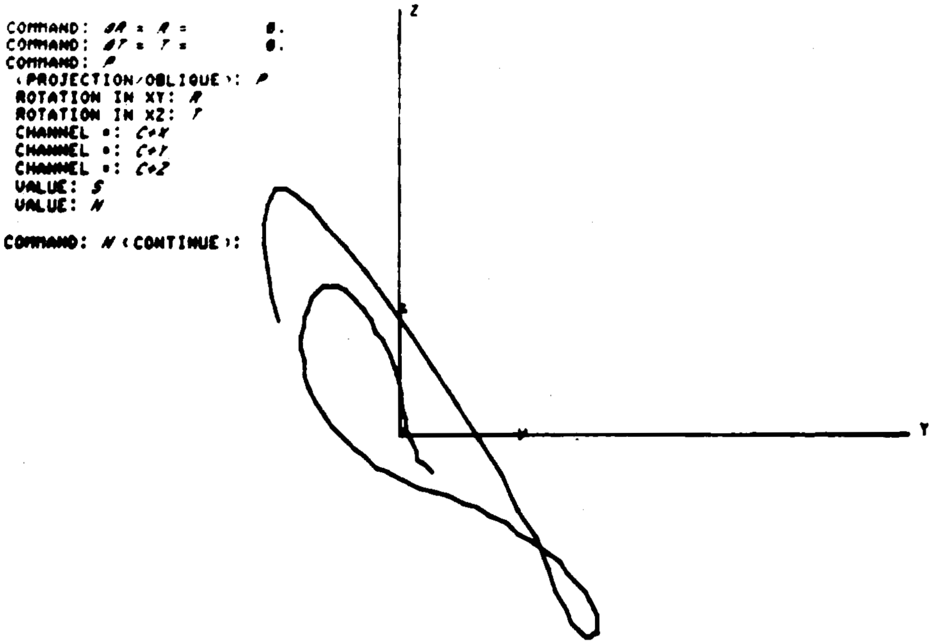
Fig. 5. Scaled and translated data.



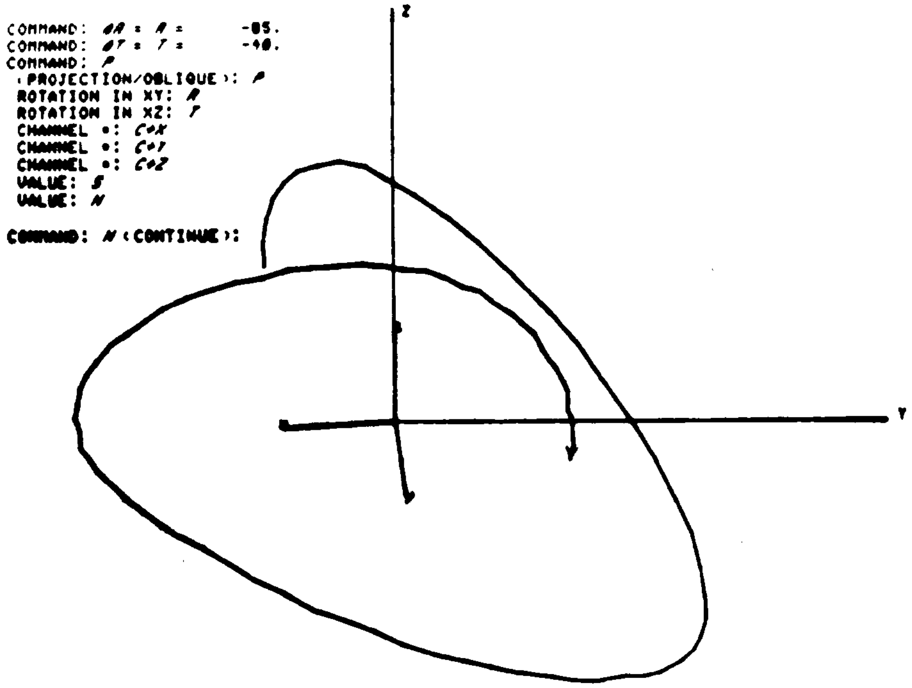
```
COMMAND: DR = R =           0.
COMMAND: DY = Y =           0.
COMMAND: P
 (PROJECTION/OBLIQUE): P
 ROTATION IN XY: R
 ROTATION IN XZ: Y
 CHANNEL 0: C+X
 CHANNEL 0: C+Y
 CHANNEL 0: C+Z
 VALUE: S
 VALUE: N

COMMAND: N (CONTINUE):
```

Fig. 6. Three-dimensional plot of particle motion with respect to time.

The disk cartridge which contains the field data can be removed from the mobile van NOVA and loaded in a second NOVA located in the computer center and networked to the IBM 360/50 as illustrated in Fig. 9. There, the data are transferred to the 360/50 disk. At this point, the experimenter can perform more sophisticated analysis of the data and make use of the higher performance peripherals. At present, the 360/50 is used to plot the data and calculation results on a Calcomp plotter and to punch some of the shorter records on cards for permanent storage. Longer data records will be stored on magnetic tape. In addition, correlations and transforms can be conveniently calculated for much larger data sets than can be processed in the minicomputer. A future project will involve a pattern recognition and feature extraction program which will run on the 360/50 to assist the experimenter in his visual analysis of data and calculated results.

The total system permits real-time field data acquisition, analysis, quick-look, followed by more casual examination in the laboratory and possible demonstration to students, and, finally, transmission to the central computer for analysis and permanent records in the form of plots, cards, and disk and tape storage.

The entire data acquisition system can be dismantled, reinstalled in either the computer center or the mobile van, and be in operation within a period of 2 h. Consequently, there is considerable flexibility in using the instrument as an acquisi-



```
COMMAND: 0R = R =      -05.
COMMAND: 0T = T =      -40.
COMMAND: P
 (PROJECTION/OBLIQUE): P
 ROTATION IN XY: R
 ROTATION IN XZ: T
 CHANNEL #: C#X
 CHANNEL #: C#Y
 CHANNEL #: C#Z
 VALUE: S
 VALUE: N

COMMAND: N (CONTINUE):
```

Fig. 7. Rotated particle motion plot.

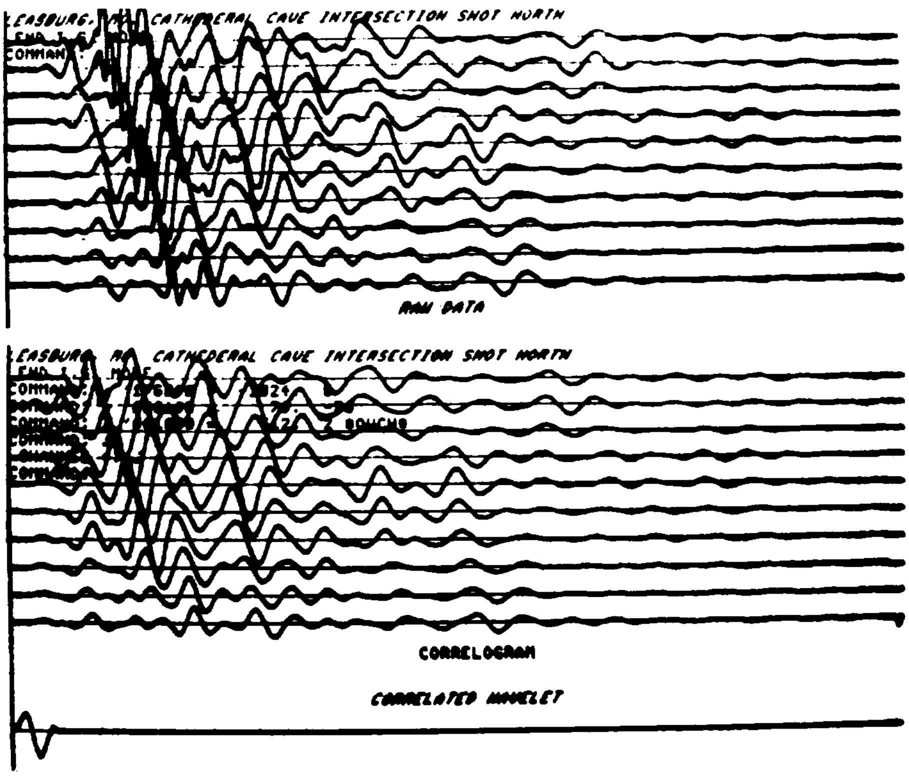


Fig. 8. Correlation function.

tion system in the field or as an instructional and research instrument in the laboratory. During the academic year, the system is normally used for instruction and processing of field data acquired during the summer.

The laboratory configuration is extremely unique in providing a training facility for geophysics students. By use of this instrument, these students can acquire a thorough familiarity with elastic wave methods through study of waveforms, such as that shown in Fig. 10, which is a composite of 2 displays of normalized and shaded data. Study of particle motion, correlation theory, numerical filtering, and deconvolution is also aided by manipulation of real data with an immediate visual result of the operations. Many variations of the filter parameters, for example, can be obtained in a very short period of time, thus giving the student a very sound feeling of each process. Fig. 11 shows the result of two ideal bandpass filters on the output signal of a 3-component seismometer. Furthermore, the student is only required to obtain a very superficial

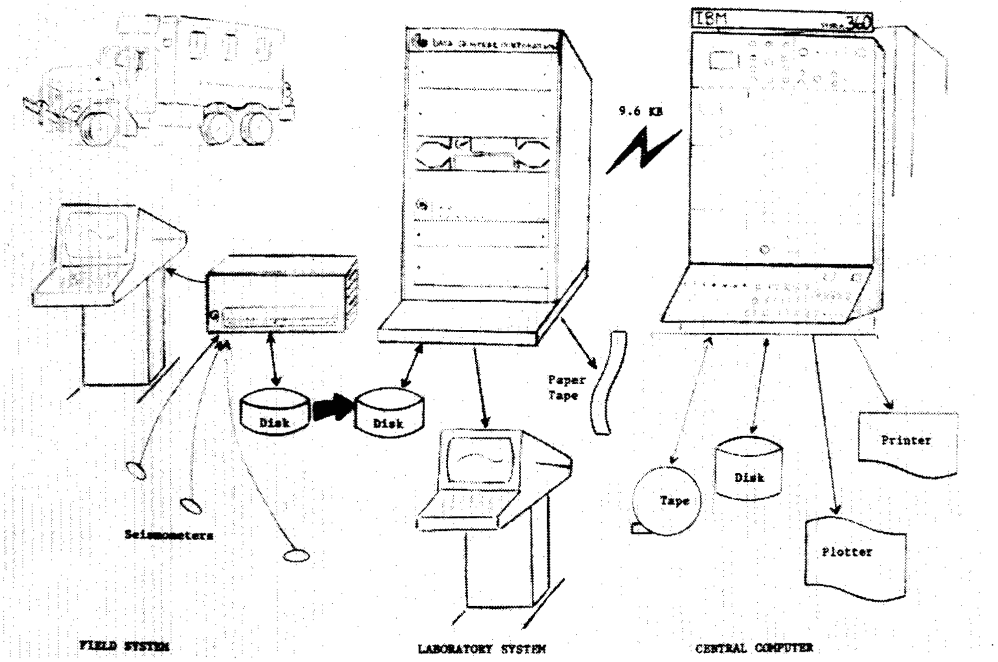


Fig. 9. Seismic data acquisition and processing system.

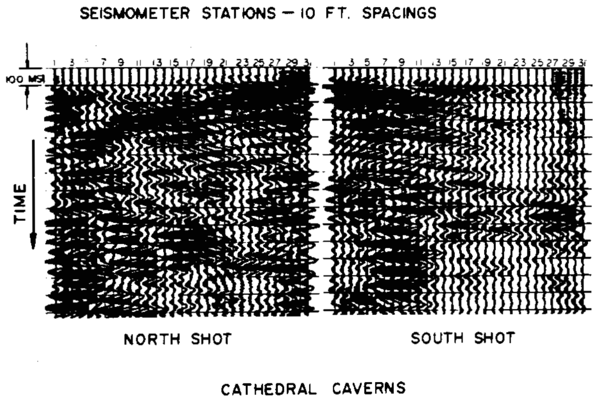


Fig. 10. Composite of normalized and shaded seismic data.

knowledge of the computer programs, and no programming as such is necessary.

B. Cloud Physics Research

One of the remote stations in the minicomputer network is located in the Cloud Physics Research Center (see Fig. 1). The minicomputer system consists of a NOVA 800 with 24K core, a disk, cassette unit, alphanumeric display, digital I/O, A/D, and D/A converter system, and teletype. Fig. 12 illustrates the computer configuration and identifies I/O functions. The system is used to handle the control and data acquisition requirements of a cloud simulation chamber. The chamber is a 10-sided prism approximately 18 in in diameter and 24 in high. In a typical experiment, a known sample of air is introduced into the chamber and, under a controlled expansion, the gas is cooled and produces the increased relative humidity required for cloud or fog formation. All physical parameters of the chamber such as pressure, temperature, vapor density, expansion rate, and aerosol content are measured and controlled in a precise and highly reproducible manner. One requirement is the chamber walls be cooled at the same rate as the expansion cools the gas so that the gas sample appears to be that of a continuous atmosphere. The minicomputer monitors chamber sensors, energizes thermoelectric modules for cooling the chamber walls, and controls the chamber expansion in such a way that a representative change in atmospheric conditions is accurately simulated.

A schematic of the total cloud chamber system is shown in Fig. 13. The computer controls the activation and deactivation of equipment such as thermal regulation equipment, aerosol generator furnaces, constant temperature baths, circulatory systems, and the water-flow system. The chamber must be flushed and filled with a gas sample of tightly controlled specifications. The chamber walls are stabilized at a preset initial temperature. A complete experiment with the chamber takes several days of preparation.

When the experiment begins, the computer energizes the thermoelectric modules and causes them to cool the walls to a preset schedule. It then takes data coming in from the pressure sensor, computes the adiabatic gas temperature, corrects it for liquid water content effects, and then sends a control signal to the expansion mechanism motors. The expansion is controlled in such a way that the gas temperature stays the same as the wall temperature. Data needed for the analysis of the experiment are stored on the disk. Critical data are also displayed on the alphanumeric terminal to give the operator a running account of the experiment. Some adjustments can be made during the course of the experiment if this is desirable.

When the expansion is ended, the chamber is flushed with dry air, pumped down to a low pressure, and sealed.

The data acquired during the experiment are stored on disk. These data are later transferred over the direct-connect communication link to the 360/50 computer. The 360/50 computer performs the computational analysis of the data and produces the experimental results in the form of plots or printer output. The data are also stored on central computer disk or tape.

The minicomputer plays a central and vital role in the acquisition of data and the control of the experiment. A significant feature is the ability of the minicomputer to provide a real-time display of critical parameters. This allows the operator to monitor the experiment while it is in progress. He can observe these critical parameters and control the transition from one stage of the experiment to the next. Corrections

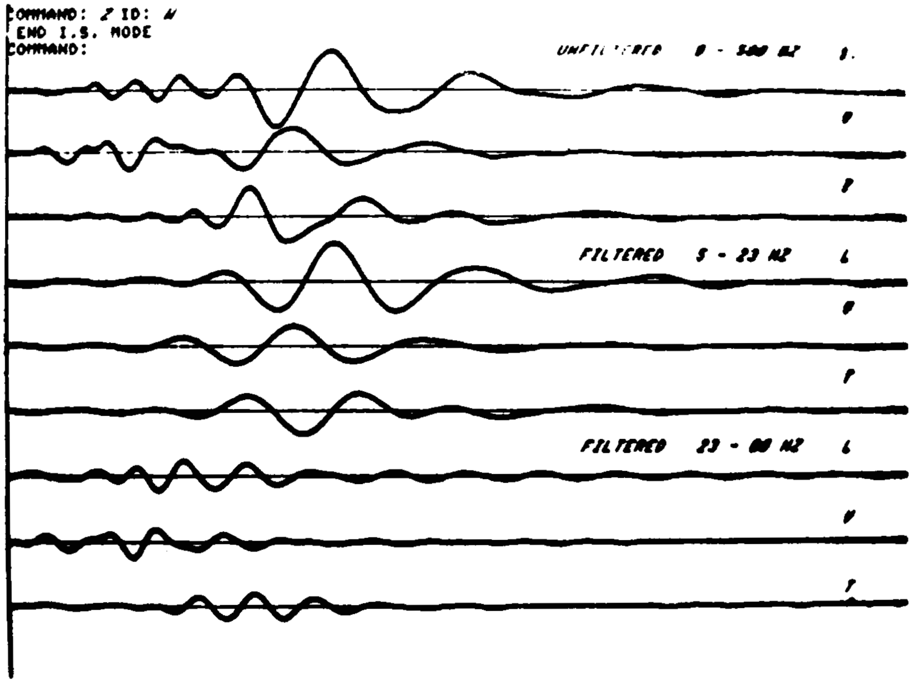


Fig. 11. Band-pass filtering.

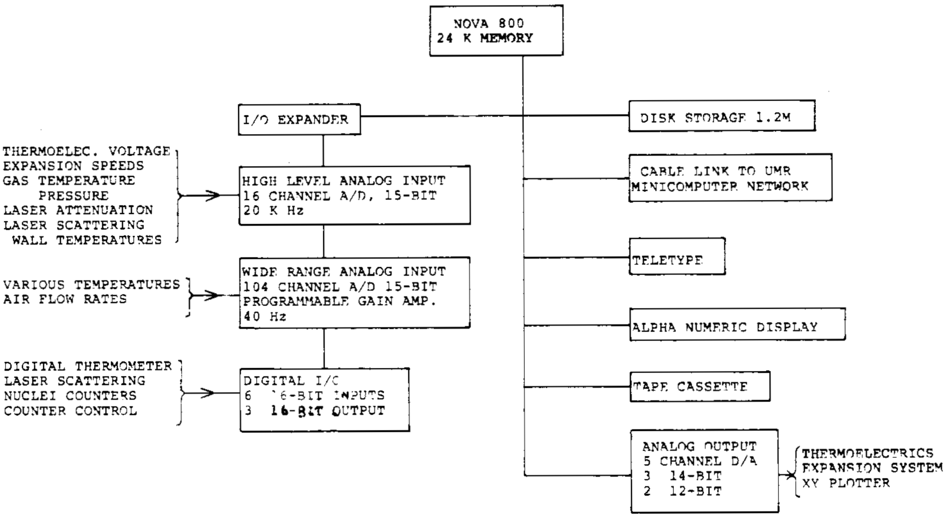


Fig. 12. Cloud physics minicomputer station.

can be made as the experiment continues. Without this feature, an experimenter may have to cycle the experiment several times before getting valid data. This can be very costly since it takes several days to set up and run a single experiment.

C. Computer Graphics

One of the initial motivating factors for the development of a minicomputer network was to establish a computer graphics capability at UMR. Early in the development, it appeared attractive to support a graphics terminal from the central large computer but through a remote minicomputer. Historically, the computer graphics system was the first applications system operational on the network. Many of the handlers, data communication techniques, and protocol used in the computer graphics application provided the basic program modules for the generalized areas of remote data acquisition and control.

The graphics system [5] is essentially 2 programs: 1 written for the remote NOVA in NOVA assembler language and 1 written for the IBM System 360 in PL/1. The remote NOVA program is written such that the user can build a system description off-line, that is, without the PL/1 program being active. When the System 360 program does become active, the data are transmitted without user intervention.

Some of the limitations in the System 360 program are the relatively long execution times, the large core block required, the overlay structure, and the time required to initiate this program. The use of a minicomputer partially overcame these problems. Since the minicomputer draws the elements and provides for local editing, the System 360 program does not perform these functions. This saves both execution time and core. The feature of off-line description building allowed the time necessary to initiate the System 360 program to be used for constructive purposes.

This latter feature is typical of the other applications involving the mininet and, indeed, illustrates the overall philosophy of the network; that is, the limited power of a remote minicomputer is used to acquire data and provide a certain amount of local off-line processing capability before transmission to

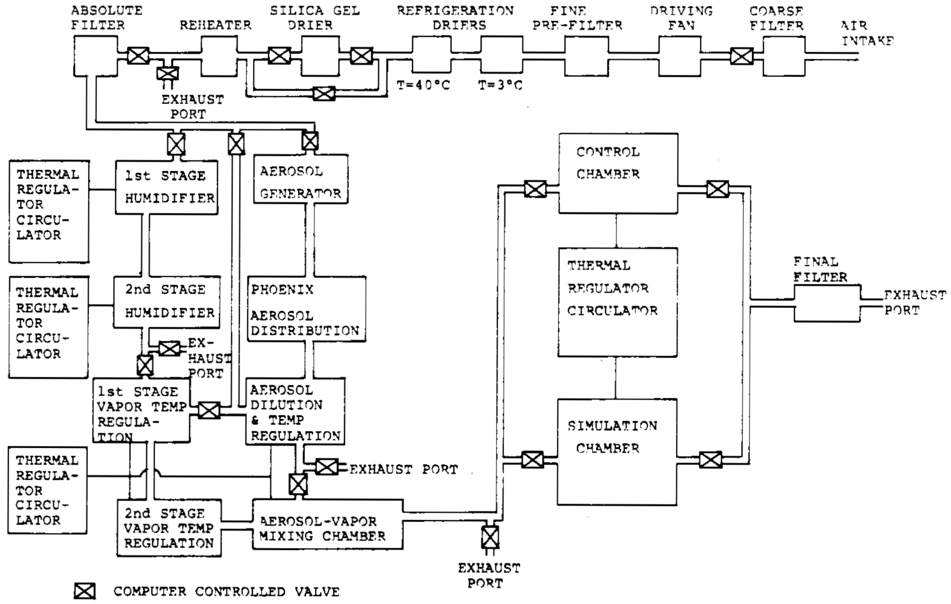


Fig. 13. Cloud chamber schematic.

the central computer. In this case, the remote is used to "acquire" a data base describing the user's digital system flowchart. The central computer only needs to be active after the data have been acquired and during the actual analysis of the data. In the case of the graphics system, this makes it useful in an instructional laboratory environment where the painfully slow design process might proceed for a period of several hours. The central computer would only need to be used at the end of this period to provide a test of the student's design via simulation. The need to dedicate the batch system is thus eliminated while at the same time avoiding a problem which has plagued many other attempts at economical laboratory automation, namely, that of trying to provide real-time response from a shared computer system.

IV. PLANNED APPLICATION AREAS

A power system laboratory model is under development at UMR and supported in part by the minicomputer network [6]. The availability of the laboratory model permits experimentation with a wide range of application programs and control algorithms. The model itself can be altered to represent a variety of system network configurations and anomalies. Furthermore, the model can be scaled on a time and magnitude basis to test application programs and algorithms under a range of events and rate of event occurrences. The hardware portion of the model consists of a motor-generator combination to represent plant turbines and generators, pi-equivalent networks to represent the transmission links, and static and dynamic loads to represent the distribution network. The model is under control of the electrical engineering minicomputer backed up by the central computer (Fig. 1). The computer system is responsible for 1) data acquisition, 2) analysis and control decisions, and 3) control actuation. Control actuation exists on two levels: 1) gross control and 2) simulation control. In the real power system, a fully expanded minicomputer system may be used to perform all of these functions. But for the model developed here, those functions with large computing and storage requirements and which permit relatively slow response times are performed on the central computer.

An additional remote minicomputer station is located in the UMR physics department. The NOVA 800 minicomputer is in the process of being connected to the central facility. When operational, this station will be shared among several project areas. In one project, the minicomputer is used to control, monitor, and acquire data from a microwave spectrometer. The frequency of the spectrometer is controlled by the computer. Data from repetitive frequency scans are averaged by the computer to provide smoothing. Although some monitoring and smoothing can be done locally, the bulk of the analysis is done on the data after transmittal to the central computer. This minicomputer is shared with a separate project which uses an ion spectrometer to measure heavy-ion and heavy-atom cross sections. Again, the computer is used to control and monitor the experiments. One part of the analysis consists of determining a "best fit" of the data to an analytical function. Because of the complexity and size of this analysis, these calculations will be carried out in the central computer.

The chemical engineering department also has a NOVA 800 minicomputer station which is being coupled to the network. One application of this station consists of automatically acquiring data from a heat transfer and distillation apparatus for analysis by a control program. The results of the minicomputer analysis are displayed on a terminal located in a laboratory which is remote from the minicomputer system. Students can inspect the experimental results at the terminal and enter control commands to modify the experiment. The minicomputer system also acquires data from chemical enzyme reactions through an ultraviolet spectrophotometer. The on-line analysis of the data provides the set-up conditions for the next experiment. The data link to the central computer will be used primarily to supply experimental data to the process control programs and simulators which are too large to reside in the remote minicomputer.

V. SUMMARY

The minicomputer network and related automated laboratories provide a total system, with the remote minicomputers performing the data acquisition, control, and information display, while the central computer performs the experimental analysis over larger data sets and provides access to higher performance peripherals, such as disk, tape, printer, and plotter.

The automated minicomputer laboratory system consists largely of hardware and software compatible systems at the remote sites. This has the significant advantage of permitting hardware and software sharing among the minicomputer stations. Systems can be expanded, reduced, or reconfigured with relative ease. Maintenance is also enhanced by this arrangement. In addition to the laboratory automation applications, the minicomputers are available for student instructional purposes. Instruction can be given on a single machine, but students are free to sign up for, and use, hardware at any remote station they choose.

In summary, the paper describes a variety of automated laboratory stations, all connected to a central computing facility. The total system is a highly coordinated activity and provides for a high degree of interaction among the laboratory sites.

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Cost Effectiveness of Computerized Laboratory Automation

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***Abstract*—The objective of this investigation was 1) to develop a methodology for determining potential productivity increases and cost savings to be realized from computerized automation of laboratory instruments, and 2) to evaluate the cost effectiveness of increased automation in the IBM San Jose Research Laboratory, using the developed methodology. The various factors are discussed which were considered in arriving at an algorithm for calculating cost and productivity for both manually operated and automated instruments. The algorithm is defined explicitly.**

The results of a survey using this methodology are presented. The survey covered 75 experiments involving 57 instruments, a number of which have been connected to a computer for several years. The instruments considered include gas-liquid and gel permeation chromatographs, mass spectrometers, IR and optical spectrometers, microdensitometers, electron spectrometers (Auger and microprobe), X-ray spectrometers, thermal analyzers, NMR spectrometers, miscellaneous instruments, and a variety of custom-built experimental apparatus. The distribution of cost for various instrument categories is presented. Automation cost and the underlying assumptions are discussed in detail. The particular implementation considered in the survey is based on a sensor-based computer (IBM System/7) which is shared by several experiments and in turn linked to a general-purpose host computer (IBM 360) for program preparation and extensive data analysis.

The results obtained indicate significant cost savings for about 80 percent of the experiments considered. The remaining 20 percent for which automation could be justified only on the basis of increased productivity are also discussed. The distribution of automation costs points up the relatively high cost associated with the development of application programs. The fairly consistent distribution of cost for a wide variety of experiments suggests that the cost savings and the calculated increase in productivity due to automation could be expected in other multi-instrument laboratories.

INTRODUCTION

THIS STUDY was motivated by an expected increase in computerized automation of instruments in the IBM Research Laboratory in San Jose, Calif. The objective of the study was to find out if one can establish generally applicable criteria for justifying such expenditures.

Computerized automation of laboratory instruments can be justified for any one, or a combination, of the following reasons.

1) Reduction of the actual cost of an experiment or sample run.

2) Shorter turnaround, i.e., get answers faster. Also implies greater productivity; more experiments may be performed by a given number of people with a given set of instruments.

3) Improved quality of data by eliminating human error and by taking advantage of the ability to acquire significantly greater amounts of data in a short period of time.

4) Ability to perform experiments impossible without computerized automation.

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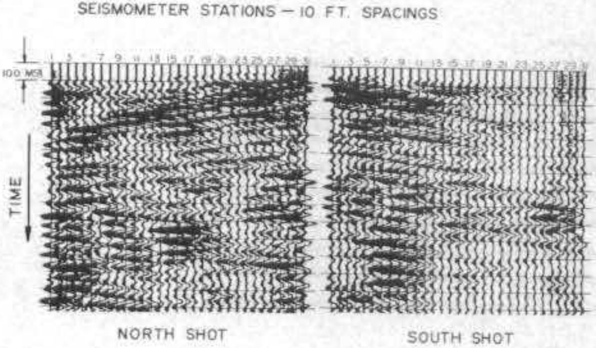
Fig. 3. Mobile laboratory van.



CATHEDRAL CAVERNS

Fig. 10. Composite of normalized and shaded seismic data.