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A Microseismic System for Monitoring Slope Stability

By C. Melvin Lepper, Allan P. Poland,
and C. Thomas Mullis

UNITED STATES DEPARTMENT OF THE INTERIOR

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A MICROSEISMIC SYSTEM FOR MONITORING SLOPE STABILITY

by

C. Melvin Lepper,[1] Allan P. Poland,[2] and C. Thomas Mullis[3]

ABSTRACT

Microseismic energy is generated when stresses accumulated in rock formations are released in the form of fracturing. The acoustic emissions resulting from these rock fractures and movements are detectable as velocity signals in the earth near the energy source.

A Bureau of Mines microseismic system that is capable of detecting the acoustic emissions from pit slope movements is described. The digital circuitry incorporated in the system allows a microprocessor program to immediately calculate and present the location coordinates for the seismic energy source in the mine pit wall.

This monitoring system is compact, portable, reliable, and relatively inexpensive and rapidly provides accurate information to the mine operators about the stability of a pit slope.

INTRODUCTION

The Bureau of Mines has developed an open pit wall monitoring system for on-site analysis of slope stability. Continuous remote surveillance of potential slide areas is made possible. The system features radio transmission of stability data directly to receivers and recording equipment that can be located in mine offices.

Open pit mine walls are, by economic necessity, mined to a designed maximum stable slope angle. However, this practice often results in the wall slope being too steep, hence unstable, in areas plagued by unanticipated, unpredictable, weak zones and structural defects. The pit wall is now subject to some degree of failure; failure that is usually manifested by the slide of huge (millions of cubic meters) volumes of pit wall material into active mining areas at the pit floor (fig. 1). These slides endanger pit miners, destroy pit haulage roads and rail systems, stop production, and generate huge losses incurred in the repair and cleanup operations.

Unstable areas usually go unnoticed until conditions such as tension cracks, "smoking," excessive sloughing, or toe heave give physical evidence of instability. By this time, there is no reversal of the unstable condition, only a chance to delay the inevitable slide of material (overburden) into the pit opening until some remedial action can be taken. It is during the period of known or suspected instability that there is a definite need to be able to determine the degree of instability; that is, provide predictions

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FIGURE 1. - Massive pit wall failure, Liberty Pit, Ruth, Nev.

as to change in stability and time to total failure or slide of material into the pit.

The need for in situ slope stability analysis prompted the Bureau of Mines to develop microseismic (rock noise) detection and source location equipment. There were two main objectives; (1) to provide a means of slope failure prediction and warning through daily monitoring techniques and (2) to enable mine operators to evaluate the success of remedial action such as surface unloading or cessation of mining.

ACKNOWLEDGMENTS

The authors wish to express their appreciation for the contributions of J. R. Simplot, Conda, Idaho, and Phelps Dodge, Morenci, Ariz., and for their assistance in providing test areas within active open pit mines for installation and evaluation of the microseismic system. The authors also wish to recognize the contributions to this project made by Meng-Cherng Sun, mining engineer, Denver (Colo.) Research Center, in the field of microprocessor program development and applications.

BACKGROUND

The Bureau has conducted research dealing with various applications of microseismic technology for intermittent periods since the early 1940's (1).[4] Throughout this work, the goal has been to establish the working parameters, develop the analytical capabilities, and provide the necessary instrumentation for inexpensive, long-term monitoring of a suspected failure area. Previous research has included studies into characterization of rock noise (microseisms), application of microseismic data to determine rock mass stability and changes in stress, and developing equipment and techniques to automate microseismic source location.

Early research was directed toward evaluating the stability of underground mine roof, hence predicting mine roof failures. However, in conducting studies into open pit mine wall design, the Bureau recognized the underground microseismic work as having application to pit wall stability problems. This was based on the knowledge that instability in pit walls is accompanied by rock mass movement and high local stresses, both of which generate detectable rock noises. First investigations were begun in the early 1960's using copies of microseismic gear developed for underground studies. Noise detection was limited to frequencies of about 500 to 900 Hz (low for underground work), and data were in terms of rock noise rates.

Changes in noise rates were evidence of stress changes within the rock masses and were determined to be a measure of change in wall stability. These conclusions resulted from work done in a U.S. Borax and Chemical Co. mine near Boron, Calif. (12) and the Kennecott Copper Corp. Kimbley Pit near Ely, Nev. (10, 18-19) during the period 1963-68.

Since research in the sixties, the digital electronics technology "explosion" and the rapid strides in data processing and iterative capabilities have made possible major advances in collection, storage, and reduction of microseismic data. One advance is the development of microseismic source location capability, which enables slope stability researchers to not only detect and count microseismic events, but also to determine where each event originated. It is this feature that permits identification of specific problem locations within a failure plane or zone and provides hard data for analysis of the actual mechanics of failure. Thus, the technology necessary to develop a workable, practical slope stability monitoring system was available. It remained to build, test, and prove a system.

The project work reported here was directed toward the design, fabrication, and testing of a fully integrated and automated slope stability monitoring system. The result is a system that will automatically detect, locate, and record a microseismic "event" in less than 5 seconds and one that will operate under severe field conditions with minimal maintenance.

SYSTEM CONCEPTS AND COMPONENTS

Layout

The slope stability monitoring system described in this report is based upon the use of detector arrays. An array is a group of detectors connected to a readout instrument. The individual elements of the array may be connected to the recording instrument either individually or in combinations of series and parallel to produce a desired result. Arrays are of two types--linear and areal. For this application, areal arrays such as that shown in figure 2 are

[4]Underlined numbers in parentheses refer to items in the bibliography preceding the appendix.

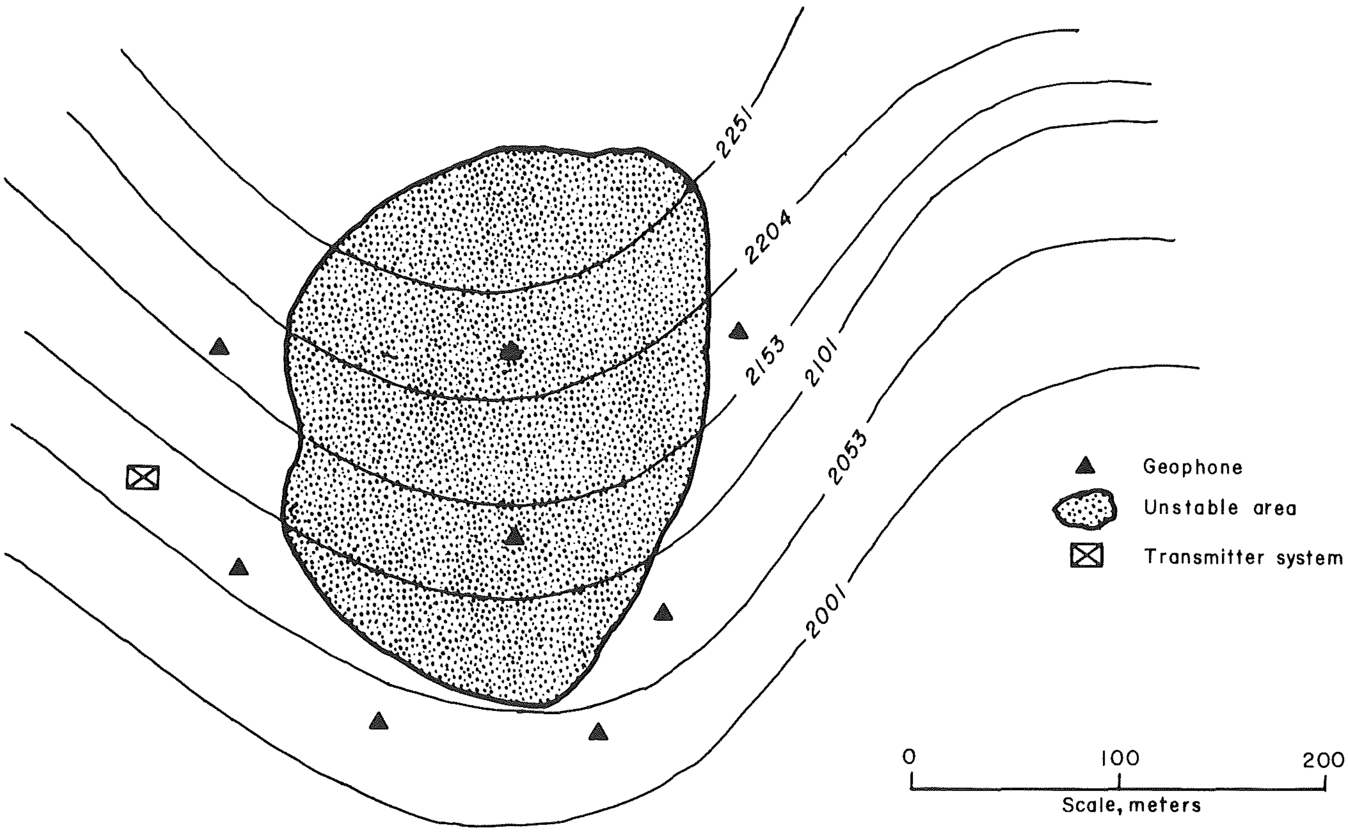


FIGURE 2. - Array layout to illustrate optimum detector placement.

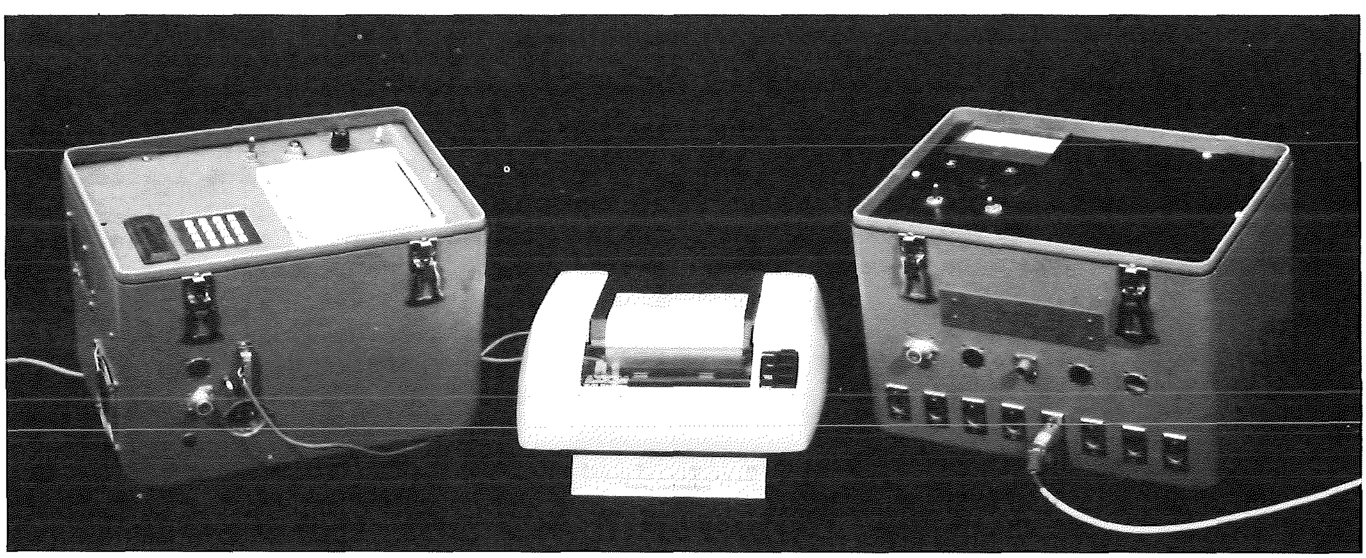


FIGURE 3. - Primary system components: left to right, receiver, printer, and transmitter.

used because the information from this configuration is more usable in the source location programs that are resident in the system.

The primary electronic system components consist of a transmitter unit, a receiver unit, and a line printer as shown in figure 3. Other components include geophones, a transmitting antenna, a receiving antenna, a battery pack, and a solar electric panel with a voltage regulator to maintain the battery charge at the transmitter field location. Geophones are used as the microseismic detectors along with small preamplifiers for signal conditioning. All of these system components are described in detail in this report.

The deployment of the monitoring system is illustrated in the conceptual drawing in figure 4. Note that a repeater station is shown as an option to the system. The Bureau has not utilized a repeater system because it was not necessary for mine tests conducted thus far, but it can be made a part of an operating system if required to get data from a remote transmitter location to a mine office over rough geographic conditions or for long-distance data transmission.

Operation

The system performs its function of detecting movements and providing notice of the events to the mine operator in a manner that deserves some explanation.

When pit slope stress changes occur, microseismic energies are released. Geophones mounted to competent rock in the geologic formation generate small output voltages proportional to the amplitude of the energy release. The output signals from the geophones are amplified and

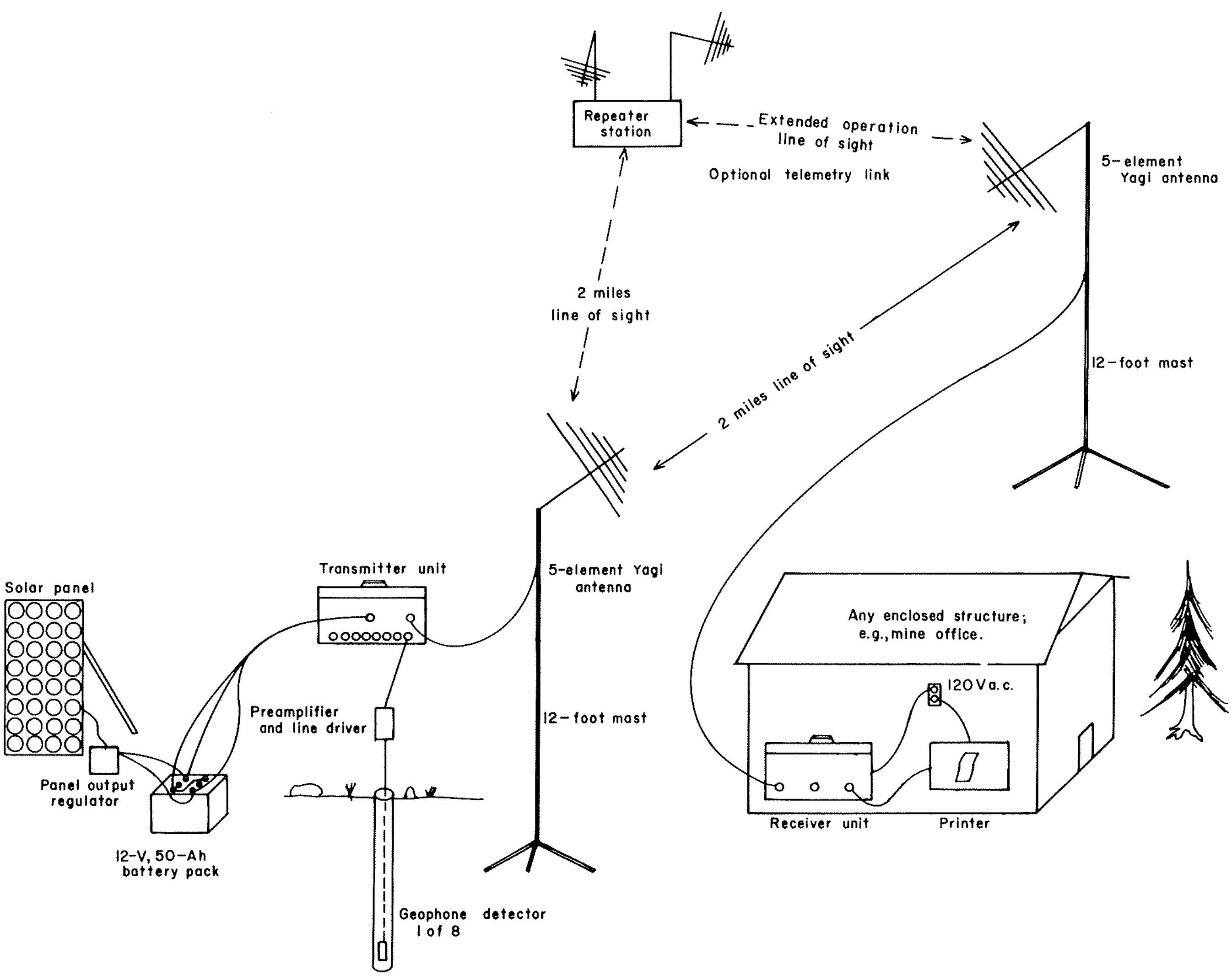


FIGURE 4. - Conceptual drawing of monitoring system deployment.

filtered by a small preamplifier unit. When the amplified geophone signals reach a predetermined level, a threshold detector trips and produces a narrow d.c. signal pulse that is carried to the transmitter unit by connecting cables. The transmitter unit collects data from all eight channels of the system, time coding each arrival. The unit then dumps this data from resident memory into circuitry that generates digitally coded 1- and 2-kHz tones. These encoded audio signals are then applied to a low-power FM-RF (frequency modulation-radio frequency) transmitter and thence to a high-gain transmitting antenna that is part of the data telemetry link.

The RF signals are detected at the receiver by a high-gain receiving antenna and applied to the front end of a small FM receiver unit tuned precisely to the proper frequency. The receiver demodulates the incoming signals, reproducing the two-tone coded data strings. These data are then applied to the microprocessor circuitry in the receiver unit. The data are printed out immediately in raw form, and temporarily stored in memory. If a sufficient number of geophones have responded (a minimum of four is required), a source location program is activated that computes the X, Y, and Z coordinates of the source of the energy release in the pit wall. The coordinates, date, and time (accurate to a second) are printed out. From these data, the mine operator can easily plot the source points of stress change or failure on a mine map, and based on both the location and the frequency with which the events occur, make a subjective evaluation of pit wall stability.

Transmitter System

Electronics

The transmitter unit transmits the microseismic data from the pit wall movements to the receiver by an RF telemetry link. The transmitter unit has several other functions. It performs the collection and storage functions for the data generated by the geophones and contains the necessary detection and switching circuitry to turn the telemetry transmitter module on and off. It also encodes all incoming data into tones for use in the transmission activities. It contains the d.c.-to-d.c. power conversion required for its internal circuitry and for the preamlifiers. A flow diagram of the transmitter unit is shown in figure 5.

The tranmitter unit will be described by sections to provide an easier understanding of all its functions. All electronic circuitry in the transmitter unit is resident on four PC (printed circuit) boards. The four circuit cards are held in place by a card cage shown in figure 6. This cage contains a double 22-pin back-plane bus that provides for interconnections between cards and allows

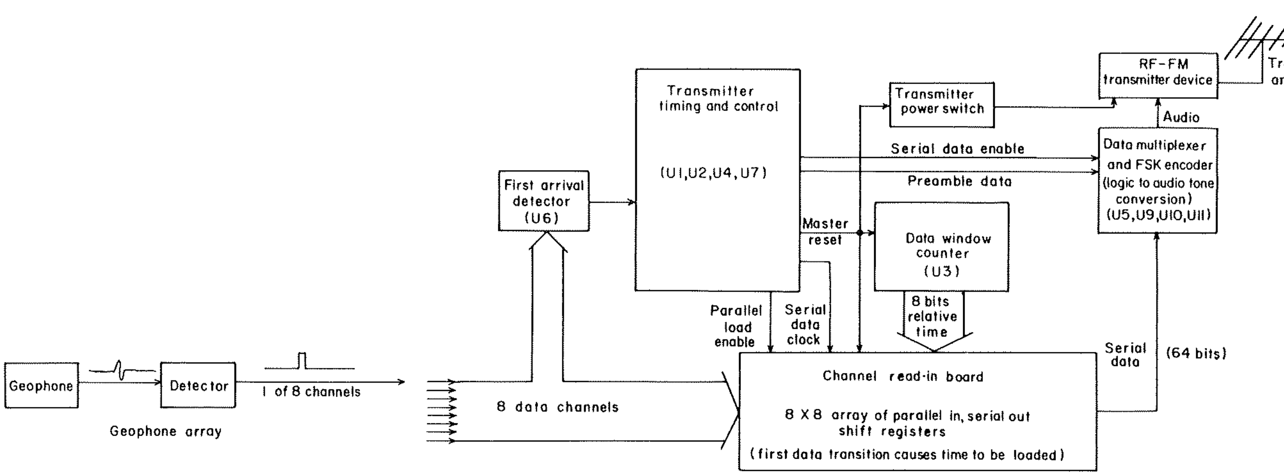


FIGURE 5. - Transmitter unit flow diagram.

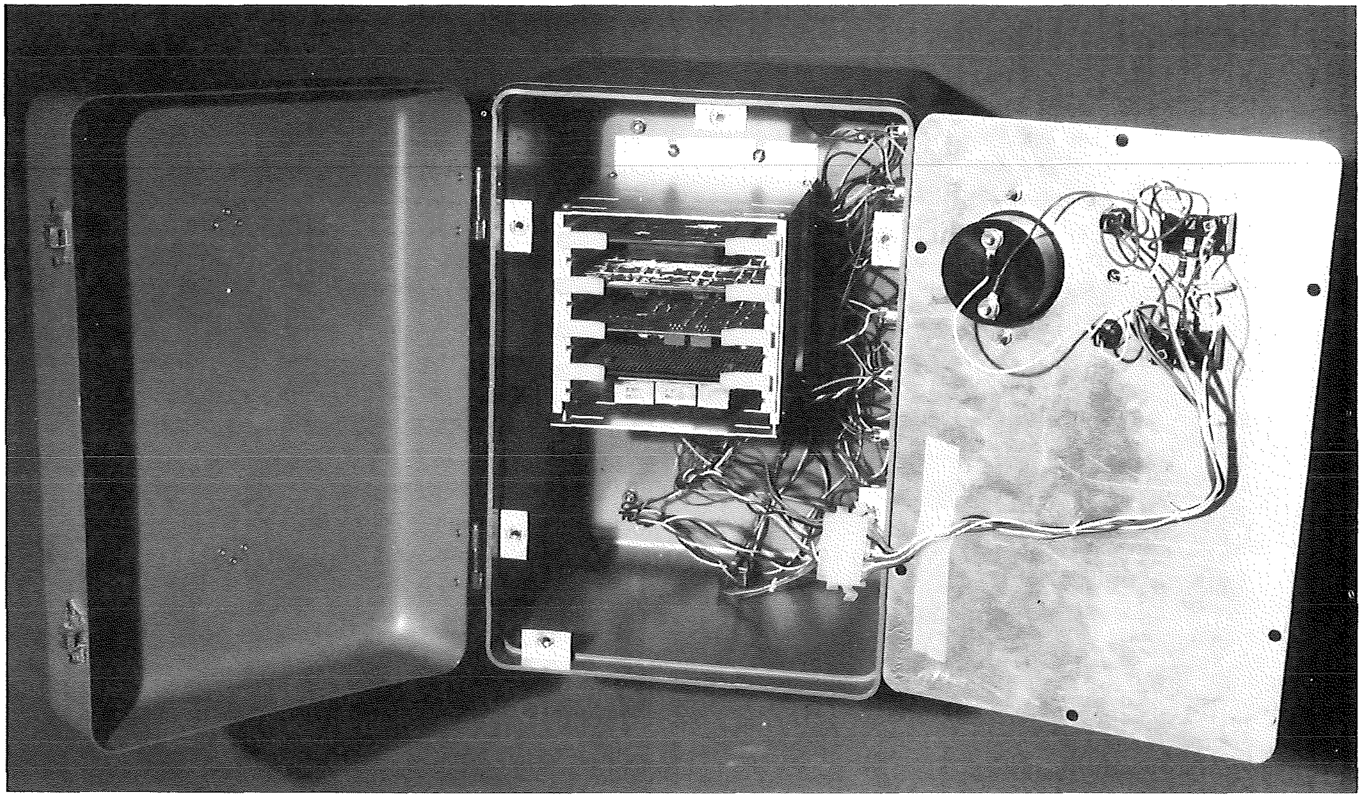


FIGURE 6. - Interior view of transmitter unit showing circuit card cage.

for convenient input to and output from the electronic circuitry. In addition, the card cage provides restraint and protection to the circuit boards and the edge connectors, and allows keyed orientation of the cards. Rugged construction practices have been adhered to in this entire system to insure system reliability under the most severe environmental conditions.

Two d.c.-to-d.c. converters are mounted on the power supply card. These two Datel Systems, Inc.[5] sealed power modules (converters) are shown in figure 7. The modules are supplied with single polarity 12-V battery power and produce positive and negative 15-V, regulated output voltages. Two modules were used for this application because a single unit with adequate output current capability could not be obtained. The technical specifications of these modules are given in table 1.

[5]Reference to specific equipment, trade names, or manufacturers does not imply endorsement by the Bureau of Mines.

TABLE 1. - Modular dual-output, d.c.-to-d.c. converter

Model number	BPM-15/100-D12
Output voltage	±15 V d.c.
Output current	±100 mA
Output capacitor, internal	2.2 μF
Output voltage accuracy	±1 pct
Output current limiting	150 pct
Output impedance	0.2 Ω
Maximum output noise and ripple	1 mV rms
Maximum transient response	25 μs
Input voltage	+12 V d.c.
Input voltage tolerance	-10 to +25 pct
Full-load current draw	390 mA
No-load current draw	75 mA
Line and load regulation	±0.02 pct
Electric shielding, to common	Internal copper
Efficiency	60 pct
Operating temperature	-25° to +71° C
Physical dimensions:	
Length	5.08 cm (2 in)
Width	5.08 cm (2 in)
Height	1.14 cm (0.45 in)
Weight	90 g (3 oz)
Connector pins	0.05 cm (0.02 in) diam., gold plated

The data and transmitter control card is shown in figure 8. The circuitry on this card performs several functions. It detects the arrival of data coming from any one or several geophones and sets up command pulses to initiate all data-taking circuitry. When the first arriving signal from any of eight geophones is detected by the electronic circuitry, all other electronics are prepared to receive data on the seven other channels. When all activated channels are loaded with data from this event, the data are dumped and transmitted to the receiver. The electronics then reset and are ready for the next incoming event. The wiring diagram in figure 9 shows eight channels of input acceptable into chip U6, which is an eight-input NOR[6] gate. With no signal applied to the chip inputs, the output is held high (+5 V). A positive logic signal (from the geophone preamplifiers) on any one or more chip inputs causes the chip output to go low (ground potential). Chip U7 then goes high, effectively acting as an inverter for the logic signal. Chip U4 is a quad R/S (reset/set) flip-flop (NOR logic) that creates timing pulses for other circuitry in the transmitter unit.

[6] A Boolean algebra logical operator that implies "not or."

Integrated circuit chip U1 is a 14-stage binary ripple counter that divides the crystal frequency of 1.024 MHz to provide master control of the cycle timing and the data window length, utilizing binary counter chips U2 and U3 respectively.

Chip U5 is a triple 1-of-2 switch used to control the unmodulated data string to the following control circuitry. The two tone generators, U9 and U10, are Burr Brown model 4423 precision sine wave oscillators. U9 operates at 2 kHz and U10 at 1 kHz. These two tones are connected to the analog switch U11, a Siliconix model DG 164BP. This switch uses the unmodulated data timing string to create a synchronized, two-tone,

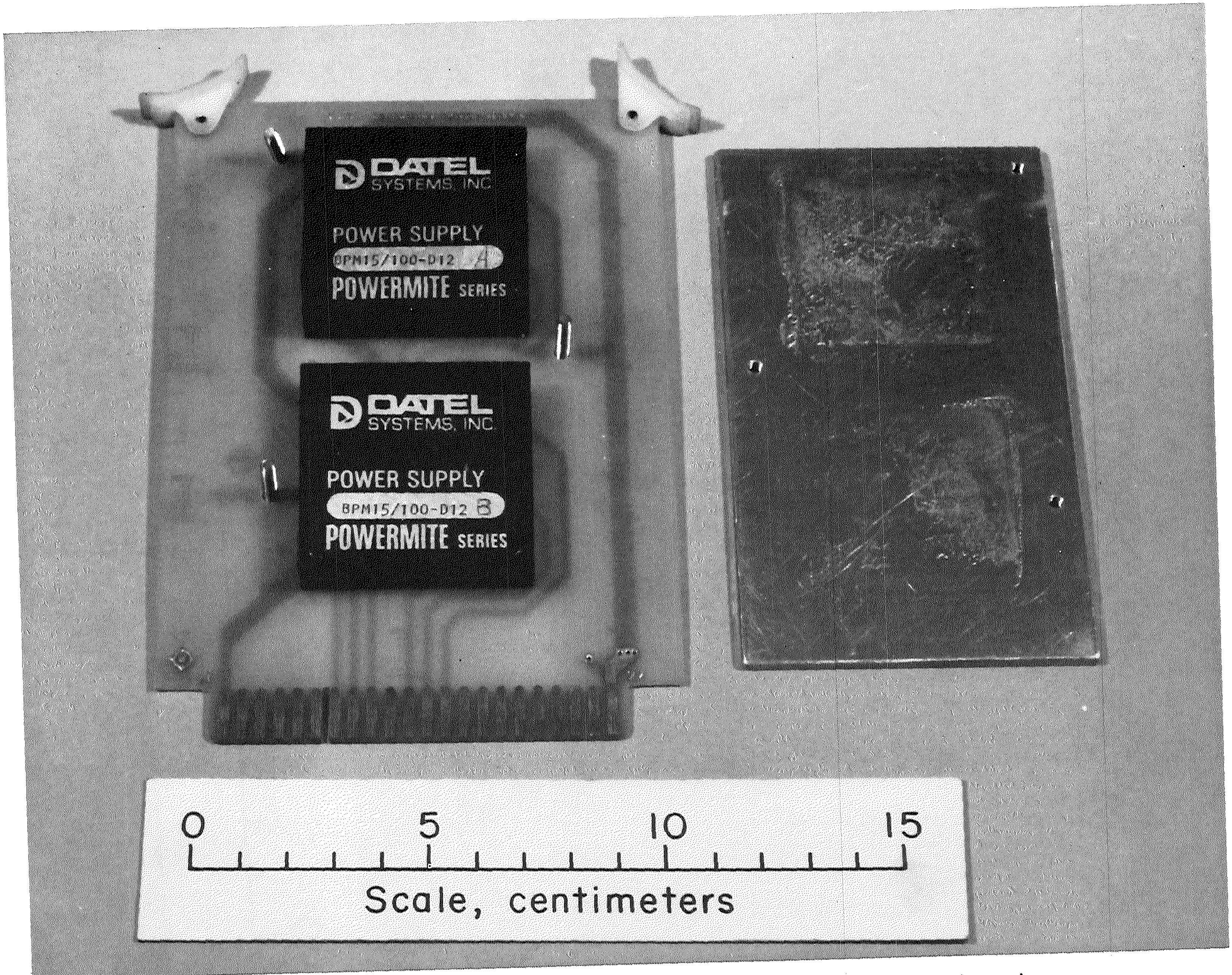


FIGURE 7. - Modular d.c.-to-d.c. converters mounted on plug-in power supply card.

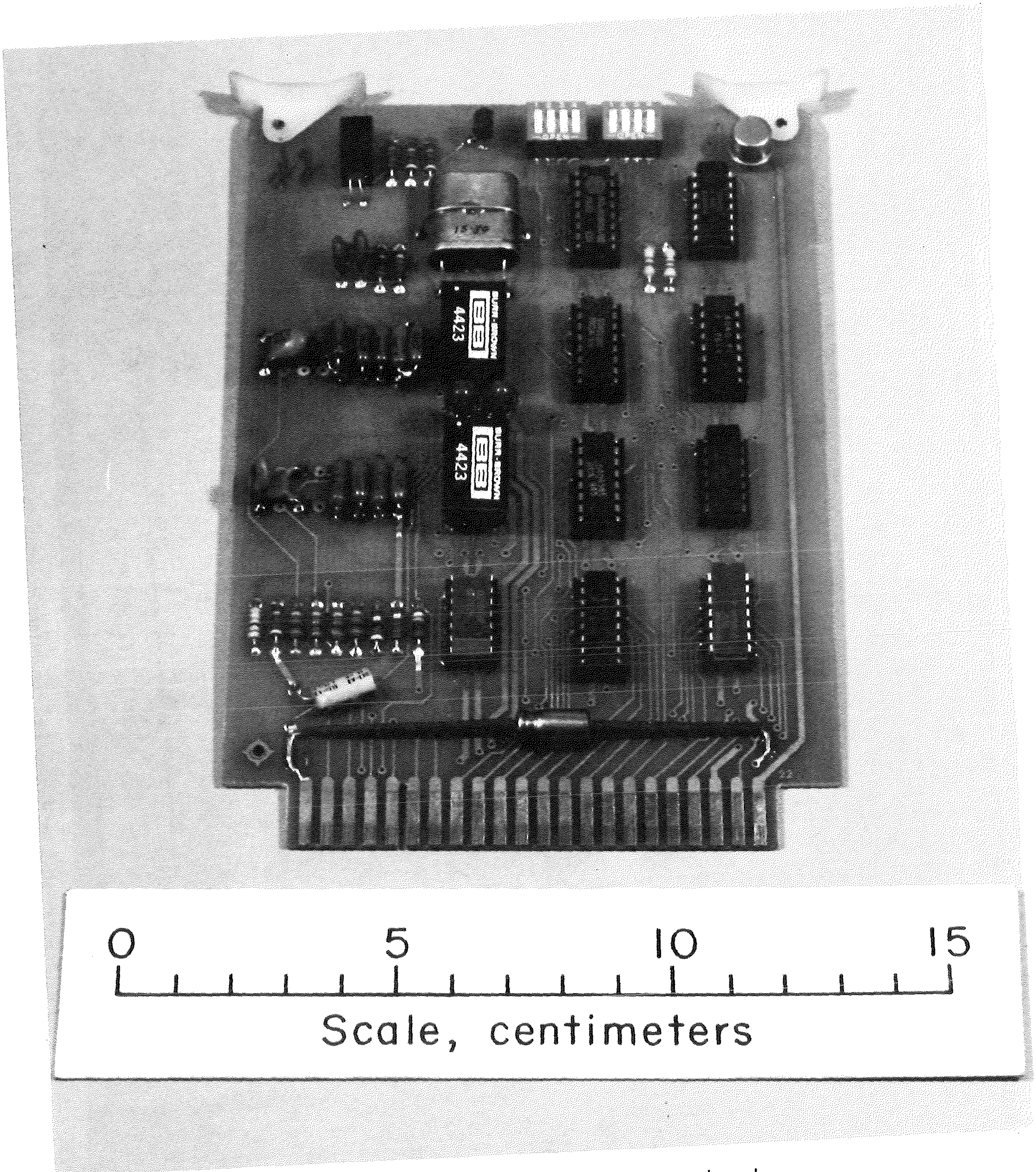
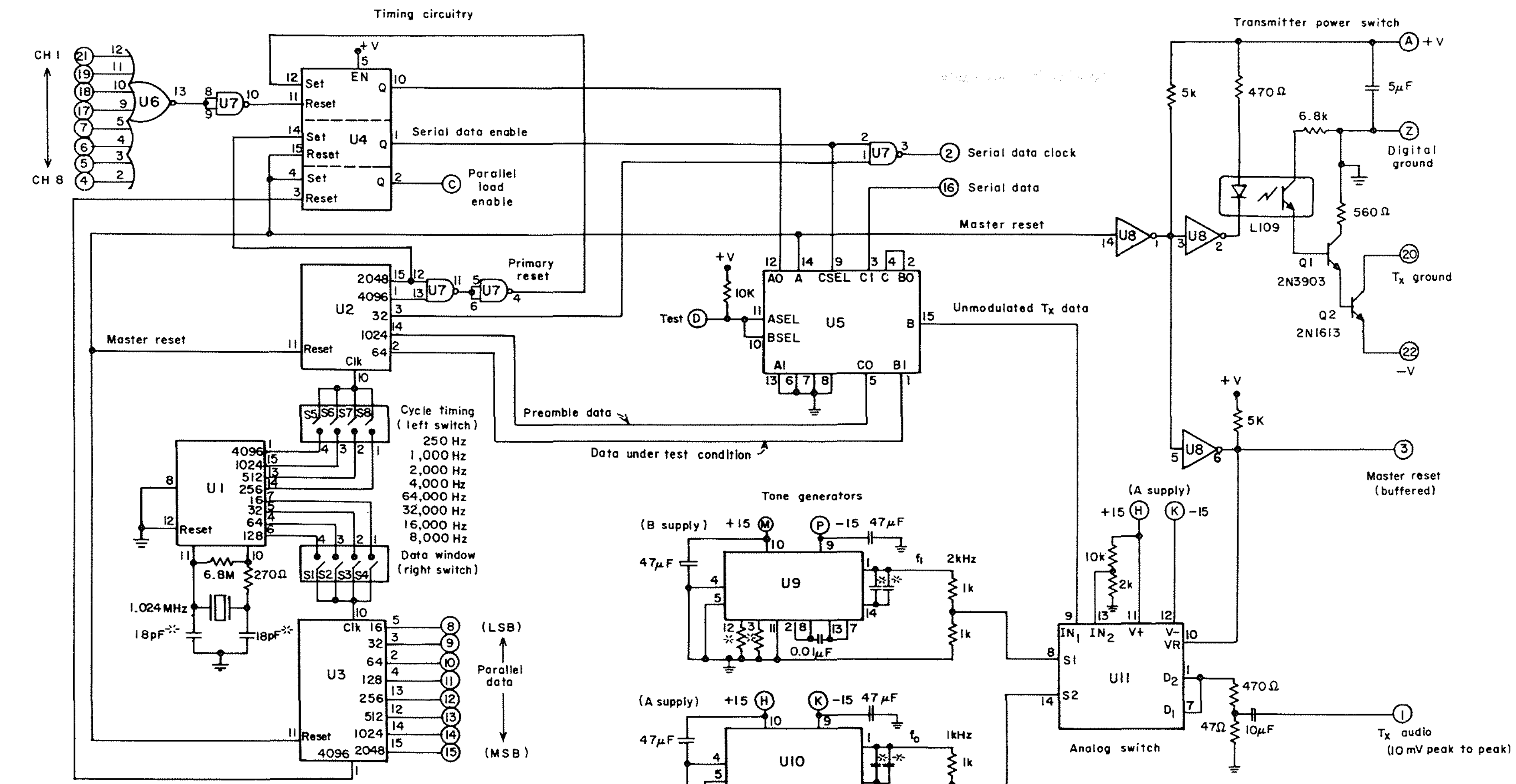


FIGURE 8. - Data and transmitter control card.



Chip designation	Chip type	Number of pins	V+ pin	Ground pin
U1	4060	16	16	8
U2	4040	16	16	8
U3	4040	16	16	8
U4	4043	16	16	8
U5	4053	16	16	8
U6	4078	14	14	7

Chip designation	Chip type	Number of pins	V+ pin	Ground pin
U7	4011	14	14	7
U8	75492	14	11	4
U9	BB4423	14		
U10	BB4423	14		
U11	DG164BP	14		

* Component values selected to tune circuits to precise frequency. See text for details.

NOTE: All resistors are 1/8 watt.

○— Indicates bus connections

FIGURE 9. - Circuit diagram for data and transmitter control card.

encoded data package for transmission by the RF telemetry link.

The circuitry consisting of U8 (three sections), L-109, Q1, Q2, and the interconnecting components are the RF transmitter module power switch and a master reset generator that is used for other circuits throughout the system.

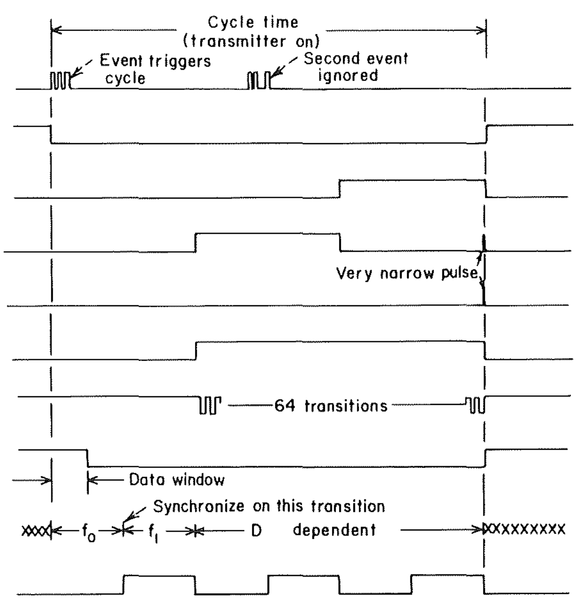
The data and transmitter control timing functions are shown in figure 10. Also shown in this figure are the data window and cycle timing information pertinent to the control functions of the circuitry.

All timing and frequency determining circuits in this system incorporate components with temperature coefficients of 60 ppm/° C or better. This insures accuracy of timing and low drift with the temperature extremes that are imposed upon the instrument in mine environments.

The channel read-in board is shown in figure 11, and a simplified wiring diagram in figure 12 shows the arrangement of the chips that perform the function of taking and holding the microseismic data. Three chip types are used on this board--4013's, which are Dual D flip-flops; 4528's, which are dual retriggerable monostables; and 4021's, which are eight-stage shift registers.

The 4013 accepts the microseismic data input and provides a negative-going pulse to the 4528, which in turn sets up the load enable in the 4021.

The 4021 is then parallel loaded with an eight-bit word. When commanded to do so, the data in all eight shift registers are dumped serially, beginning with channel 1 and progressing through channel 8. The entire circuitry is then reset and is ready to accept the next event or series of events. Figure 13 illustrates how the data are loaded, stored, and dumped for the eight-channel system. The data, when dumped, are transferred onto the serial data bus (pin 16) for further processing in other parts of the instrument.



4060 (U1)		
Pin	Divide by	Frequency
7	16	64 kHz
5	32	32 ↑
4	64	16
6	128	8
14	256	4
13	512	2 ↓
15	1,024	1 kHz
–	2,048	500 Hz
1	4,096	250 ↑
2	8,192	125 ↓
3	16,384	62.5 Hz

4040 (U2,U3)	
Pin	Divide by
9	2
7	4
6	8
5	16
3	32
2	64
4	128
13	256
12	512
14	1,024
15	2,048
1	4,096

Switch	Data window, msec	LSB time, msec
S1	256	1.0
S2	128	.5
S3	64	.25
S4	32	.125

Switch	Cycle time, msec	Serial data enable, msec	Bit time, msec
S5	12,288	8,192	128
S6	3,072	2,048	32
S7	1,536	1,024	16
S8	768	512	8

FIGURE 10. - Timing diagram for transmitter control.

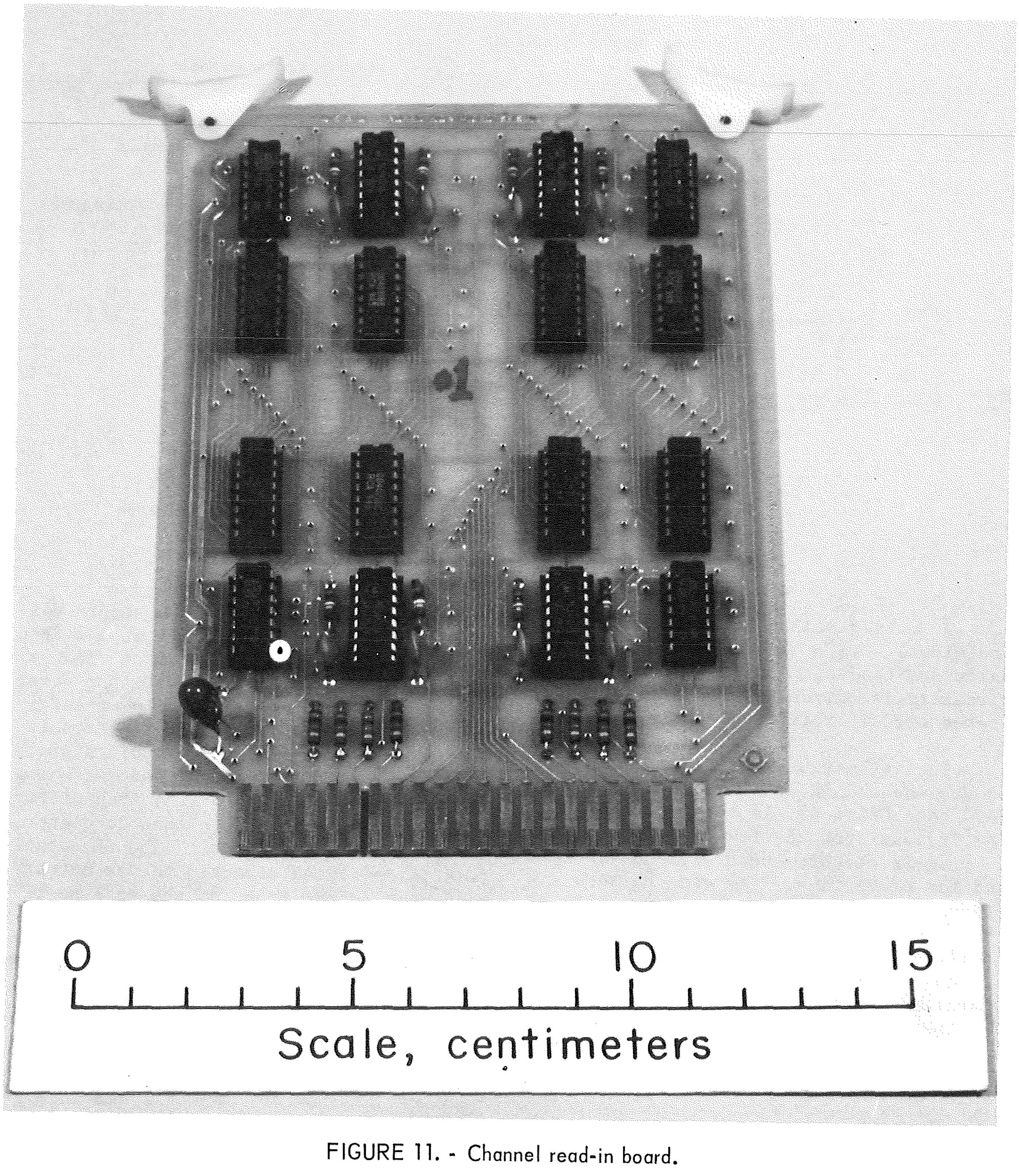


FIGURE 11. - Channel read-in board.

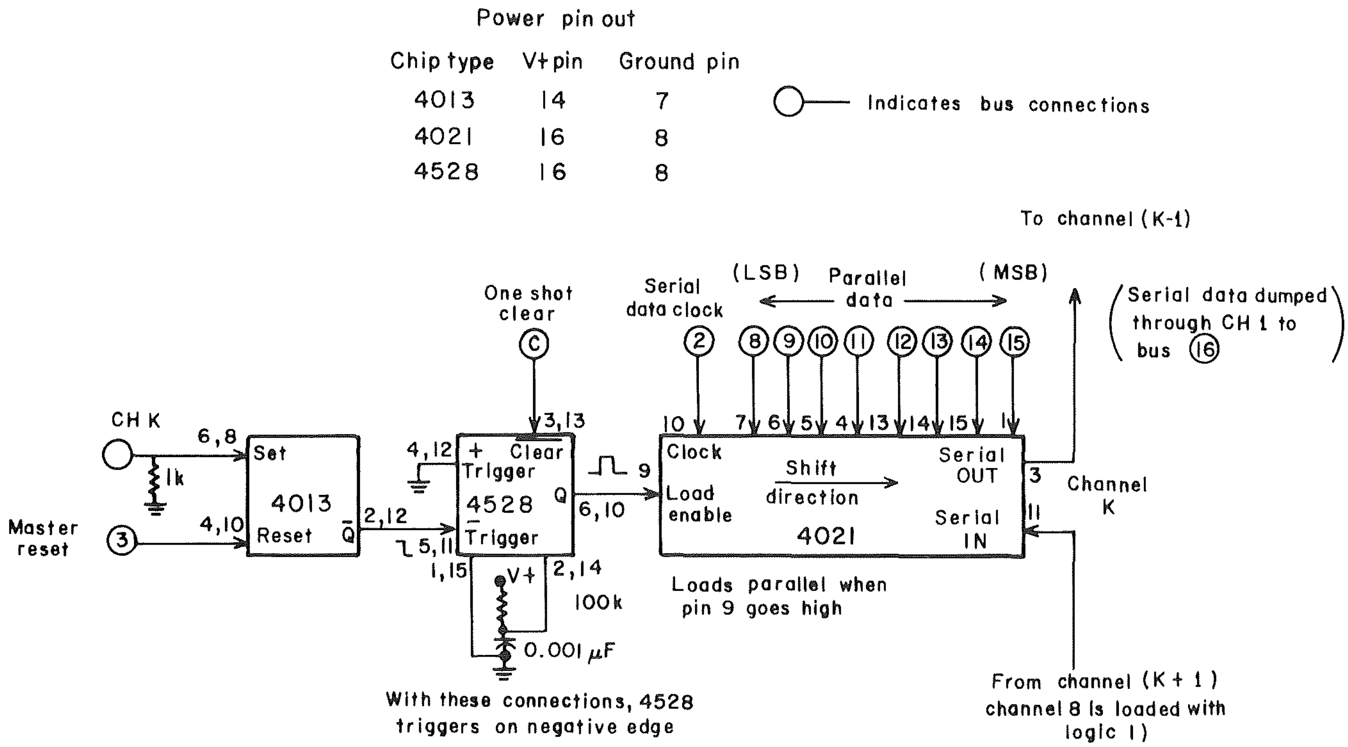


FIGURE 12. - Circuit diagram for one of eight channels.

A more detailed explanation of the individual CMOS (complementary metal-oxide semiconductor) chips used in this circuitry is given in any digital integrated circuit reference book (7).

The transmitter circuit card is shown mounted in the transmitter case card cage (fig. 6) in the left end slot. The transmitter device is mounted on a plug-in circuit card for convenience and for protection. As can be seen in figure 14, plug-in modules are used in the construction of this device. This facilitates troubleshooting and servicing by the substitution of modules. The spare modules are relatively inexpensive. The technical specifications of this device are presented in table 2. Although the specifications call for a supply voltage of 15 V d.c., the device has been operated satisfactorily from a nominal 13.2-V d.c. battery supply. Output power is reduced slightly by the lower supply voltage, but no other adverse results have been experienced. The audio signals from the tone generators and switching circuits are coupled to the transmitter device through the 22-pin bus connector, as are power and grounds. The RF output lead is connected directly to an antenna connector on the front of the case to reduce energy losses and eliminate the possibility of operating the module without the antenna connected, which could damage the output circuit components. No other connections are required.

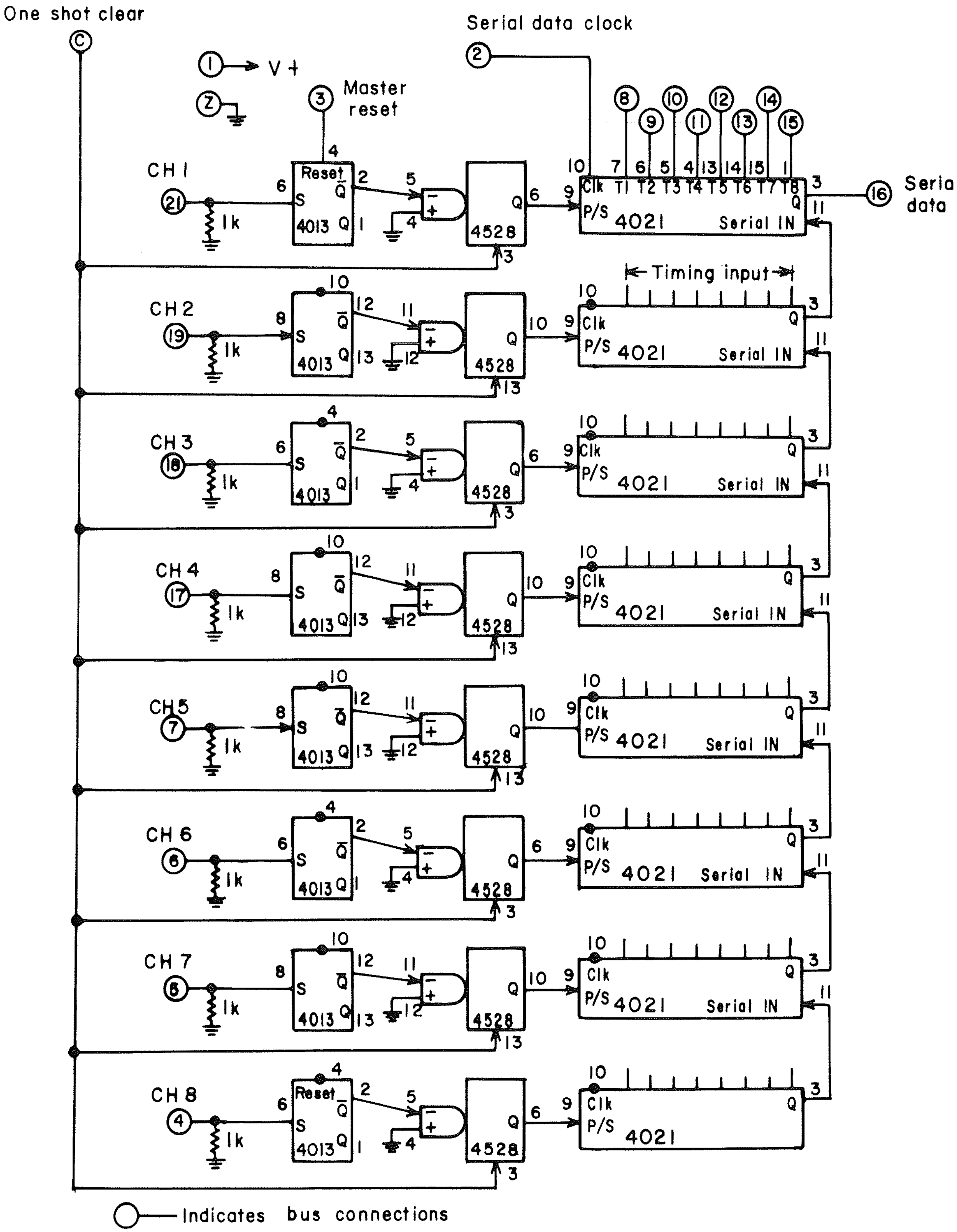


FIGURE 13. - Eight-channel data coding and transfer sequence diagram.

TABLE 2. - FM transmitter general specifications

Frequency range	132-174 MHz
Frequency stability	±0.0005 pct (-30° to +60° C)
RF output impedance	50 Ω
RF power output (50-Ω load)	0.4 W at 15 V d.c.
Emission type	15F2, 16F3
Power supply voltage	+15 V d.c. nominal
Operating range	+12.8 to +17.3 V d.c.
Power supply current	180 mA at 15 V d.c.
Audio input impedance	5 kΩ at 1 kHz
Audio input at 1 kHz for 3.3 kHz deviation	5-10 mV rms
Audio response, 300 to 3,000 Hz	+1, -3 dB of standard EIA 6 dB per octave preemphasis characteristic
Maximum audio distortion	6 pct at 2/3 rated system deviation with 1 kHz modulation
FM hum and noise	50 dB below 2/3 rated system deviation
Spurious and harmonics	49 dB below carrier
Physical dimensions:	
Length	8.43 cm (3.32 in)
Width	8.43 cm (3.32 in)
Height	2.54 cm (1 in)
Weight	99.1 g (3.5 oz), less external leads
Duty cycle, without degradation	Continuous

EIA Electronics Industry Association.

The output frequency is controlled by a temperature stable crystal oscillator operating at 9.465277 MHz. This frequency is the fundamental from which the 170.375-MHz RF carrier frequency is obtained after three stages of frequency multiplication (two triplers and a doubler, a factor of 18) to produce the final frequency of 170.374986 MHz.

Instrument Case

The transmitter unit, shown in figures 3 and 6, and its related circuitry are housed in a Zero Manufacturing Co. Model ZIP 840 case. This case was chosen for its durable 1.525-mm (0.060-in) thickness 6061-0 extruded aluminum construction, and its good sealing characteristics. The removable lid is fitted with a carrying handle for transporting the entire unit. The full-baked enamel finish affords excellent protection for the case from the elements, however, where chassis-type grounds are required, care must be taken to remove the enamel and expose bare metal to get satisfactory electrical connections.

The instrument case is supplied with a blank instrument panel and the mounting hardware. This panel must be punched or drilled to install the operator accessible controls and indicators which consist of a DPST (double pole, single throw) on-off switch, a SPST (single pole, single throw) test switch, two fuse holders (one for positive power in, the other for negative power in), one LED (light-emitting diode) indicator that lights when the transmitter module is on, and one d.c. voltmeter for monitoring battery status. Location of these items on the panel is optional provided that they do not interfere with the PC card cage that stands upright on the bottom inside of the case. To facilitate maintenance of the components mounted inside the case, the panel-mounted controls are joined to the remainder of the internal wiring through a seven-terminal connector, thus the entire top panel may be completely removed for service when necessary.

The transmitter case was organized so that all external connectors are mounted on the front of the case. This

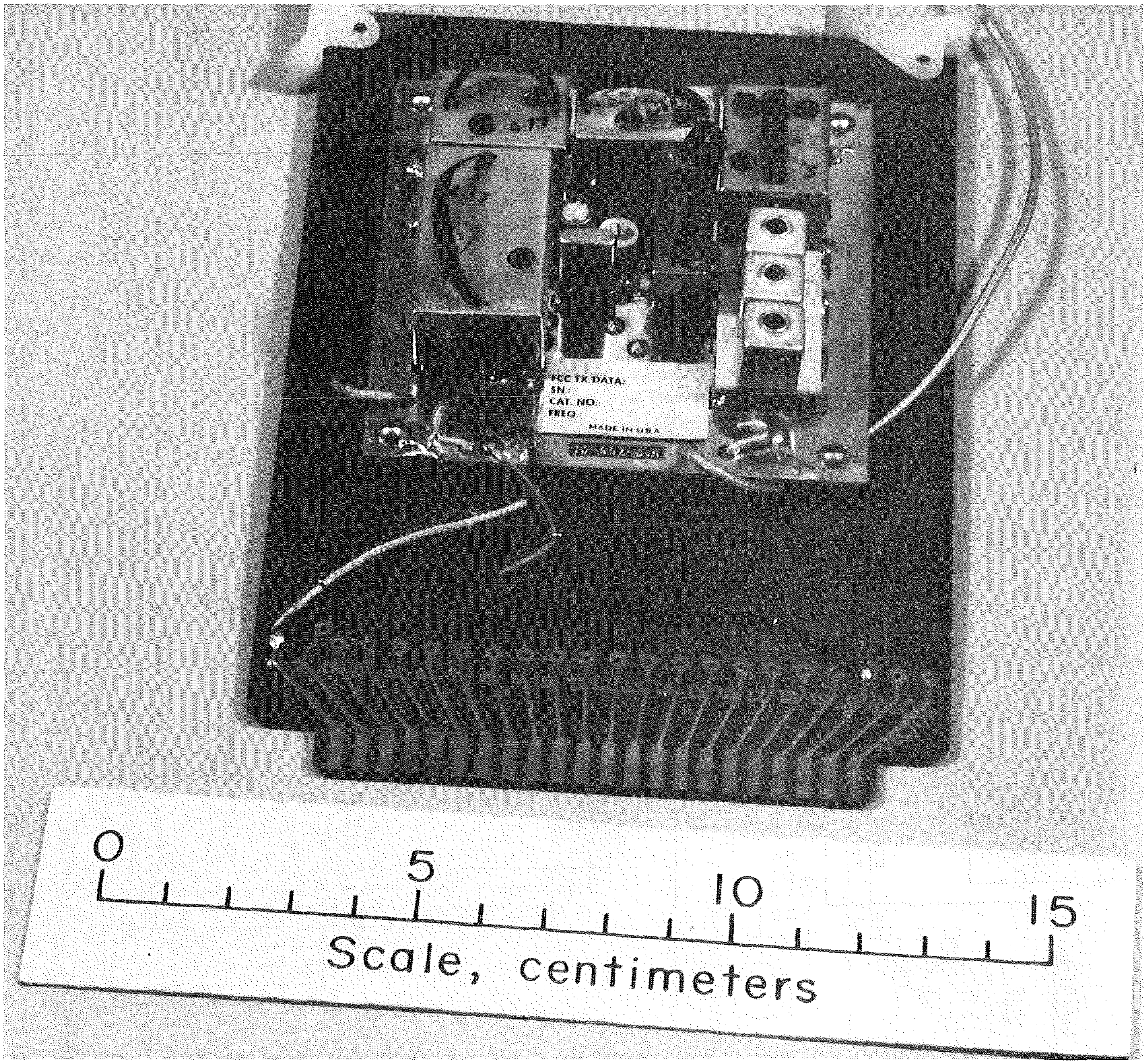
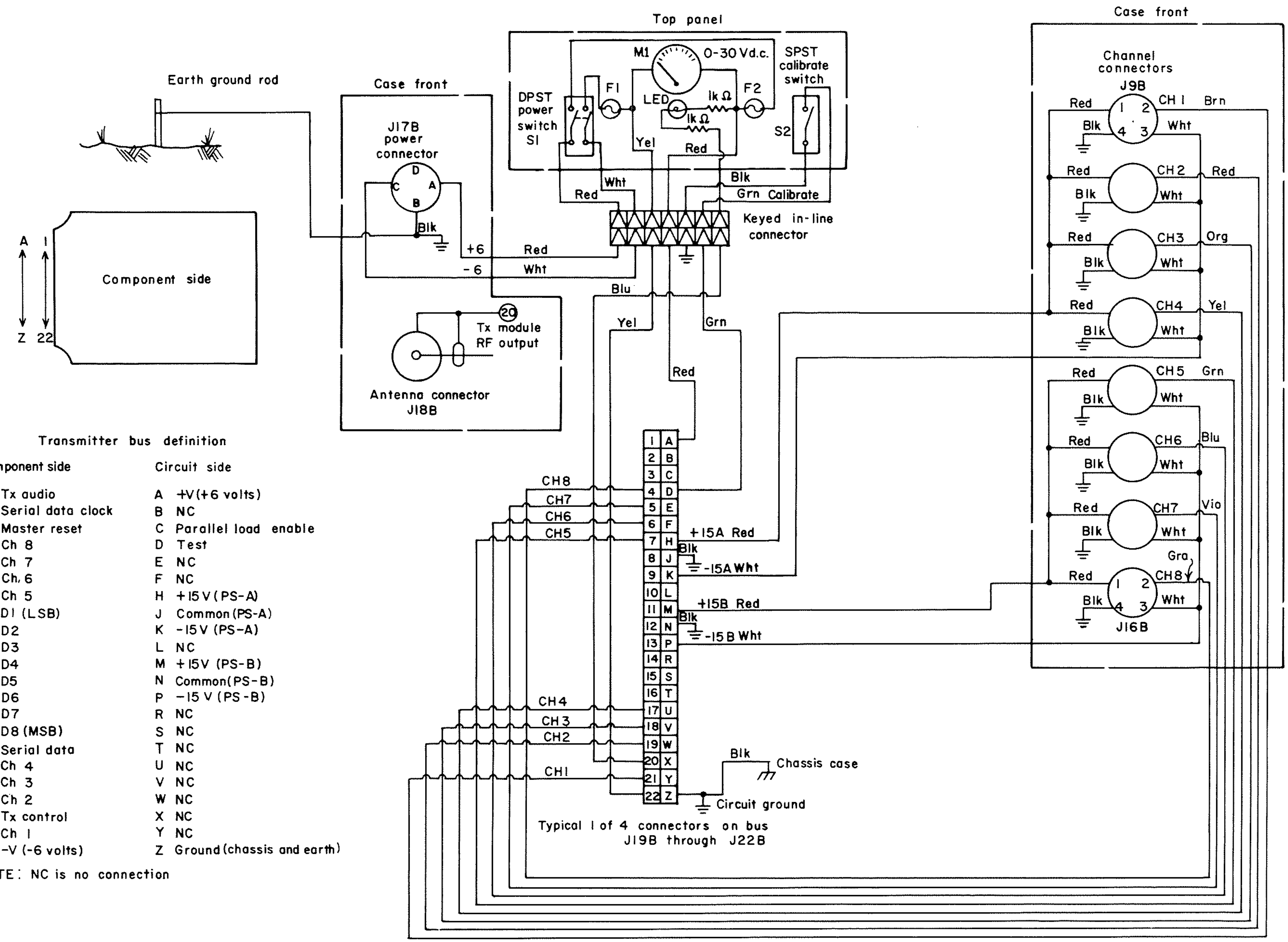


FIGURE 14. . Transmitter device mounted on plug-in card.

arrangement permits the unit to be operated with the lid to the box closed and latched, thus reducing the possibility of dust and moisture entering the enclosure during long-term unattended field operation. There are a total of 10 connectors for external electrical connections on the case; eight geophone channel inputs, a battery power input, and an RF antenna output. Each geophone cable input is an International Telephone and Telegraph Canon XLR-4 bulkhead connector. The power input jack may be any three-conductor bulkhead connector capable of carrying 2 A at 12 V d.c. All antenna connections utilize a standard RF coaxial connector. It is recommended that all connectors be chosen with threaded-barrel or with some other form of interlock to insure positive mating of male and female connector halves, thus preventing accidental disconnection of cables.



Transmitter bus definition

Component side		Circuit side	
1	Tx audio	A	+V (+6 volts)
2	Serial data clock	B	NC
3	Master reset	C	Parallel load enable
4	Ch 8	D	Test
5	Ch 7	E	NC
6	Ch 6	F	NC
7	Ch 5	H	+15 V (PS-A)
8	D1 (LSB)	J	Common (PS-A)
9	D2	K	-15 V (PS-A)
10	D3	L	NC
11	D4	M	+15 V (PS-B)
12	D5	N	Common (PS-B)
13	D6	P	-15 V (PS-B)
14	D7	R	NC
15	D8 (MSB)	S	NC
16	Serial data	T	NC
17	Ch 4	U	NC
18	Ch 3	V	NC
19	Ch 2	W	NC
20	Tx control	X	NC
21	Ch 1	Y	NC
22	-V (-6 volts)	Z	Ground (chassis and earth)

NOTE: NC is no connection

FIGURE 15. - Schematic for transmitter unit hard wiring.

Figure 15 shows the full schematic for wiring associated with the transmitter unit. All signal wiring is No. 22 stranded copper, and all power supply and distribution wiring is No. 18 stranded copper. Color coding greatly simplifies original wiring or wire tracing during troubleshooting and maintenance.

Power Source

A reliable source of power to the transmitter is a critical element of the overall system when considering long-term unattended field operation. In view of this, relatively expensive lead-calcium battery sets (fig. 16) were procured. Technical specifications are given in table 3. Battery size and capacity were determined for applications where the battery is provided with a photovoltaic source. These cells provide good long-term, shallow-discharge service when supported adequately by an intermittent recharging source such as a solar panel. Despite the solid state design of all system components, the transmitter demands a continuous battery drain of 625 mA when all eight channel preamplifiers are active. Intermittent turn on of the signal transmitter module caused by detection of microseisms increases this drain to about 775 mA for roughly 3 seconds. A problem was found in that this current demand often exceeded the recom mended shallow-discharge range on the lead-calcium cells. During shorter winter days, the drain on the battery system exceeded solar panel charging capabilities. Outside the shallow-discharge range, these are very slow recovery cells. These cells are a vented liquid electrolyte type that may leak if overturned. Consequently, airlines will not carry these batteries and shipping must be done by truck.

TABLE 3. - Battery data

Manufacturer	C & D	Gates
Type........................	Lead-calcium wet cell DCPSA-3	Lead-acid wet cell BC
Construction...............	Vented	Sealed
Rating at 25° C (77° F) Ah:	50 per 500-hr test 42 per 100-hr test 31 per 8-hr test	26 per 20-hr test 25 per 10-hr test 20 per 1-hr test
Voltage, V d.c.:		
Nominal..................	2.0	2.0
Minimum..................	1.95	1.75
Assembly details...........	3 plates per cell in plastic container	Spiral rolled plate with separator in an electrolyte filled cylindrical can
Number of cells used.......	6	12
Physical dimensions, mm (in) per cell:		
Length...................	91 (3.58)	157 (6.18)
Width....................	187 (7.36)	NAp
Height...................	262 (10.31)	NAp
Diameter.................	NAp	6.18 (2.59)
Weight kg (lb) per cell....	4.15 (1.89)	1.67 (0.76)
Specific gravity of electrolyte...............	1.3	Proprietary
Transfer efficiency at 25° C...............pct...	Undetermined	83
Percent of extracted energy returned, 8 hr at 2.5 V...	Undetermined	120

NAp Not applicable.

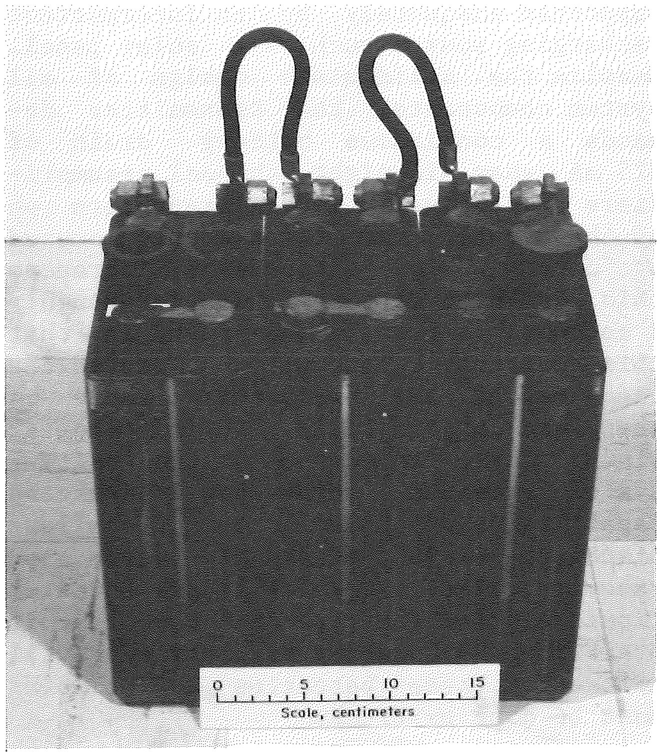


FIGURE 16. - C & D vented electrolyte lead-calcium cells.

To overcome the discharge rate problems while retaining the other more desirable battery characteristics, sealed cell lead-acid batteries were purchased and placed in service at Morenci, Ariz., and Denver, Colo. A bank of these cells is shown in figure 17. The technical specifications are listed in table 3. These cells, supported by solar panel recharging, have already provided continuous service for 6 months without maintenance of any kind. Since these are 25-Ah cells, in order to maintain the same rated total capacity as provided by the vented lead-calcium cells, 12 cells were series-parallel connected to provide the required +6-V, -6-V, and single polarity 12-V source voltages. This 12-cell arrangement actually provides greater total ampere hour capacity for an 8-hour test and accounts for the improved service. This is confirmed by better key specifications such as the percent of extracted energy returned per unit time, and transfer efficiency, which substantially improve the synergistic character of the solar panel and battery system. Another advantage is the ease with which the sealed cells may be packaged and shipped without fear of spillage. Airlines will accept this type cargo for transport, an advantage when it is desirable to relocate this system.

Solar Panel and Regulator

The solar panel and charging regulator shown in figure 18 were obtained as a part of a total remote power system package designed by computer analysis. The Solar Power Corp. provided this analysis in conjunction with the purchase of its Model M14-01301 solar electric panel. Selection of this panel was based on such parameters as design load, available sunlight hours per day (annually adjusted), and battery recharge power requirements. This panel has a maximum output capability of 20 V at 2.0 A. Each battery, regulator, and panel system selection is site specific for historic environmental conditions. The entire panel is constructed in such a way that it is completely weatherproof under a wide range of adverse conditions. The regulator supplied with the solar panel is a Solar Power Corp. model BVR-14-1. This is a voltage-type regulator that controls the panel output power allowed to return to the battery pack, limiting the voltage based on levels set by the operator. The specific regulator output voltages are determined from the recommended charging voltages for the battery system in use, and can be adjusted between 0.0 and 20.0 V. Use of such a regulator is essential in this application since unregulated panel output could cause overcharging, resulting in outgassing of battery electrolyte sufficient to boil the battery dry, or damage the sealed cells. Such a condition would not only cause the system to fail but could inflict permanent damage on the cells.

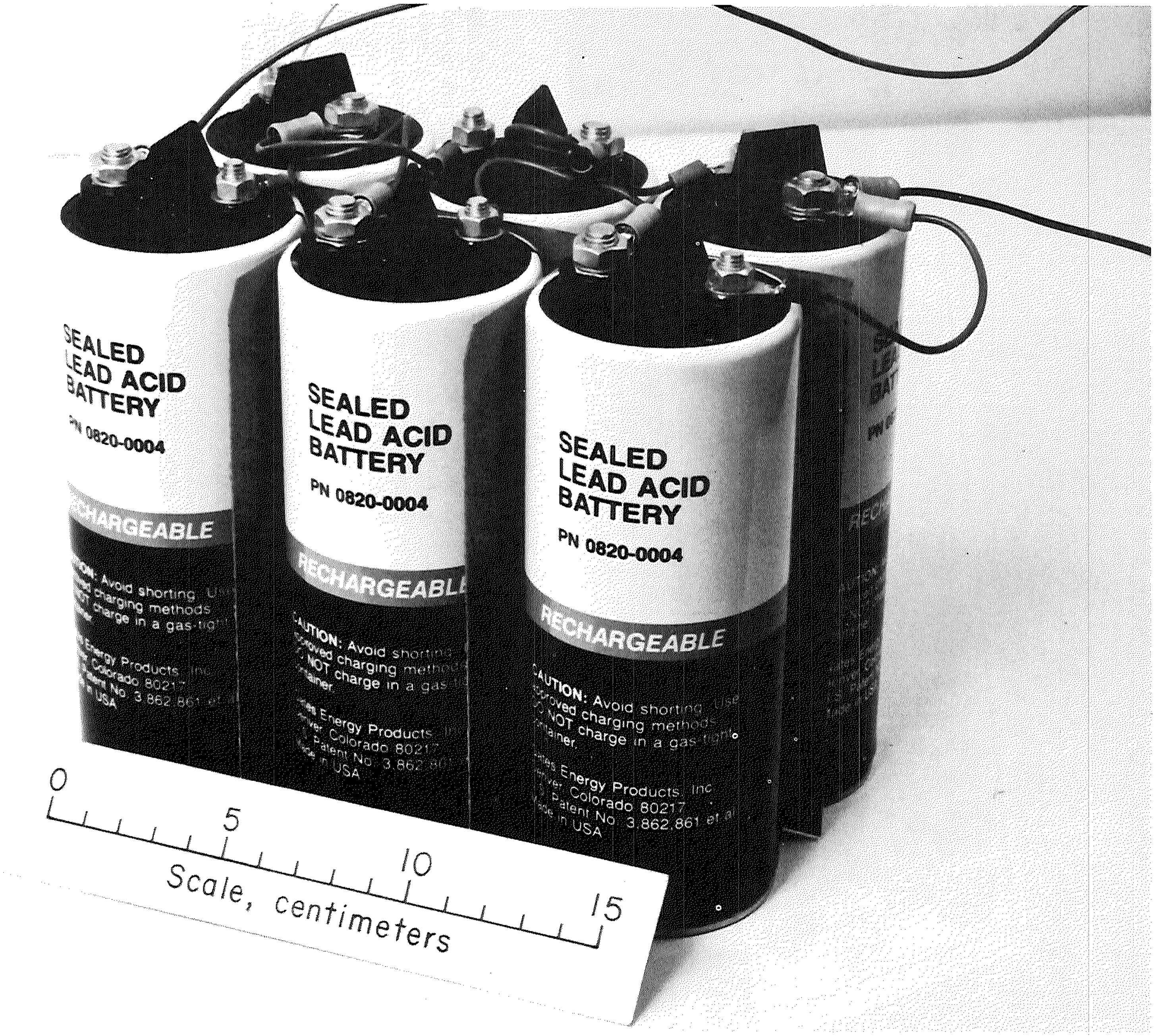


FIGURE 17. - Gates sealed lead-acid cells.

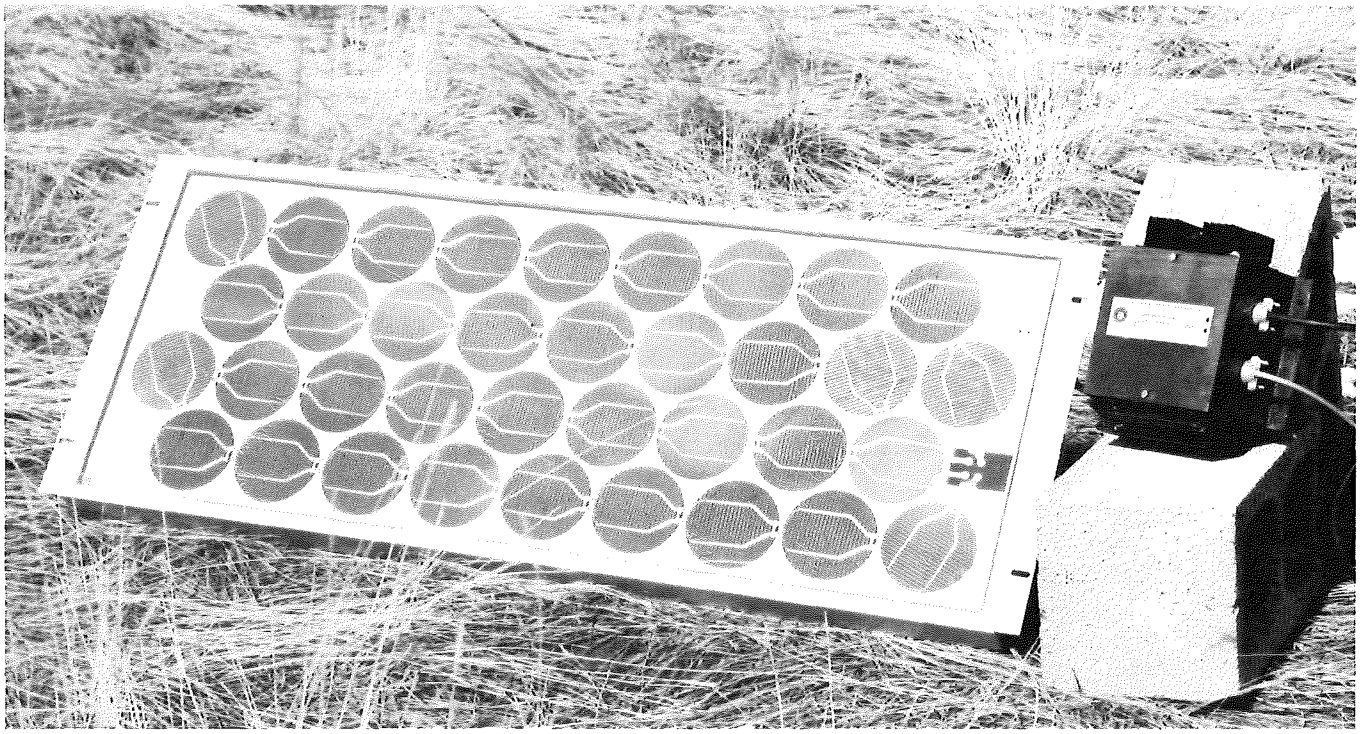


FIGURE 18. - Solar electric panel and voltage regulator.

Antenna

The antenna selected for the transmitter is shown in figure 19. It is a five-element, 52-Ω Yagi that was factory tuned by Scala Electronics to the specific frequencies required. It is a horizontal polarity antenna that has a major power lobe gain of 9 dB. Table 4 provides complete specifications.

Since the output impedence of the transmit module is about 50 Ω, peak power transfer to the antenna requires a section of coaxial cable with a characteristic impedance nearly the same. A length of standard RG-8 cable with threaded RF connectors was prepared and used. For relatively short lengths of antenna cable (10 m or less), standard RG-58 coaxial cable may also be used with a minimum of loss.

TABLE 4. - RF antenna specifications

Manufacturer.................	Scala Electronics Corp.
Model........................	CA 5-150-H
Type.........................	5-element Yagi dipole
Impedance....................	52 Ω
Frequency range..............	150-170 MHz (factory tuned)
Connector type...............	RF uhf
Polarity.....................	Horizontal
Gain, major power lobe.......	9 dB
Element material.............	Anodized aluminum
Assembly time................	5 minutes (color coded)
Assembled dimensions:	
Width......................	0.8 m (31 in)
Length.....................	1.1 m (44 in)
Height.....................	0.1 m (4 in)
Weight, with mounting bracket	13.1 kg (6 lbs)

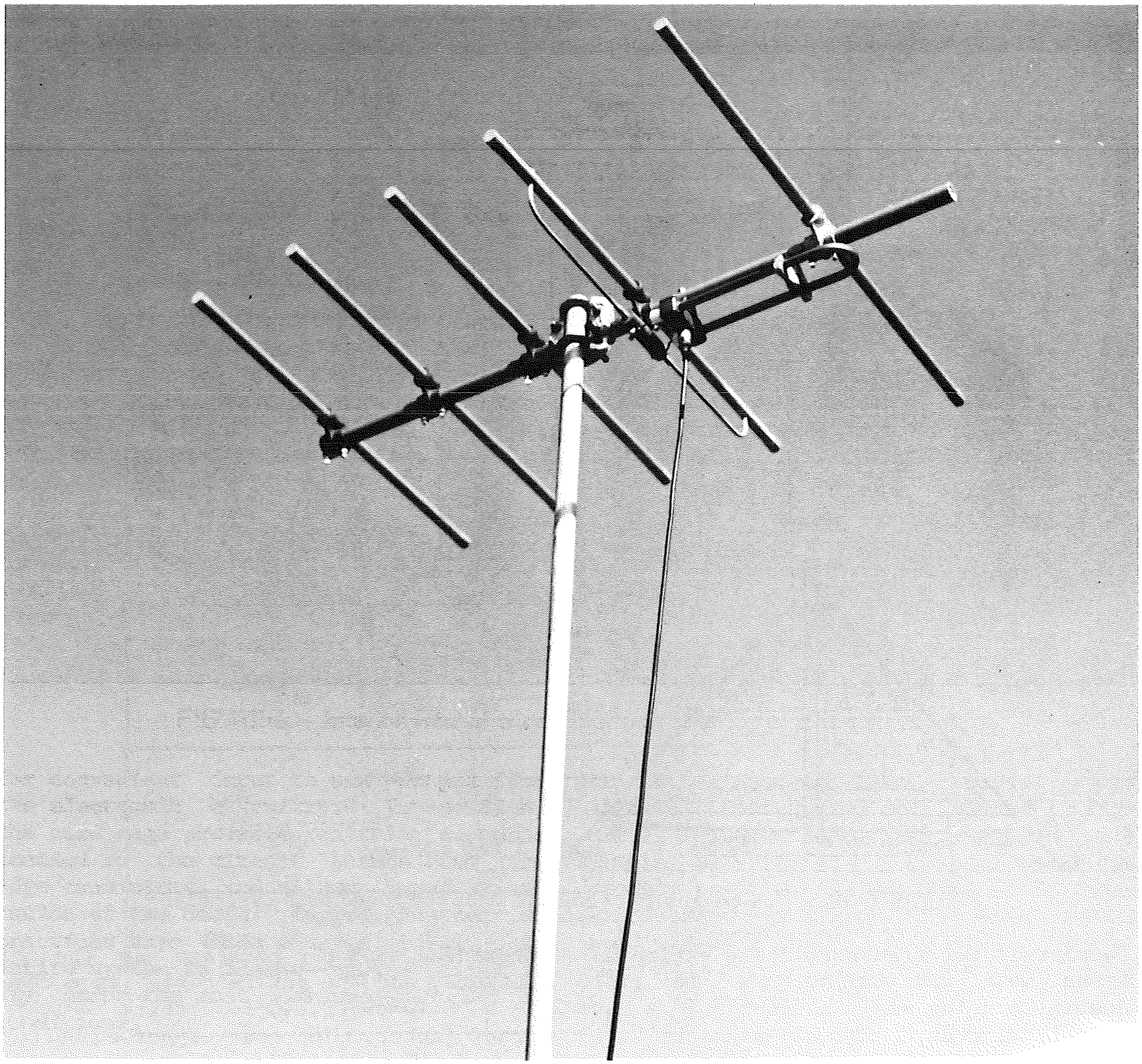


FIGURE 19. - Five-element, horizontal-polarity Yagi antenna.

In view of the essentially undirectional radiation pattern of this antenna, the physical alinement or aiming of the transmit antenna toward the receive antenna is an important consideration. The total distance over which this telemetry link will be usable can be adversely affected by poor alinement of the antenna.

In order to elevate and stabilize the assembled antenna unit, a special portable mast was designed and fabricated by the Bureau. It consists of two 6-foot sections of 3.18 cm (1-1/4 in) o.d. aluminum tubing with a removable tripod type stand. The mast sections may be shipped or transported in pieces and joined at the installation site using a 15.24 cm (6 in)-long, 3.18 cm (1-1/4 in) i.d. coupling piece and eight screws. The tripod attaches to the mast with a set of upper and lower donut-shaped rings fitted with set screws. The tripod may be folded

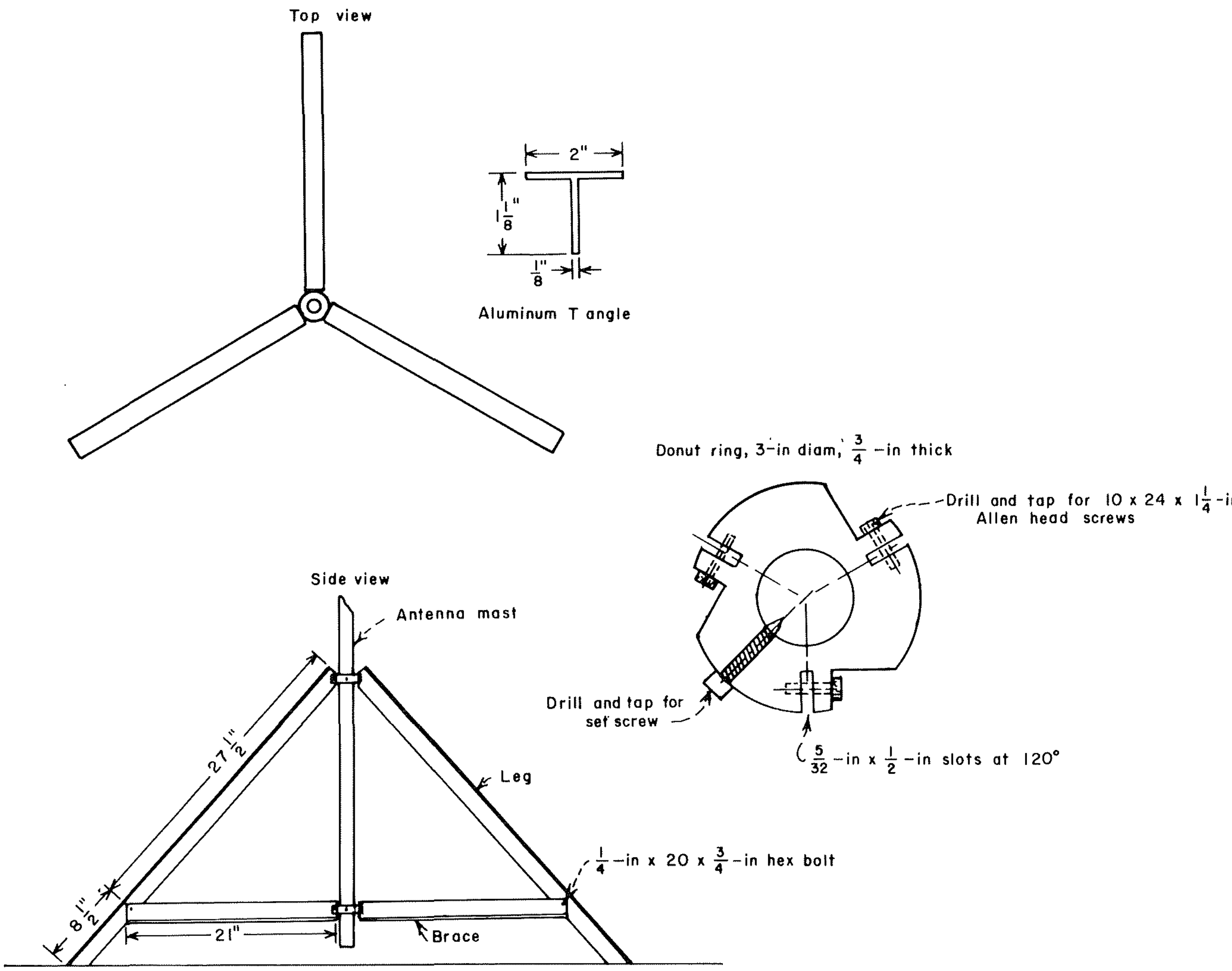


FIGURE 20. - Design details of antenna mast and tripod base assembly.

completely for transport. The entire antenna mast and tripod can be field assembled using small handtools in a matter of minutes. The all-aluminum construction on the mast assures years of useful, maintenance-free life in the field. Detailed drawings for this assembly are given in figure 20.

Cables

Distances from the geophone preamplifiers to the transmitter unit may often exceed 100 m, thus proper choice of signal cable is necessary to assure high fidelity and noise-free operation of the data collection system. This system utilizes Belden 8424 shielded cable containing four-color-coded 20-gage stranded copper conductors. The braided shield provided 83.5 pct coverage of the conductors, and the entire cable is encased in a 0.10-cm-(0.040-in) thick weatherproof jacket. The four copper conductors have d.c. resistances of just over 10 Ω per 300 m (1,000 feet) each.

This cable conducts power to the preamplifier from the ±15-V, solid-state, d.c.-to-d.c. converters in the transmitter. The red-colored conductor carries the +15-V conductor and the white is the -15-V conductor. The remaining black-and green-coded conductors are the ground return and geophone signal lines, respectively. The shield is grounded to the earth at the XLR-4 connector on the transmitter input jack to eliminate induced noise from electrical sources.

In-mine cable placement should be done with care since the cables may be damaged or completely severed by debris from sloughing slopes and benches. Though some rodent damage was experienced, the cable used is considered advantageous over other rodent-resistant types.

Repeater Station

An FM repeater station may be readily corporated into the telemetry link of this system. Some field monitoring situations may be sufficiently remote or in areas of such relief that a line-of-sight limitation may require the use of a repeater.

Such stations are commercially available in a variety of types and output wattages. Most are single-channel expandable units that are supplied with one set of crystals (receive and transmit) determined by user specifications. The microseismic system, as it is currently designed, will accept an off-the-shelf uhf (ultrahigh frequency) repeater station. A vhf (very high frequency) station in the 450- to 512-MHz band may also be used, but a different receiver module must be used in the system receiver unit. Repeater station specifications are generally recommended by trained sales personnel based on such parameters as distance, terrain, and frequency assignments for specific locations. Line of sight would still need to be maintained on an antenna-to-antenna basis from transmitter to repeater to receiver, but the distance over which the data could be relayed is limited only by the power available in the repeater. One other possible limitation exists in that the repeater would probably require a local a.c. power source to insure reliable continuous operation.

Geophones

Technical Considerations

When geologic structures move or when rocks fracture as a result of stress concentrations, multifrequency acoustic energy is released. These acoustic emissions are velocity gradients that emanate in all directions from their source. The ability of a medium to pass a certain specific signal frequency is an important factor in transmissibility determinations. There are no absolute figures that always apply to the transmission of the audio spectrum through in situ geologic media, but it has been well established and demonstrated that low-frequency signals travel more easily through earth materials with less attenuation, as witnessed by earthquake signal detection. On the other hand, high frequencies are attenuated severely as they pass through the earth. Thus, as the distance between source and detector increase, one can expect to experience more difficulty in detecting higher frequencies. The spherical radiation pattern of acoustic energies causes the signal energy to diminish in an inverse square relationship with distance, so that signal levels arriving at specific points on the surface above an energy release may be very small.

The inverse square law is stated mathematically as

$$A' = \frac{A}{r^2}, \qquad (1)$$

where A' = signal amplitude at distance, r,

r = the distance from the source to the detector, assuming a source of negligible radius,

and A = the original signal amplitude at the source.

The spreading loss is thus well defined and understood, and it is independent of frequency over the range of 1 Hz to 100 kHz. This inverse square law attenuation is accurate only for an isotropic homegeneous media, but since there is no such thing as widespread homogeneity in geologic structures, other factors must also be considered when trying to evaluate attenuation factors for acoustic energy signals.

There is another important amplitude attenuation factor due to absorption (7), which results from the frictional dissipation of energy in the form of heat. It follows the exponential function

$$\alpha = k\ f^n,$$

where α = the signal attenuation factor

k = a constant,

f = frequency,

and n = an exponent number.

This relationship defines the attenuation due to absorption as a function of frequency. The value of the frequency exponent is not in agreement among investigators. Many physical factors enter into this loss phenomena, such as material type, grain size, density, porosity, degree of water saturation, dynamic loading, and others. Experimental values indicate that the exponent falls somewhere between 0.5 and 2.0 (where α is in dB/λ, and f is in kHz), with strong evidence that it is most likely 1.0 ±0.1 (5-6). In this project work, it was assumed that attenuation due to absorption is directly proportional to frequency, or $\alpha = k\ f^{1.0}$.

The compressional wave velocities of earth materials range from about 200 m/s for loose soils to over 7,500 m/s for some very competent in situ rock types under high loading at depths in the earth. Average rock velocities are about 1,500 m/s. The wavelength of a signal is determined by the velocity of the signal through the media and the frequency of the waveform, and is stated by the relationship

$$\lambda = \frac{v}{f}, \tag{3}$$

where λ = wavelength in meters,

v = velocity in meters per second,

and f = frequency in hertz (cycles per second).

Hamilton (6) has determined that the absorption factor for acoustic and RF signals can best be stated in terms of attenuation per unit wavelength or

$$\alpha = \text{dB}/\lambda. \tag{4}$$

This investigator has also determined that the numerical values for attenuation fall between about 0.05 and 1.25 dB/λ, with the average value being about 0.5 dB/λ. Based on this range of values, figure 21 has been prepared to show the possible range of attenuation of signals for various parameters.

The total absorption loss, β, is defined by

$$\beta = N\alpha\lambda \tag{5}$$

where $N = r/\lambda$.

As an example, assume a sonic signal of 100 Hz propagating through a 240 m rock formation with a sonic velocity of 1,500 m/s,

$$\lambda = \frac{1{,}500\text{m/s}}{100\text{Hz}} = 15\text{m}. \tag{6}$$

If α = 0.5 dB/λ, β for 240 m of this rock is calculated to be 8 dB. That is

$$\beta = \frac{240\text{m}}{15\text{m}}\ (0.5\ \text{dB}/\lambda)(\lambda) \tag{7}$$

$$\beta = 8\ \text{dB}$$

Eight dB is approximately 0.6 of the original signal amplitude, which is lost due to absorption. The total signal amplitude loss then is the product of the spreading loss and the absorption loss.

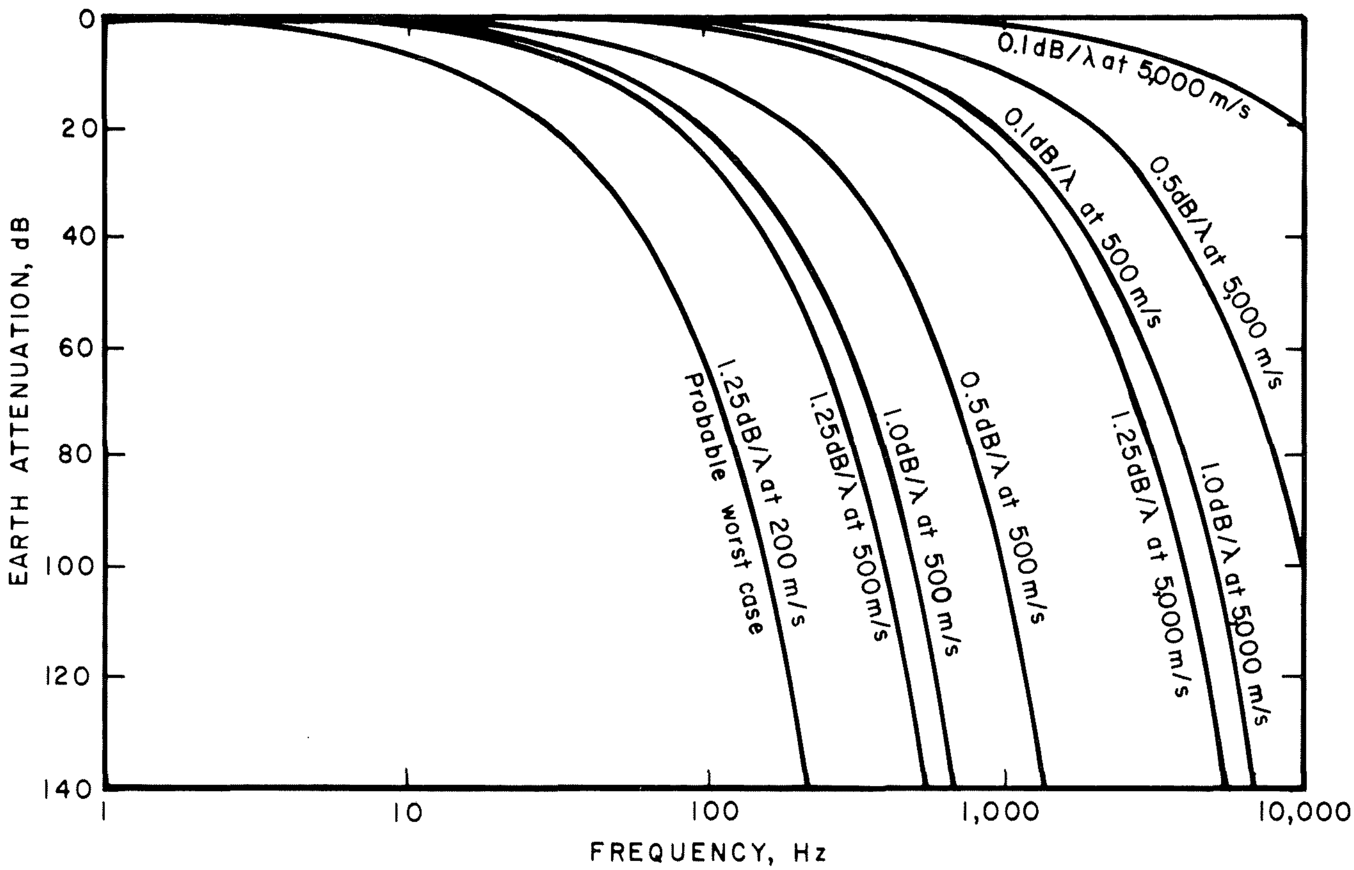


FIGURE 21. - Range of attenuation values of seismic energy based on various rates and frequencies.

The signal amplitude present at the detector is described by equation 8.

$$A'' = A \left[\frac{r_0}{r^2} (1 - \beta) \right], \quad (8)$$

where A'' = signal amplitude remaining at any distance, r,

A = original signal amplitude,

r_0 = radius of source or reference radius measurement,

r = The distance from the source to the detector,

and β = loss of amplitude due to absorption, in decimal number.

From this discussion, it is apparent that severe attenuation of sonic signals occurs in the earth, and that these factors must be considred when choosing instrumentation for microseismic applications.

The loss factor calculations are not always easily done in the field, so some approximation method is needed to permit design of field equipment and to make adjustments of this equipment on site. For field applications where an educated guess of the amplitude of acoustic signals is necessary, the use of the inverse cube rule ($1/r^3$) will give a usable approximation of remaining amplitudes for short distances from the source to the detector in the frequency range of 100 Hz to 5 kHz.

From the preceding, it must be concluded that the attenuation of acoustic energy from slope movements is usually very high. Sensitive devices must be employed to detect these minute particle velocities. Two general types of sensitive detectors are used to sense seismic signals; geophones and accelerometers. Geophones are velocity-sensitive detectors and are used in great numbers for all types of seismic work. Accelerometers are used occasionally in seismic work for special applications.

The term microseismic implies very low amplitude signals. Moving-coil geophones (by far the most popular type) are being used as the detectors for this project application. The selection of the geophones for this effort was made based upon field experience that has provided amplitude and frequency information for microseismic energies.

Field seismicity study shows that frequency, travel distance, and geologic structure are factors to be considered to arrive at general guidelines for selecting detector bandpass requirements. From these guidelines, frequency bands for specific field situations can be identified. For example, in slope stability studies where the travel distance from energy source to detector is 200 m or less, detection of frequencies up to about 500 Hz in competent rock can be expected. If the medium is very poor quality due to mine blasting practices or just generally unconsolidated material, the upper frequency limit for detection may be only 200 Hz over the same distance.

A troublesome low-frequency noise is generated by the normal activities of mining in working mines. Power shovels, trains, and heavy trucks generate energies in the subaudible band between 1 and 50 Hz. Blasting also creates a wide-band burst of frequencies that are detectable over great distances due to the large amount of energy released in a short time interval. In order to detect microseismic signals resulting from energies generated by slope movements, some means of discrimination against mining and blasting energies must be accomplished.

Initially, geophones with a natural frequency of 8 Hz were used to detect the microseismic signals from slope movements. It soon became quite evident that most of the energy detected was mine-operation related since the frequency of most of this energy was located in the 1- to 50-Hz band.

Each application must be analyzed and the best detector selected for that job. The value of the higher natural frequency geophones (100 Hz) has been proven for slope stability applications by observed elimination of most of the noises created by the mining operations. In field tests at an open pit mine, very little data caused by cultural noises were collected by the system. For different applications, of course, other detectors may match the need more closely.

The sensitivity of the detector is another important factor to consider during selection. The output voltage of various geophones ranges from about 0.2 $V/cm \cdot s^{-1}$ (volts per centimeter per second) (0.079 $V/in \cdot ^{-1}$) to over 2 $V/cm \cdot s^{-1}$ (0.79 $V/in \cdot s^{-1}$). This is a 10:1 ratio or 20 dB. The detector sensitivity will dictate how much gain the recording instrument must have and if a line driver preamplifier is necessary at the geophone location.

Damping of a geophone is accomplished by placing a shunt resistance across the output terminals of the geophones. This electrical arrangement performs several useful functions. Primarily, it helps prevent free swinging of the coil in the geophone by effectively providing dynamic braking and thus prevents oscillation. This arrangement can also be used to lower the output voltage to some specified level compatible with other system features. Damping in this manner tends to smooth the output voltage

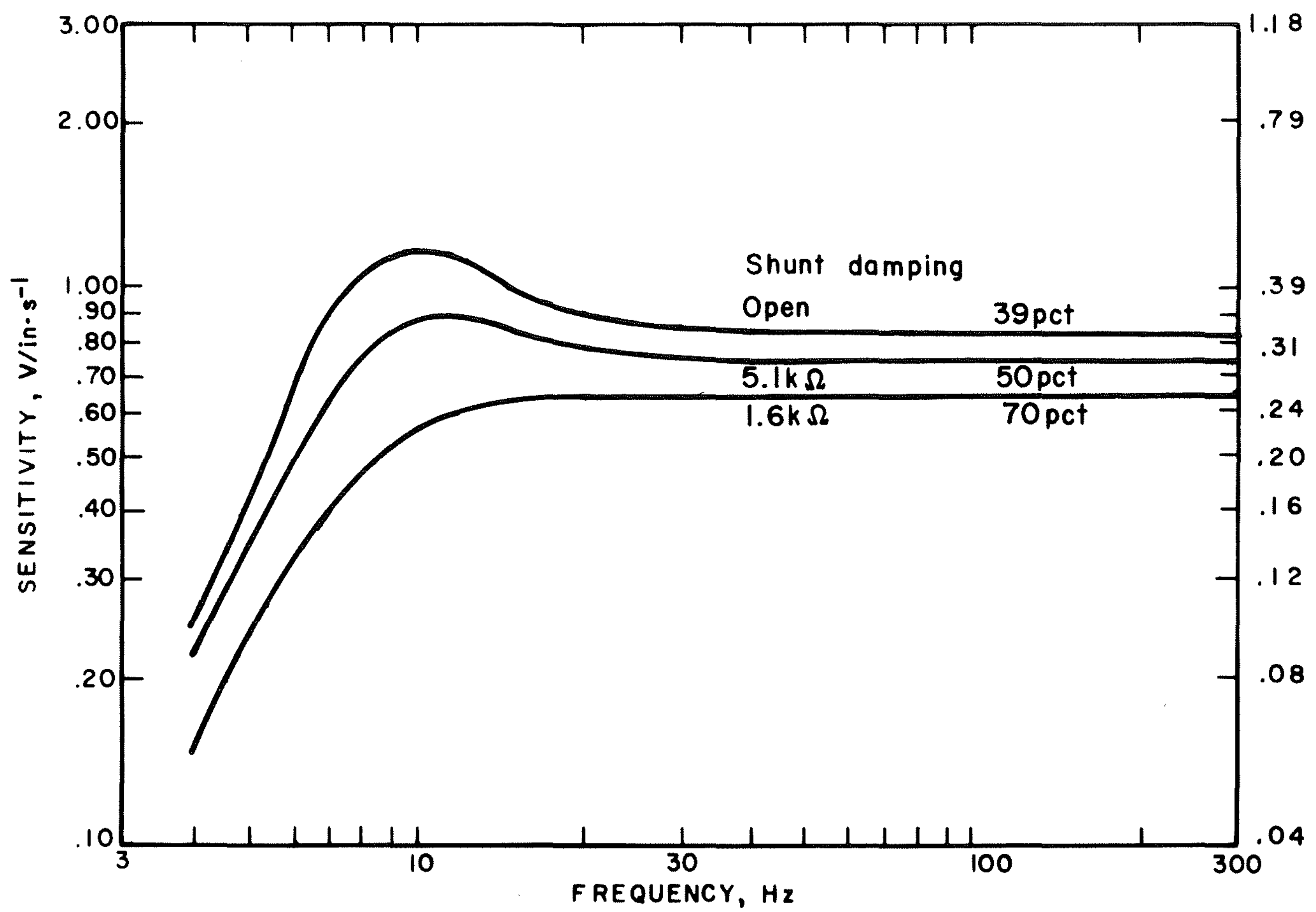


FIGURE 22. - Response curve for 8-Hz natural frequency geophones.

response curve of a geophone, eliminating natural frequency peaks and harmonic spikes on the response curve. Most geophones, regardless of application, will benefit from damping if smooth, noise-free operation is needed (8).

Figure 22 shows how the 8-Hz geophones respond to the very low frequencies. Different geophones were investigated and one was selected that helps to reject the troublesome low-frequency noises. The rolloff characteristics of the new geophones chosen helps to reject the unwanted frequencies below 100 Hz. The manufacturer's data sheet response curve of these geophones is shown in figure 23.

Types and Technical Specifications

The Geospace GS-100 geophone shown in figure 24 was selected for this project and is a 100-Hz natural frequency detector in a sealed marine-type encasement. The undamped output voltage response is approximately 0.6 $V/cm{\cdot}s^{-1}$ (0.236 $V/in{\cdot}s^{-1}$) with a 1,550-Ω coil. The geophone provides a relatively flat, clean response curve to about 500 Hz with adequate output voltage for most applications. These geophones are damped to provide exactly 0.4 $V/cm{\cdot}s^{-1}$ 0.157 $V/in{\cdot}s^{-1}$). Three of these units were dynamically tested by the Bureau.

The results of these tests are shown in figure 25 (8). Table 5 shows most of the technical specifications for these geophones.

TABLE 5. - GS-100 geophone specifications

Standard natural frequency	100 Hz ±5 Hz
Standard coil resistances at 25° C	600, 975, 1,550, 2,300 Ω ±5 pct
Coil design	Hum bucking
Clean band pass	To 650 Hz
Intrinsic voltage sensitivity:	
With 2,300-Ω coil	0.708 V/cm·s^{-1} (1.80 V/in·s^{-1})
With 1,550-Ω coil	0.575 V/cm·s^{-1} (1.46 V/in·s^{-1})
Normalized transduction constant	0.01456 $\sqrt{RC}$ V/cm·s^{-1} (0.037 $\sqrt{RC}$ V/in·s^{-1})
Harmonic distortion	2 pct or less with driving velocity of 1.8 cm/s (0.7 in/s) peak to peak at 100 Hz
Usable orientation	Intended vertical but usable through 360°
Open circuit damping	60 pct critical
Dimensions, basic unit:	
Height	3.4 cm (1.32 in)
Diameter	3.2 cm (1.25 in)
Basic unit weight	125 g (4.4 oz)
Cases available	PC-21 and QSC-27 (Marsh case)
Case environmental capability	Protection to 2.81 kg/cm^2 (40 lb/in^2)
Case seal method	Multiple O-ring seals
Case material	High impact polycarbonate
Case dimensions:	
Height	12.1 cm (4.8 in)
Diameter	4.4 cm (1.7 in)
Case weight	111 g (3.9 oz)
Anchor screw	5/16 in × 24 threads per inch

Field experience has taught much regarding practical applications of instruments to field problems. One area that cannot be overlooked is the coupling of the detector to the surrounding medium. For most installations in microseismic detection, the geophones should be installed at the bottom of a clean drill hole of adequate depth to insure penetration into competent material. This does two things; it improves the coupling to the geologic formation by avoiding loose or poorly consolidated material at or near the surface, and it reduces

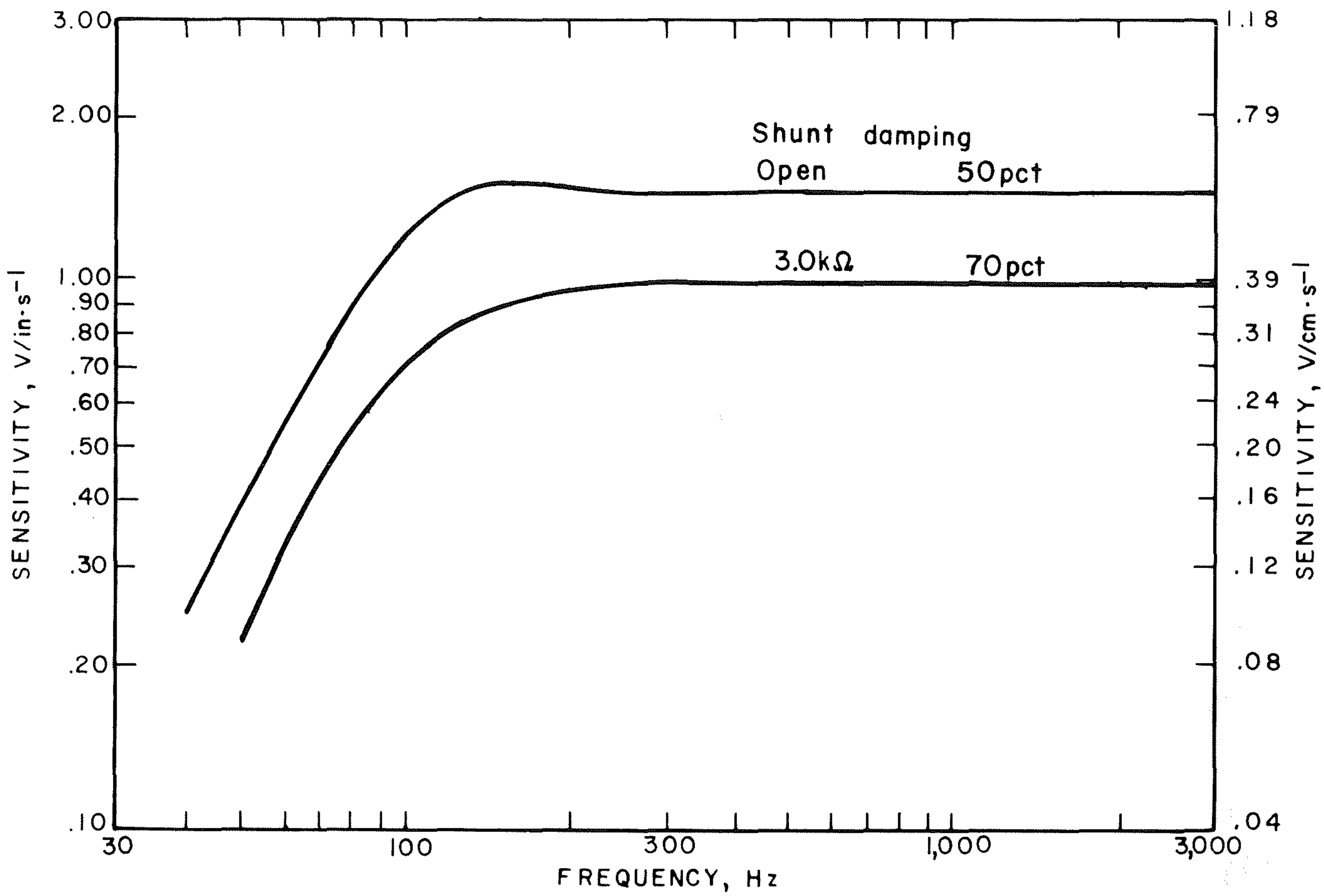


FIGURE 23. - Response curve for 100-Hz natural frequency geophones.

detection of surface noises created by wind, rain, rodent, and cultural activities.

Special Tools

The geophones selected for this project represent a significant portion of the system cost. A method was devised using special tools to permit the installation and retrieval of the geophones. Figure 26 shows one of these tools, and figure 27 provides the design details of all three special tools.

Mounting Techniques and Anchors

The method used to attach the geophone to the geologic structure is important to insure adequate coupling to the media. To accomplish this task, special anchors were designed and made. The design details of these devices are given in figures 28 and 29 along with the installation tool and a tap adapter that can be used to clean out the threads of the anchor after installation. The steel shaft of the anchor into which the geophone is threaded can be formed by any machine shop. This anchor is placed into a small amount of concrete at the bottom of a drill hole that is nominally 1 to 3 m deep. A rigid PVC (polyvinyl chloride) plastic drill hole liner has been found to be useful when placing the anchoring concrete. The liner is dropped into the hole, a large funnel is set into the top of the liner, and the concrete shoveled into the hole through the liner, thus preventing contamination of the concrete. The liner is used to "puddle" the concrete to remove air pockets and to insure good adhesion to the material at the bottom of the hole. A 10- to 20-cm depth of concrete is used in each hole. The liner is then pulled up a few centimeters and left in place in the drill hole. Using

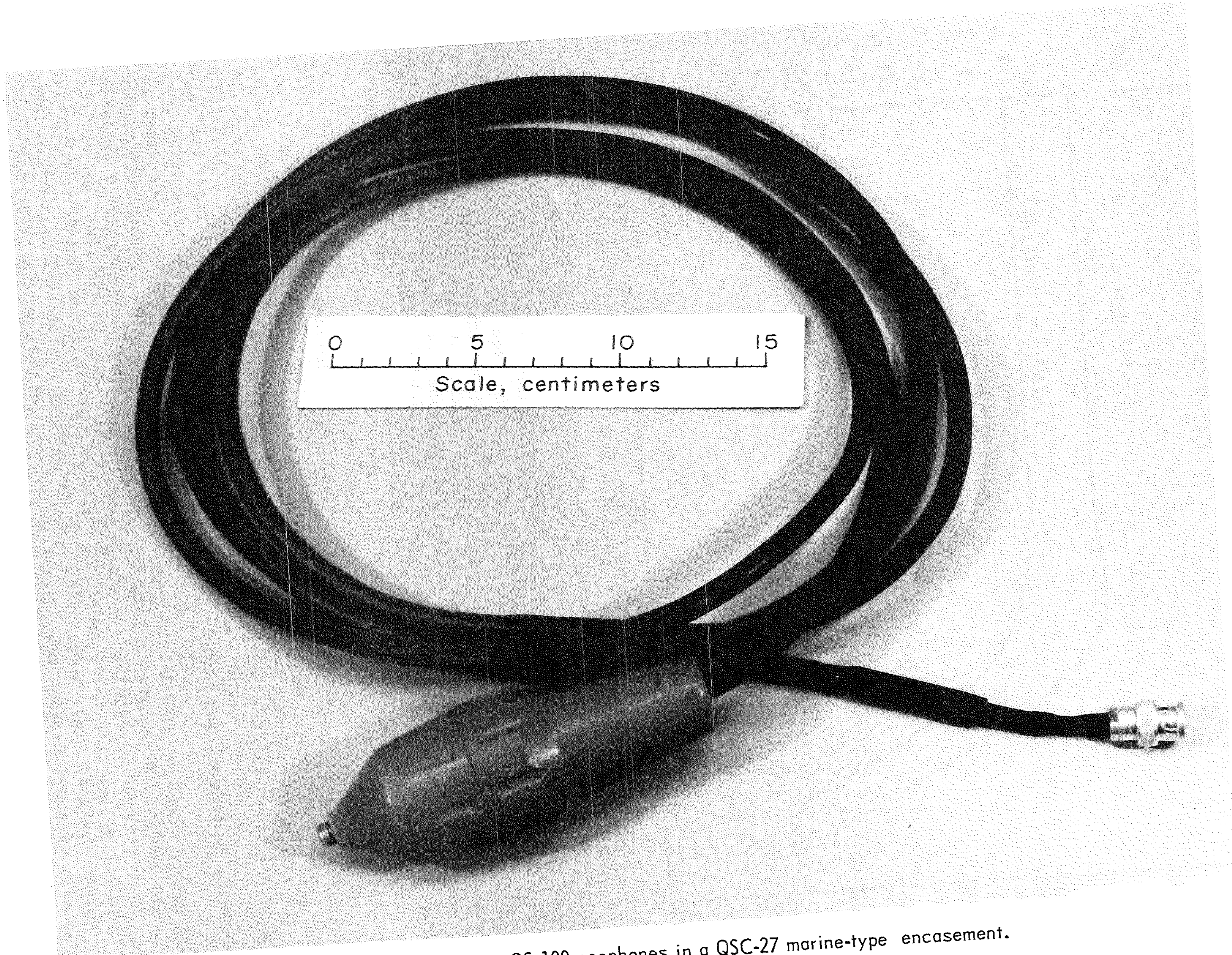


FIGURE 24. - Geospace GS-100 geophones in a QSC-27 marine-type encasement.

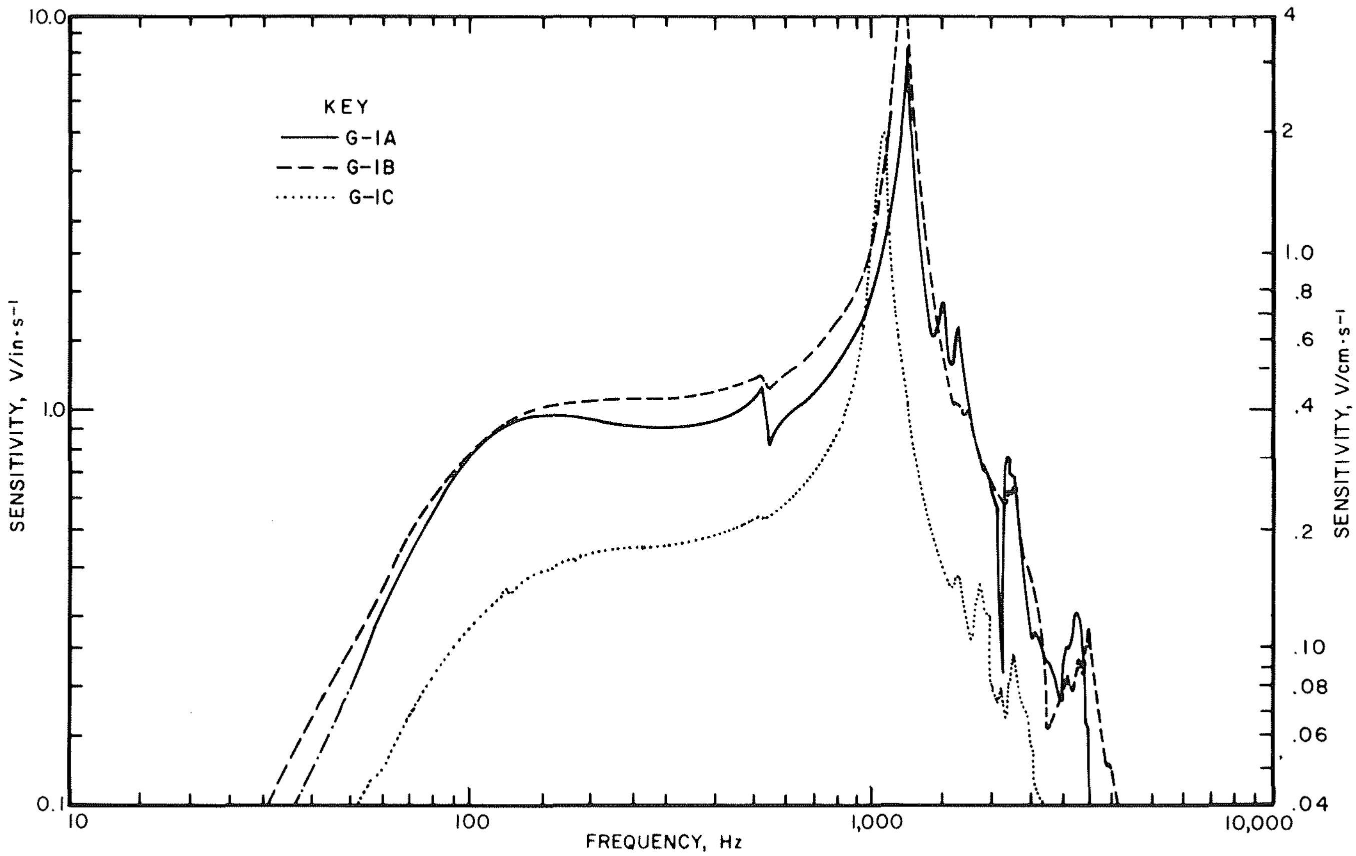


FIGURE 25. - Frequency response results of dynamic tests for three GS-100, 100Hz natural frequency geophones.

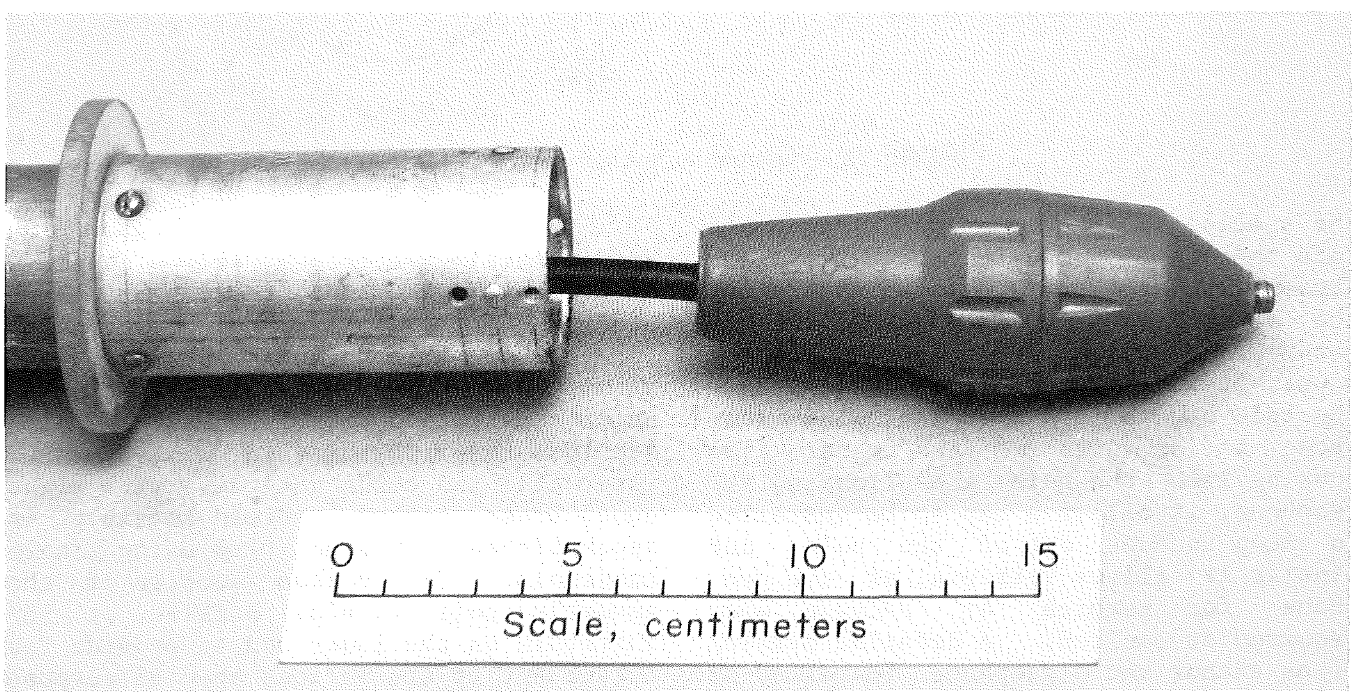


FIGURE 26. - Geophone installation-retrieval special tool.

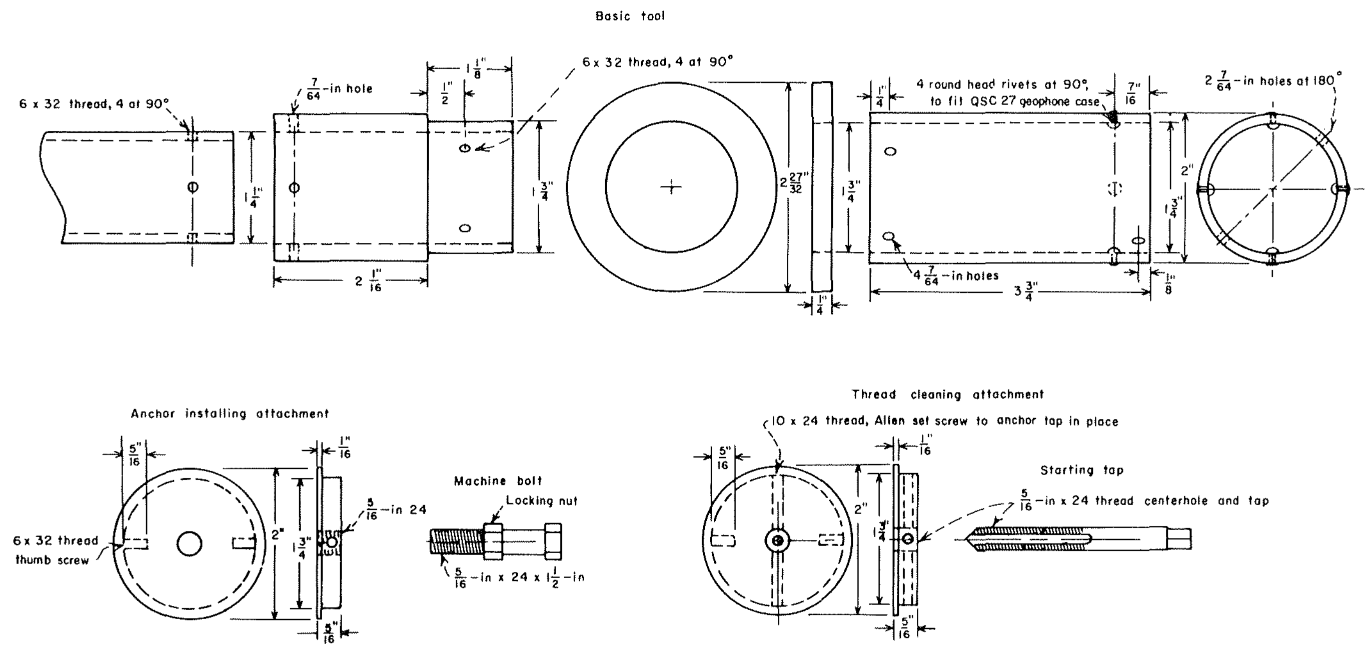


FIGURE 27. - Design details of all special tools.

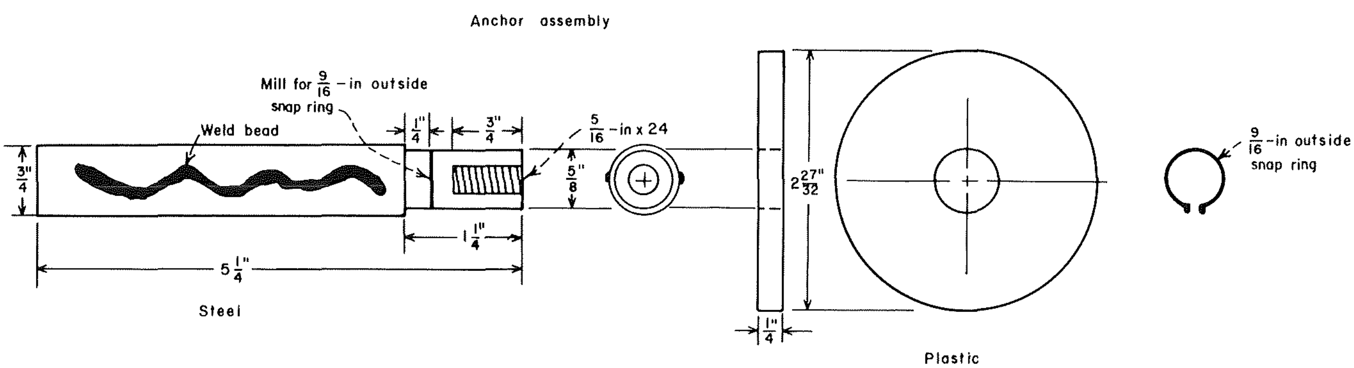


FIGURE 28. - Geophone anchor design details.

the special tools, the anchor is now set into the still wet concrete. The liner accomplishes several more functions after the anchor is set and the concrete hardens. It guides the geophone onto the mount, it keeps debris from falling into the hole on top of the installed geophone, it prevents mud and water from running into the hole and flooding the geophone, it allows a cap to be installed to keep rodents out of the hole, and finally it allows retrieval of the geophone for service or salvage when required or desired. A detailed drawing of an anchor and a geophone installed at the bottom of a drillhole is given in figure 30.

The loading pole for placing anchors and installing geophones, etc., consists of two (or more) 2 m (6-foot) sections of 3.18 cm (1-1/4-in) o.d. aluminum tubing joined by 3.18 cm (1-1/4 in) i.d. couplings. The loading pole assembly is sectioned to simplify transport. The sections and couplings are drilled at 90° intervals and held together with eight short brass screws. Field assembly is accomplished in minimum time using simple handtools. The bottom section of the assembled pole is also drilled at 90° intervals on the lower end to provide for attachment of the various special purpose tools described previously. A 0.63-cm (1/4-in) thick plastic disk attached to

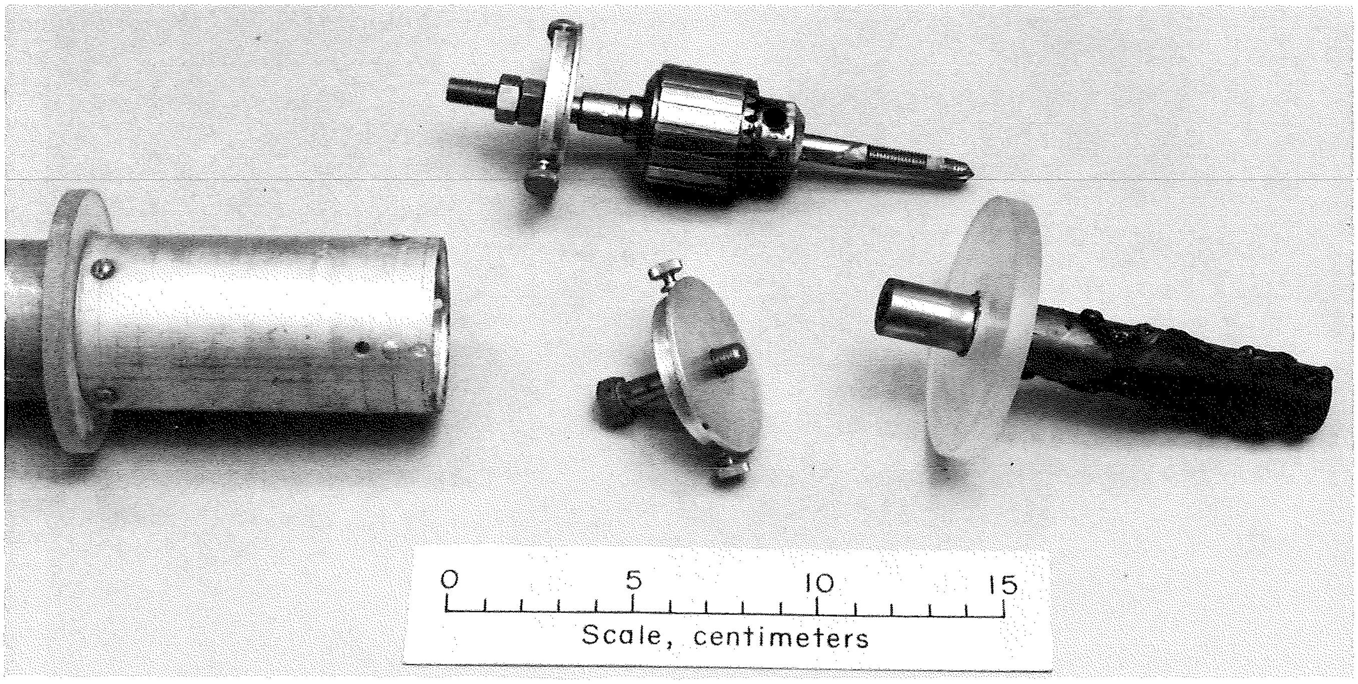


FIGURE 29. - All special tools and adaptors.

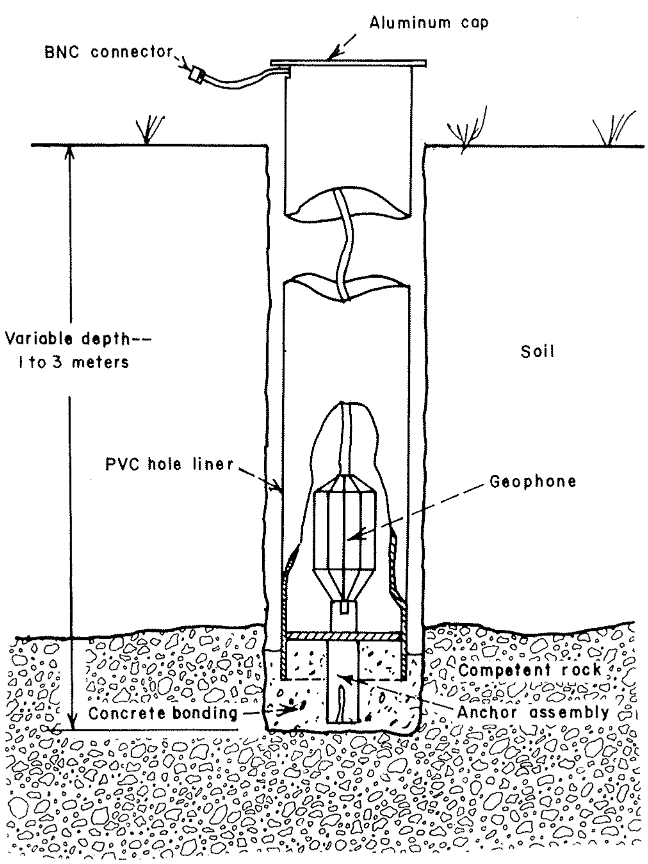


FIGURE 30. - Illustation of liner, anchor, and geophone in place in a drill hole.

the bottom of the pole provides a centering guide to assure proper alinement of each tool for its specific purpose. The disk is sized to provide clearance between it and PVC hole liner, thus allowing the tools to pass down the liner to the hole bottom for specific functions. Use of the special geophone installation-retrieval tool to install a geophone in a borehole is illustrated in figure 31.

Preamplifier

Technical Discussion

The particle velocity at the earth surface resulting from mine rock fracturing is indeed very small. To detect these minute velocity signals, sensitive detectors must be used. The velocity signal levels reaching the surface above a slope movement are usually in the 10^{-3} to 10^{-6}-cm/s range. A detector with a nominal sensitivity of 0.2 $V/cm \cdot s^{-1}$ (0.079 $V/in \cdot s^{-1}$) would generate an output voltage of 0.2×10^{-6} V for an event of 10^{-6}-cm/s (3.94×10^{-7}in/s) magnitude. Amplification of these signals is required to make them useful in a recording system. Voltage amplifiers are used to

FIGURE 31. - Demonstration of use of installation-retrieval special tool.

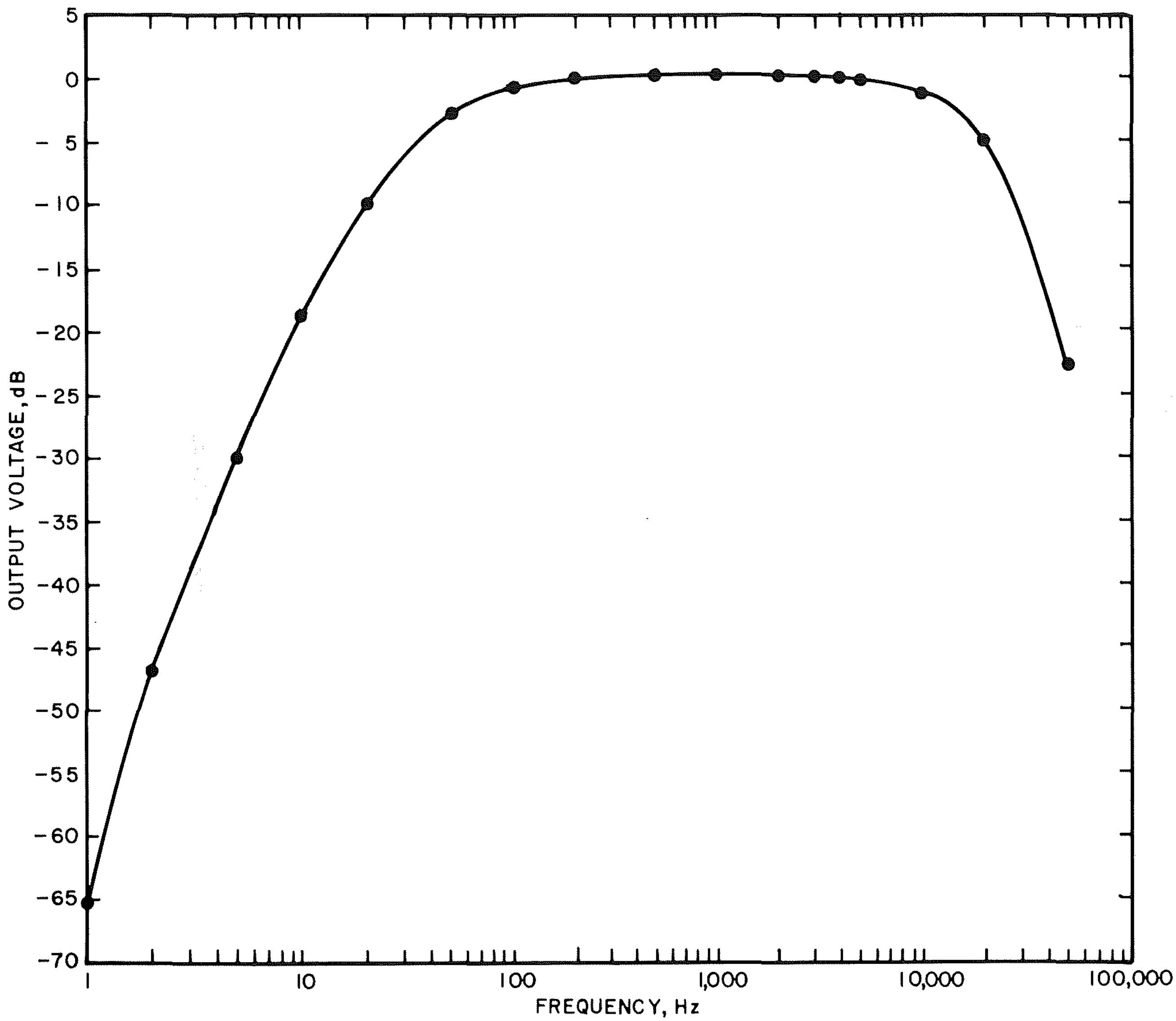


FIGURE 32. - Frequency response curve for the preamplifier analog section.

increase low signal voltages to higher voltages. Often other manipulation of the detected signals is required, such as filtering of the signals and detection of specific amplitude levels.

An amplifier that performs all of the functions mentioned is described in this section of this report, along with its technical parameters and specifications.

Design Criteria

Originally, an amplifier with a fixed gain of 60 dB was used to amplify the geophone output voltages. The original geophones exhibited sensitivities of about 0.3 $V/cm \cdot s^{-1}$ (0.118 $V/in \cdot s^{-1}$). The output voltages resulting from microseismic signals using these original pieces of equipment were on the order of 10^{-2} V peak; insufficient to activate the electronic circuitry of the system. Only very large magnitude seismic energies were detected. The lack of adequate dynamic range and the absence of low frequency rolloff filtering rendered the early design inadequate for the application.

New geophones were selected and new preamplifiers were designed, tested, and constructed.

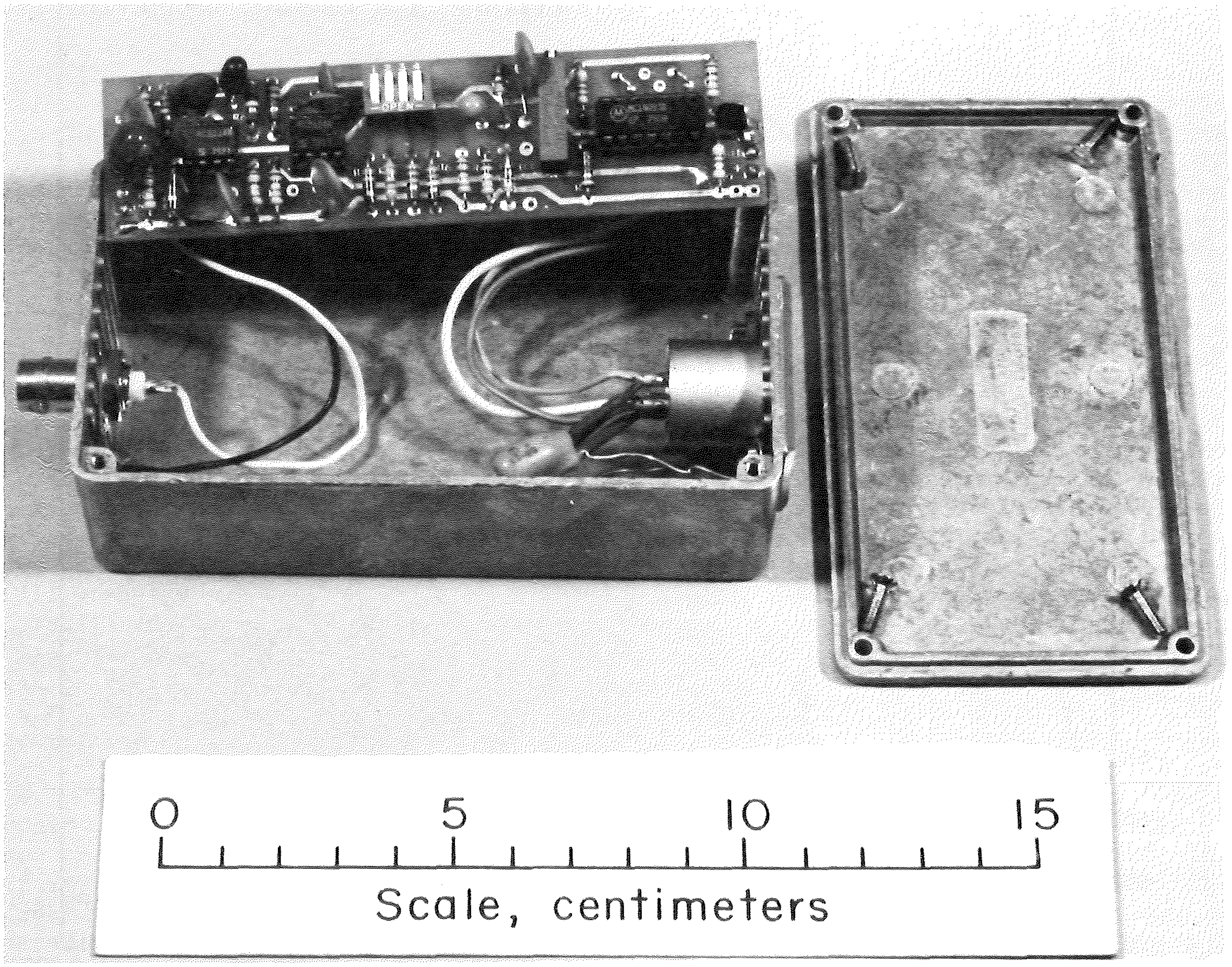


FIGURE 33. - Preamplifier circuit card and housing.

Minimum specifications were established for the voltage amplification section of the preamplifiers. These minimum requirements along with the final actual specifications are given in table 6. The response curve of the preamplifier is presented in figure 32. The low frequency end of the spectrum is purposely rolled off to help eliminate the detection of cultural noises that are prevalent below 75 to 80 Hz.

Circuit Description

The final design of the preamplifier circuit card and its housing is shown in figure 33. The four-section rocker switch provides for changing the gain from a minimum of 60 dB to a maximum of 120 dB in 20-dB steps. A schematic diagram of the preamplifier is presented in figure 34. The Signetics SE 5534 differential input operational amplifier chip was selected because it possesses very low input noise figures and a wide power bandpass. The voltage amplifier section of the preamplifier consists of two stages of amplification; the first stage fixed at 60 dB and the following stage with switchable gain from 0 through 60 dB in 20-dB steps. The performance (actual values) of the final preamplifier design is summarized in table 6. For those with a deeper interest, all electronic parts and values are identified in the appendix.

TABLE 6. - Preamplifier specifications

Parameter	Minimum requirements or desired value	Actual values or maximums
Gain range..dB..	60-100	60-120
Bandwidth..kHz..	5	8
Low cut frequency[1]...............................Hz..	80	50
Low frequency rolloff rate[2]........decibel per octave..	6	6-10
High cut frequency[1].............................kHz..	10	15
Input impedance...................................kΩ..	50	100
Output impedance...................................Ω..	1	0.3
Output voltage swing...............................V..	±12	±13
Frequency response[3]..............................dB..	±1	±1
Input noise....................................nV/√Hz..	10	4
Slew rate...V/μs..	5	13
Temperature range..................................° C..	-10 to +100	-20 to +70
Supply voltages....................................V..	±15	±22 (±15 used)
Supply current per chip...........................mA..	±4	±4
Supply current...................per preamplifier mA..	10, -10	+14, -12

[1]-3dB point.
[2]Below 60 Hz (see fig. 32).
[3]100 Hz to 8 kHz.

Also incorporated on the printed circuit card are a rectifier, a threshold detector, and a line driving stage. The rectifier allows only the positive-going portion of an amplified waveform to pass to the threshold detector and Schmitt trigger (4093BE). When a signal of sufficient amplitude arrives at the input of the Schmitt trigger chip, the trigger is activated and the transistor, Q1 (2N3904) switches on, providing a +5-V-d.c. voltage driver. This voltage is the signal sent to the transmitter unit and indicates arrival of a detectable microseismic signal at the geophone

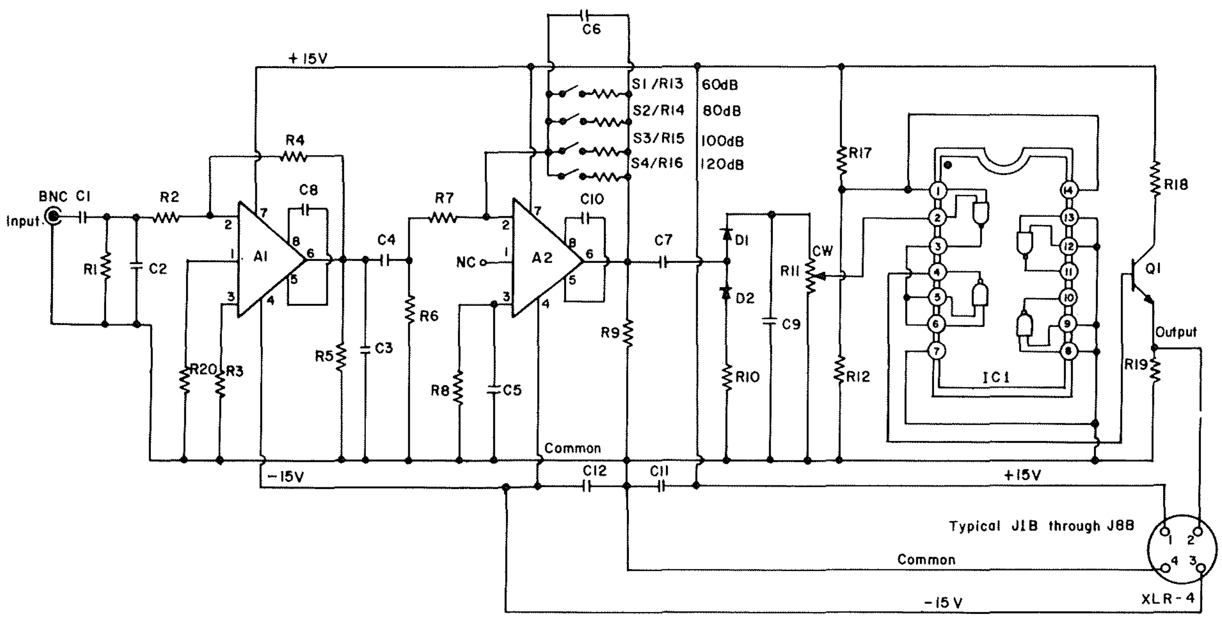


FIGURE 34. - Circuit schematic for preamplifier.

location. The minimum threshold voltage required to trip the Schmitt trigger is nominally 2.7 ±0.1 V (peak). Setting the level at this value prevents the system from triggering falsely due to small background noises, and insures reliable detection of most microseismic signals. A 20-turn trim pot (R11) allows the threshold level to be set to values greater than 2.7 V if deemed necessary.

The preamplifier is placed near the geophone to keep input noise at the lowest possible level. The output signal (+5 V d.c.) is carried to the transmitter case by one conductor in a four-conductor shielded cable. This technique eliminates noise entry into the instrument system. Two other conductors in the interconnecting cable carry +15 V d.c. to the preamplifier circuitry; and one conductor is a common return. The shield is connected to an earth ground at the transmitter to prevent spurious static and radiated noises from entering the transmitter electronics.

The input to the preamplifier unit is through a BNC bulkhead connector on one end of the aluminum box that houses the preamplifier. Supply voltages to and the output signal from the circuitry connect through an XLR-4 bulkhead type connector on the opposite end of the amplifier housing. The particular aluminum box used to house the amplifier circuit board was chosen for its convenient size and simplicity. It is, however, not hermetically sealed. Other provisions have been made to protect the amplifier circuitry from the elements. A 6-mil plastic sleeve slipped over the entire case and secured with plastic ties provides adequate protection from moisture. A simple tent formed from 0.15-cm (0.062-in) sheet aluminum can be used to protect the amplifier from excessive heat from the sun when necessary. These simple protection schemes are shown in figure 35 and have proven adequate for the environmental adversities experienced to date.

Receiver System

Electronics

Experimentation with tone decoder circuits revealed that temperature stability is a primary problem with this type of electronic circuit. Temperature stable tone decoders were designed, tested, and incorporated into the receiver. A complete flow diagram of the present receiver system is shown in figure 36. The RF-FM receiver is a manufactured unit that was purchased "off the shelf." The tone decoder board was developed by the Bureau. The data processing hardware was purchased and then modified by the Bureau to meet the needs of this application. Each section is discussed in detail in the following text. The receiver case wiring is shown in figure 37.

The RF receiver is a very small, modular FM radio receiver operable in the 162- to 174-MHz frequency band. This unit, and the RF transmitter are manufactured by Repco, Inc. The two receivers in use have proven quite reliable during 1 year of field testing. The audio output level and the noise squelch may be adjusted with two small potentiometers on the circuit board of the receiver. These are essential in setting up the operation of the data line. The squelch pot is set to eliminate all background noise passing into the audio output circuitry. The audio output level is adjusted to provide a nominal audio signal amplitude of 1 V peak to peak into the tone decoder input circuitry.

The RF receiver uses the dual conversion technique with dual crystal controlled local oscillators to accomplish its high performance in minimum space. All circuitry is encased in small plug-in modules. This facilitates maintenance as

FIGURE 35. - Environmental protection methods for field installation of preamplifier.

replacement modules are interchangeable and are not expensive. The technical specifications of this receiver are presented in table 7.

TABLE 7. - FM receiver general specifications

Frequency range	132-174 MHz
Frequency stability	±0.001 pct (-30° to +60° C)
Sensitivity	<0.35 μV/12 dB SINAD; <0.5 μV/20 dB quieting
Spurious and image rejection	70 dB below carrier
Noise squelch sensitivity	<0.25 μV
Adjacent channel rejection	80 dB (20 dB quieting), 132-174 MHz
Modulation acceptance	±7 kHz
Audio output power	500 mW at less than 10 pct distortion
Audio output impedance	25 Ω
RF input impedance	50 Ω nominal
Current drain	8 mA at 12 V d.c. (standby), 87 mA at 12 V d.c. (receive)
D.c. operating range	12 ±1.5 V d.c.
Physical dimensions:	
Length	8.43 cm (3.32 in)
Width	8.43 cm (3.32 in)
Height	2.54 cm (1 in)
Weight	175 g (6 oz.)

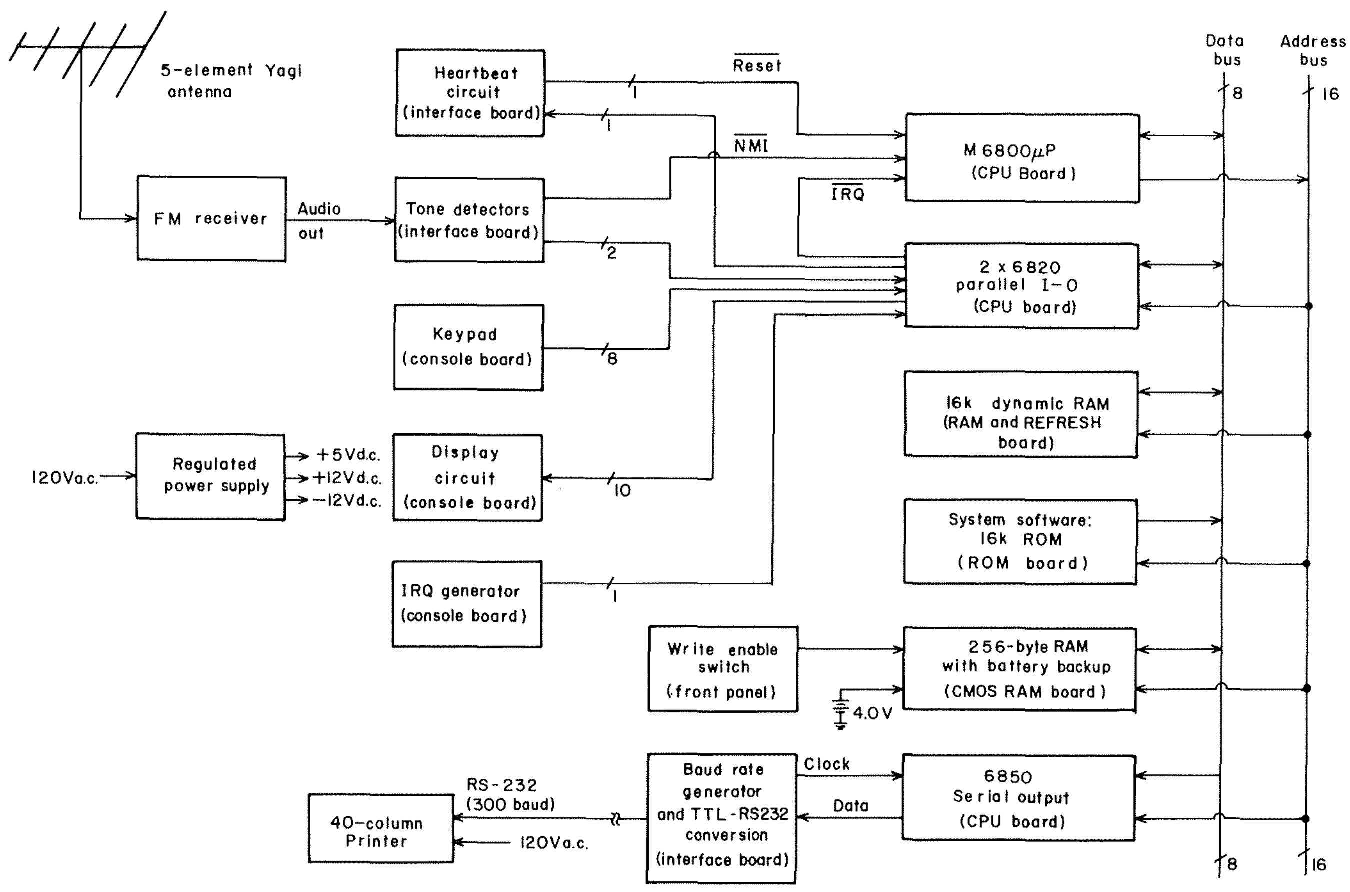


FIGURE 36. - Flow diagram for functions of receiver unit.

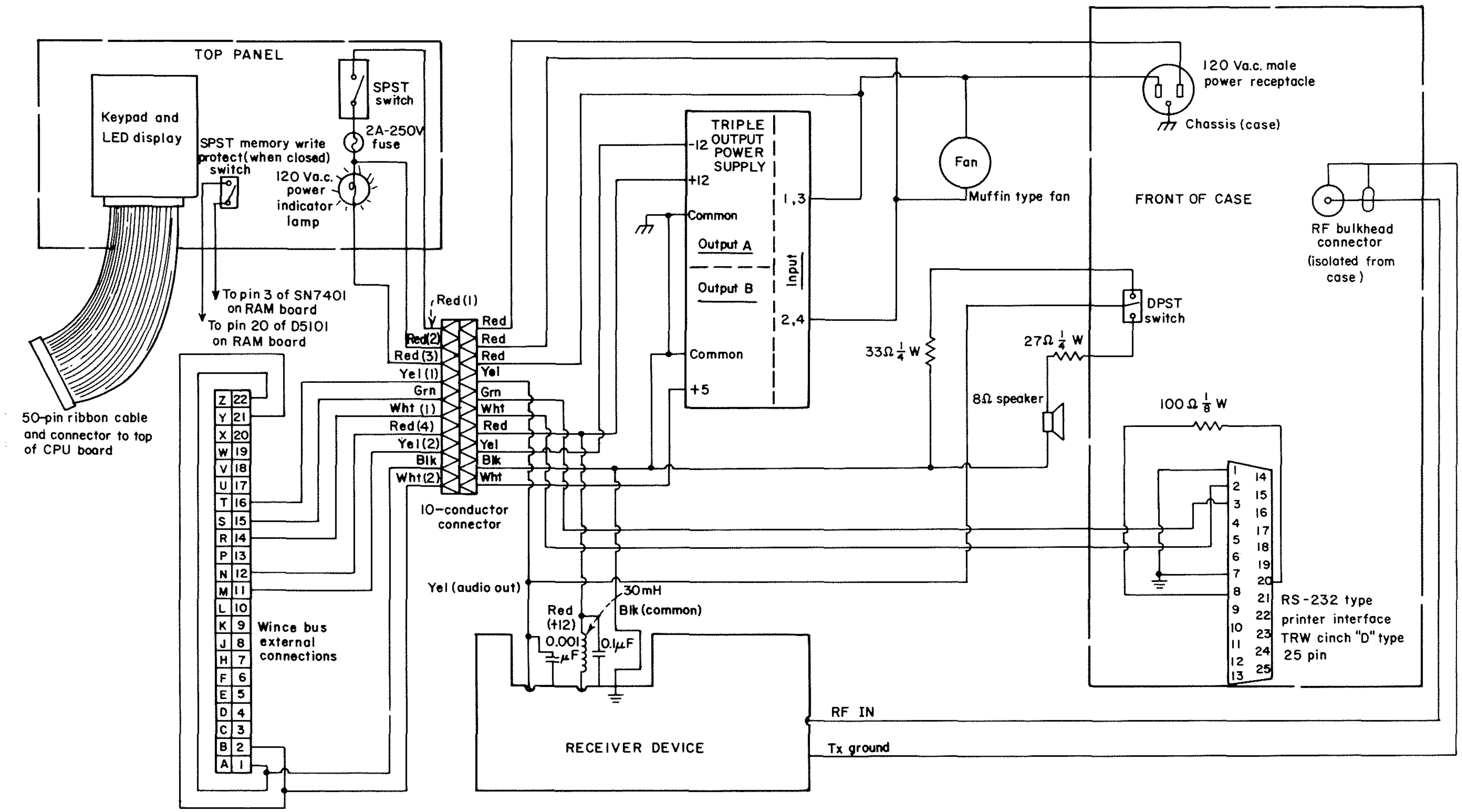


FIGURE 37. - Schematic for receiver unit hard wiring.

Alinement of the receiver can be accomplished in the laboratory using information provided by the manufacturer and good laboratory test equipment.

In operation, the antenna supplies modulated RF energy to the input of the receiver. The receiver amplifies and demodulates the RF signals to produce an audio output of 1-kHz and 2-kHz tones. These tones are connected to the inputs of the tone decoders for further manipulation and use. The tone decoders will be described in a later section.

Receiver Microcomputer

All receiver data-processing functions are managed by an onboard microcomputer, based on the Motorola M6800 microprocessor. Figure 36 is a block diagram of the microcomputer system, FM receiver, and printer. With the exception of the tone decoder and interface board, all boards in the microcomputer are manufactured by Wintek, Corp., Lafayette, Ind. These boards were selected primarily because of their size which is a 16.5-cm (6-1/2 in) by 11.4-cm (4-1/2-in) 44-pin PC board. This size is unusually compact among commercially available microprocessor boards. The six Wintek boards are shown in figures 38 through 43.

The functions of the microcomputer include the reception and decoding of microseismic data, the analysis of this data (daily statistics and source location when possible), the printing of the analyzed data, and communication with the operator via the system console.

Microcomputer Boards

A brief description of the six Wintek boards will be given that includes the basic function of each. For detailed description, see the manufacturer's reference manual (17). Five of these boards plug into a common 44-pin backplane (Wince) bus. The exception is the Console board in figure 43, which is connected only to the CPU (central processing unit) board via a ribbon cable.

The CPU board (Wintek Control Module) is shown in figure 38. This board contains the M6800 microprocessor, 32 bytes of parallel I-O (input-output) and a serial I-O port (fig. 36). A 14-conductor serial I-O is connected between the CPU board and the interface board. A 50-conductor I-O cable is connected between the CPU board and the console board.

The major part of the system read-write semiconductor memory occupies the RAM (random access memory) board (fig. 39). This board, in a maximum configuration, provides 16,000 bytes of RAM. The system uses this memory primarily for the input-output buffer and event stack. Since the memory devices are dynamic, a second board is required that provides the timing and control to maintain the memory. This board is the refresh board and is shown in figure 40. The system clock is also located on this board.

A small amount of additional read-write memory is provided by the CMOS RAM board (fig. 41). This semiconductor memory is made nonvolatile with the use of a small battery power supply backup as shown in figure 36. A switch on the front panel is used to enable or disable writing into this memory. The function of this board is to store semipermanent information such as local geophone coordinates and average velocity.

All system software is resident on the ROM (read-only memory) board (fig. 42). This board is capable of providing 16,000 bytes of memory, using Intel 2708 programmable ROM devices. Thus any required changes in the system software can be made by replacing the chips on this board.

Finally, the system console I-O located on the front panel of the instrument is a self-contained PC board, connected only to the CPU board by means of a 50-conductor ribbon cable. The console PC board contains a 16-element keypad and a 15-digit LED display as well as a crystal oscillator that is used to drive the IRQ (maskable interrupt) signal in the

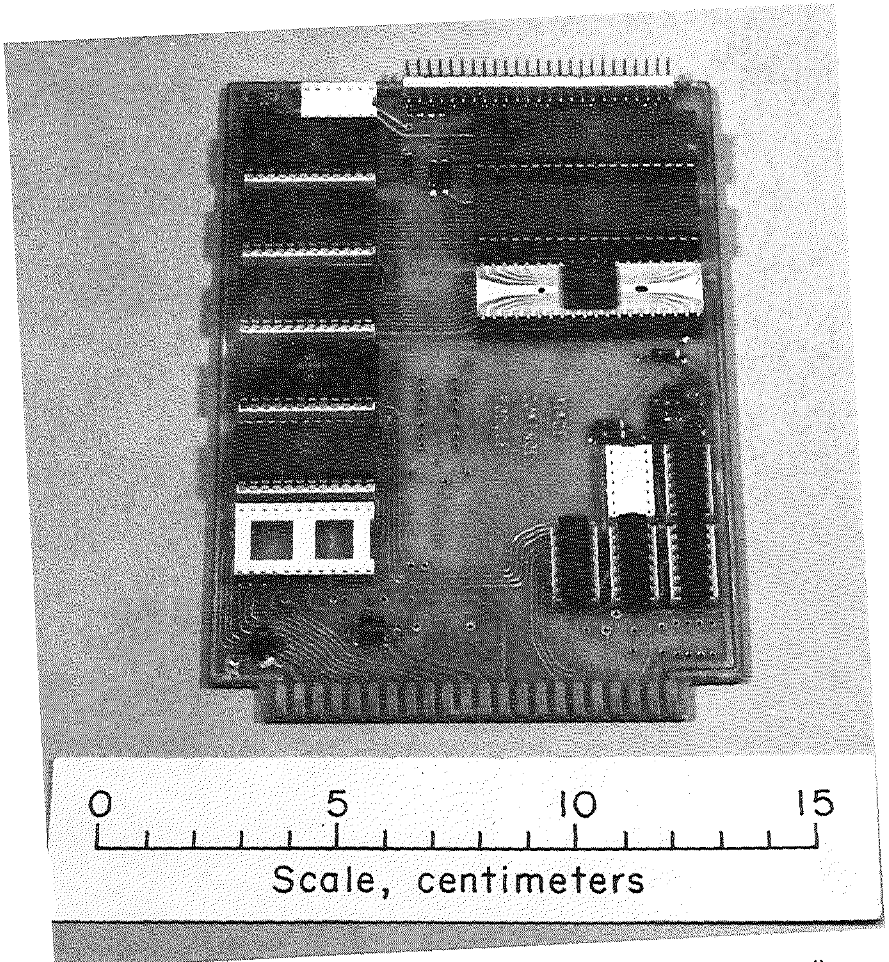


FIGURE 38. - Wintek wince control module (CPU board).

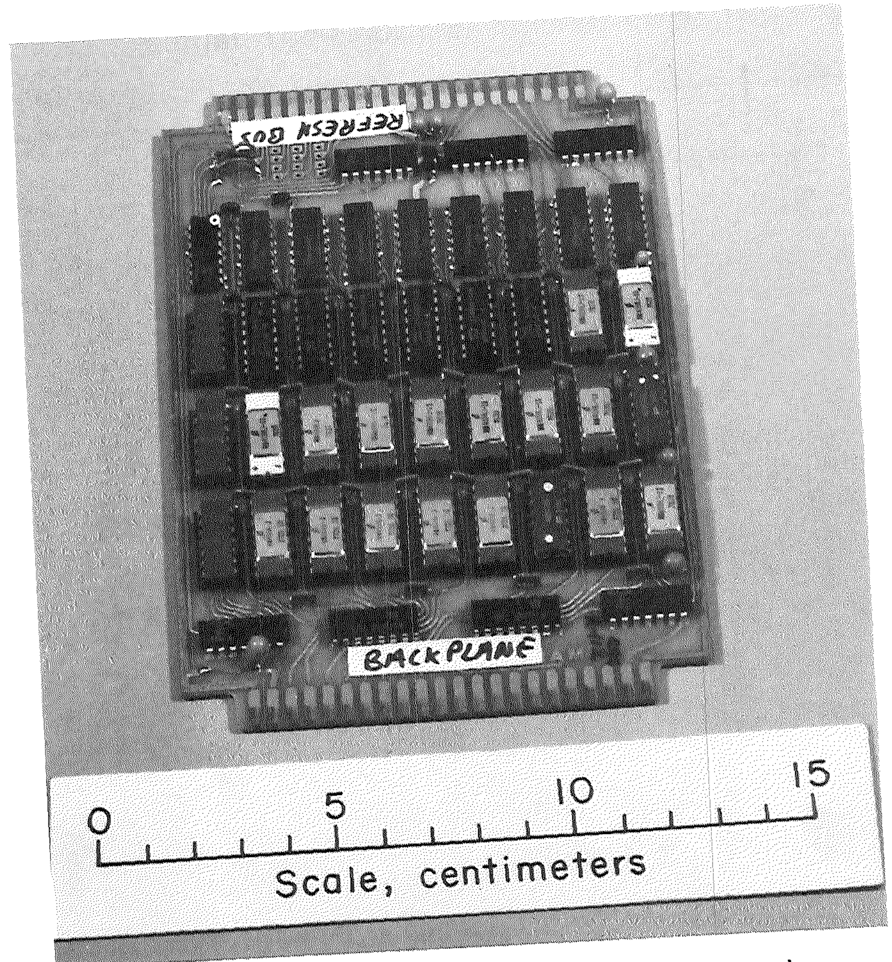


FIGURE 39. - RAM (random access memory) board.

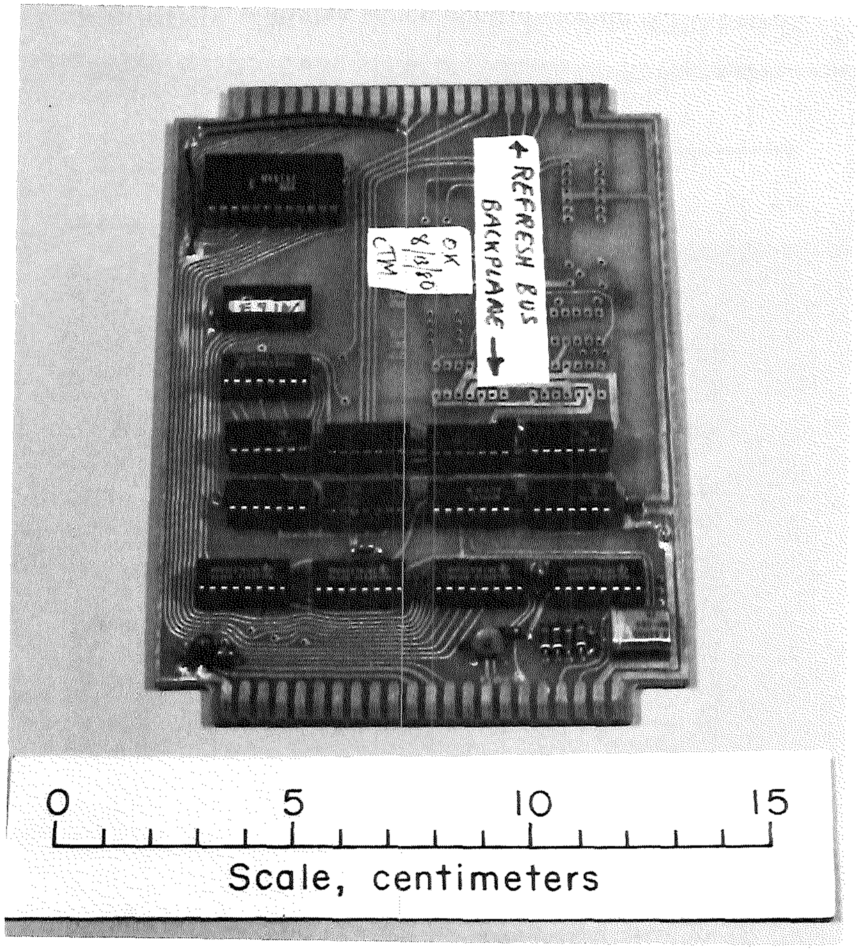


FIGURE 40. - Refresh board for support of RAM.

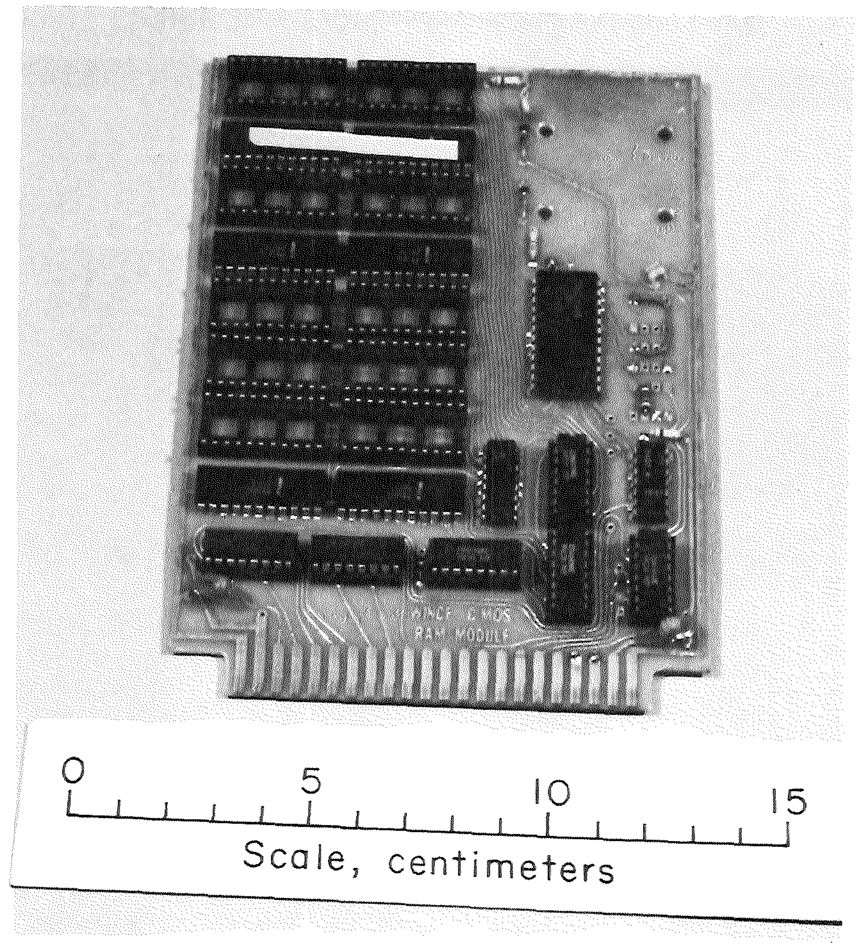


FIGURE 41. - CMOS RAM read-write board.

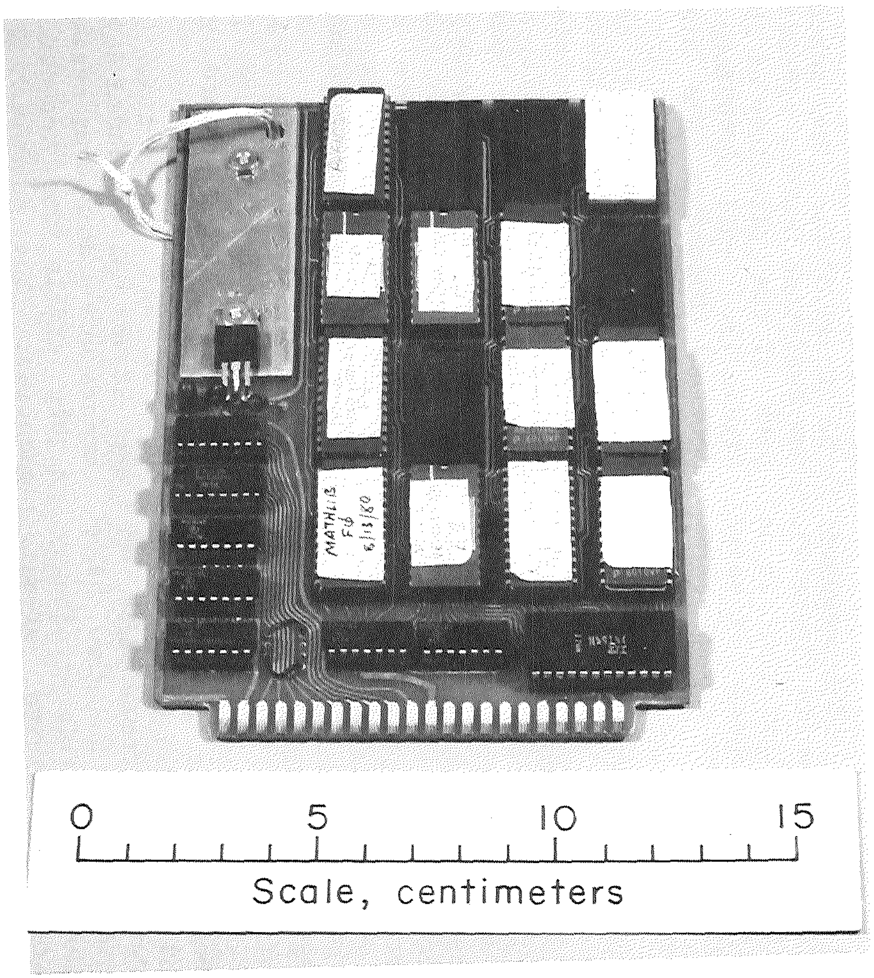


FIGURE 42. - ROM (read-only memory) board.

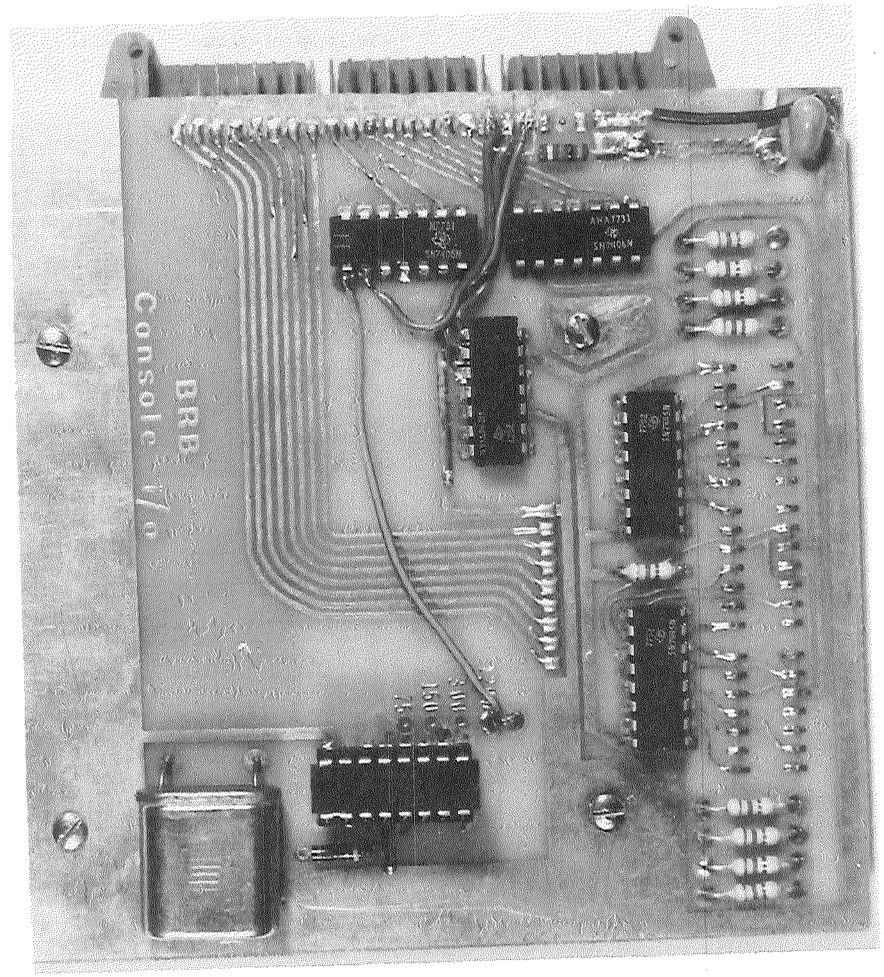


FIGURE 43. - Component side view of console I-O board.

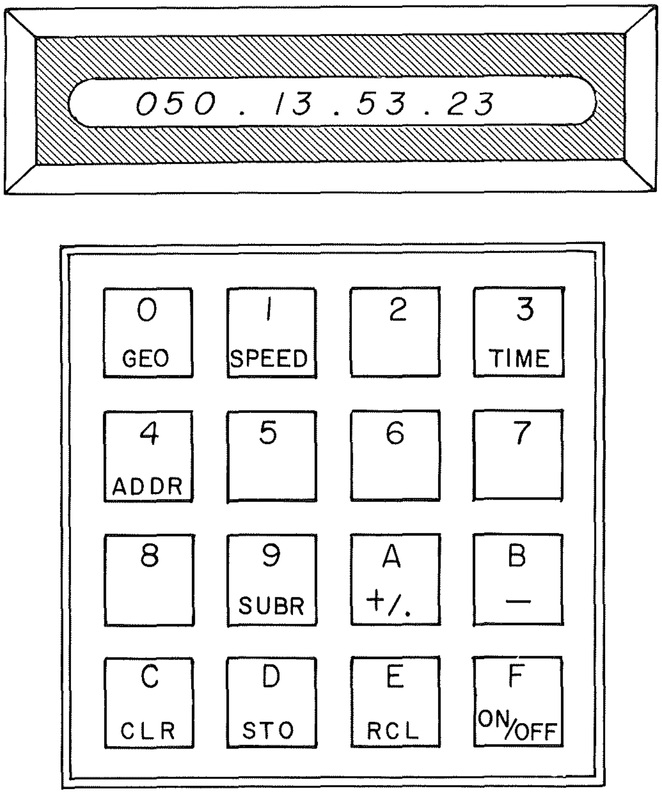


FIGURE 44. - Illustration of design and functions of keypad and display.

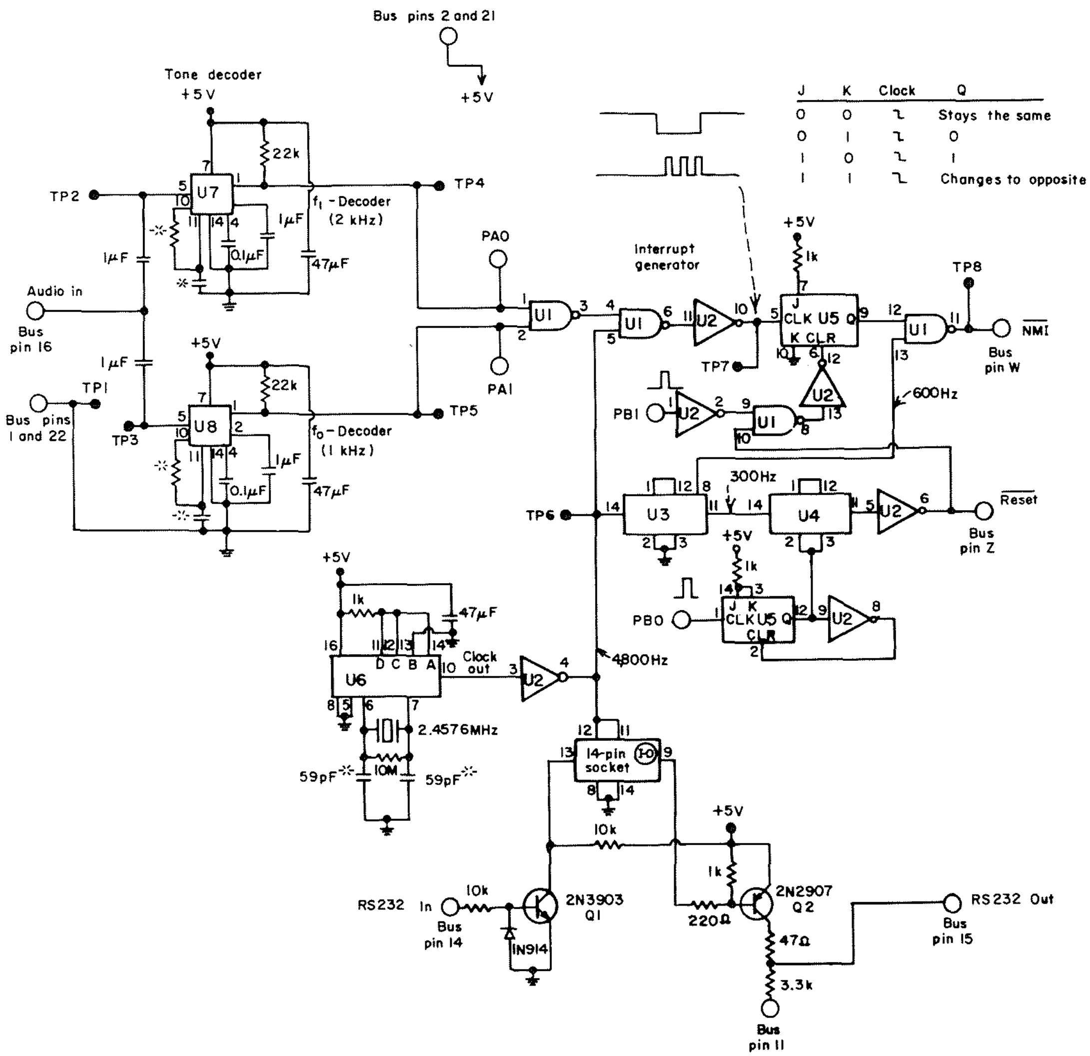
microprocessor (fig. 36). The component side of this board is shown in figure 43. The console, shown in figure 44, is on the reverse side of the console PC board and is accessible from the top panel in the instrument case.

Tone Decoder and Interface Board

The only in-house designed receiver unit board is the tone decoder and interface board. It provides interfacing of the microprocessor to the FM receiver and printer, and contains circuitry that controls the system power-on reset and NMI (nonmaskable interrupt) generation. The heart of the interface between the FM receiver and the NMI handler is the tone decoding circuitry.

Early versions of the tone decoder circuitry used the standard 567 tone decoder chip with tone frequencies of 2 and 4 kHz. An effort had also been made to modulate the carrier frequency with a square wave digital signal. Problems existed here in that Federal Communications Commission regulations do not permit modulation frequencies in this band and emission classification to exceed 3 kHz. Further, the telemetry devices were not designed to handle the rapid rise and recovery times associated with square wave modulation and demodulation. The circuitry did not employ temperature-stable external components and thus the center frequency drifted severely with changes in ambient temperature. An attempt to tune each circuit with trim pots proved impossible. The frequency drift with this arrangement was severe (due to temperature change), causing the filter pass band to quickly drift outside the tone center frequency. New and improved tone decoder and interface circuitry was developed and resides on the tone decoder and interface board.

One- and two-kHz sine wave tone generators were chosen for the new design. The military version of the 567 integrated circuit (SE 567) is a 14-pin, dual in-line "F" package. It was chosen because it has improved operating temperature specifications of -55° to +125° C. The schematic of the new dual-tone decoder circuit is seen as part of the circuitry of this board in figure 45. All frequency determining external components are highly temperature stable. Resistors are ±100 ppm/° C minimally, and capacitors are of the NPO or COG type that have temperature coefficients of ±60 ppm/° C minimally. This tight temperature stability assures close frequency control of the local oscillator and thus the center frequency of the tone decoder chips U7 and U8. In laboratory tests of the temperature stability of both the 1-kHz and 2-kHz tone decoder circuits, frequency could not be forced to drift more than ±2 Hz from the center frequency when subjected to +100° C. The tone decoder board is shown in figure 46. Note the groups of fixed value tuning capacitors and resistors on the left edge of the card in close proximity to each SE 567 chip. These devices are the temperature-stable components that yield highly stable tone decoder center frequencies. The bandwidth of the final



Chip designation	Chip type	Number of pins	V+ pin	Ground pin
U1	7400	14	14	7
U2	7404	14	14	7
U3	7493	14	5	10
U4	7493	14	5	10
U5	7473	14	4	11
U6	4702	16	16	8
U7	E567	14	7	14
U8	E567	14	7	14

NOTE: Either a reset or a PB1 pulse will turn off NMI pulse train.

IO socket (14 Pin)

PB0	⎍	Heart beat pulse disables the timed Reset (pin 6, IO socket)
PB1	⎍	PULSE will turn off the interrupt pulse train that was initiated by a tone detection (pin 7, IO socket)
PA0		Is output of f_1 detector (negative true) (pin 1, I-O socket)
PA1		Is output of f_0 detector (negative true) (pin 2, I-O socket)

Wince Bus

+5V	Bus pins 2 and 21
Ground	Bus pins 1 and 22
−12V	Bus pin 11
Audio In	Bus pin 16
RS232 In	Bus pin 14
RS232 Out	Bus pin 15
NMI	Bus pin W
Reset	Bus pin Z

* Component values selected to tune circuits to precise frequency. See text for details.

NOTE: All resistors are 1/8 watt.

FIGURE 45. - Tone decoder and interface board circuit schematic.

design tone decoders is 955 to 1,057 Hz (±10 Hz) for the 1-kHz circuit and 1,927 to 2,097 Hz (±20 Hz) for the 2-kHz circuit.

A precision timing circuit using chip U6 (4702) and a 2.4576-MHz crystal is included on the tone decoder and interface board and is the primary clock for all functions on this card. The output of U6 is a 4,800-Hz square wave signal that is gated through subsequent digital circuitry to produce the resultant NMI signal. There are eight test points (TP's) incorporated into the circuitry that are accessible on the circuit board, some of which are recognizable on the circuit card in figure 46. These TP's allow easy troubleshooting of the circuits under actual operating conditions.

Integrated circuit chips U1 through U5 form the NMI signal development circuit, which is described in the "System Software" section.

Instrument Case

The components of the receiver system are housed in a Zero Manufacturing Co. Model Zip 840 carrying case like that used for the transmitter unit. The receiver unit is shown in figure 47, the case wiring diagram is shown in figure 37.

The blank top panel supplied with the case is punched or drilled to provide for mounting the operating controls. Access to the PC cards in the cage mounted to the underside of the panel is through an opening in the top panel. Panel mounted controls include an on-off switch, a power fuse, a power indicator light, a small toggle switch that operates the battery support for the microprocessor memory, and the keyboard with an LED display register on the I-O console.

Due to the quantity of heat generated by the microprocessor, a small exhaust (muffin type) fan is installed in one side of the case. An air intake port is cut into the case in such a position that fresh air is drawn across the PC cards in the cage. Although the build-up is not destructive, the heat generated by the combination of microprocessor and power supply operation in the closed case adversely affects some functions of the basic Wince system, making cooling a necessity in warm environments.

In order to monitor the incoming 1- and 2-kHz tone bursts from the transmitter, a small cone-type audio speaker is installed in the receiver instrument case. In the event that the printer fails to operate, no means normally exist, other than the speaker, to determine when the transmitted signal is arriving at the receiver. Thus, a keen ear can be a valuable diagnostic tool when evaluating operational problems with the telemetry link. The speaker can be disabled by a toggle switch on the front of the instrument case.

Like the transmitter, all connections required to support the receiver are placed on the front of the case so that the unit can be operated with the lid closed. These external connections consist of a 120-V a.c. power plug, an RF coaxial bulkhead connector for the antenna, and a TRW Cinch "D" type printer interface plug.

The top panel is cut out to provide access to the PC cards for repair or replacement without removing the entire panel. A plastic cover was machined to fit the panel opening to provide dust protection for the PC cards and to close the opening to insure that cooling air would flow over the critical circuitry on the cards in the card cage. With this arrangement, it is necessary to remove the panel from the instrument case only in the rare event of power supply problems, I-O console maintenance, or receiver module service.

Power Supply

The microprocessor, which is essentially an off-the-shelf Wintek unit, requires +5, +12, and -12 V from a well-regulated external supply. These d.c.

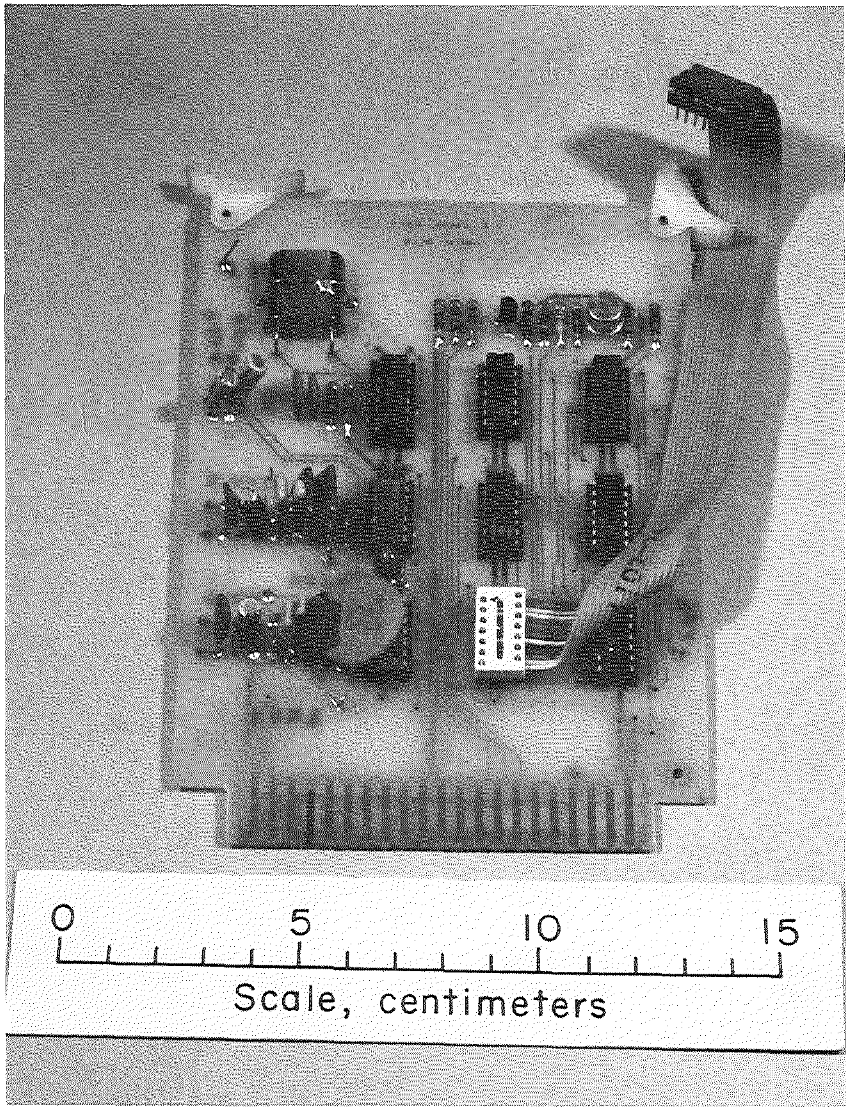


FIGURE 46. - Tone decoder and interface board.

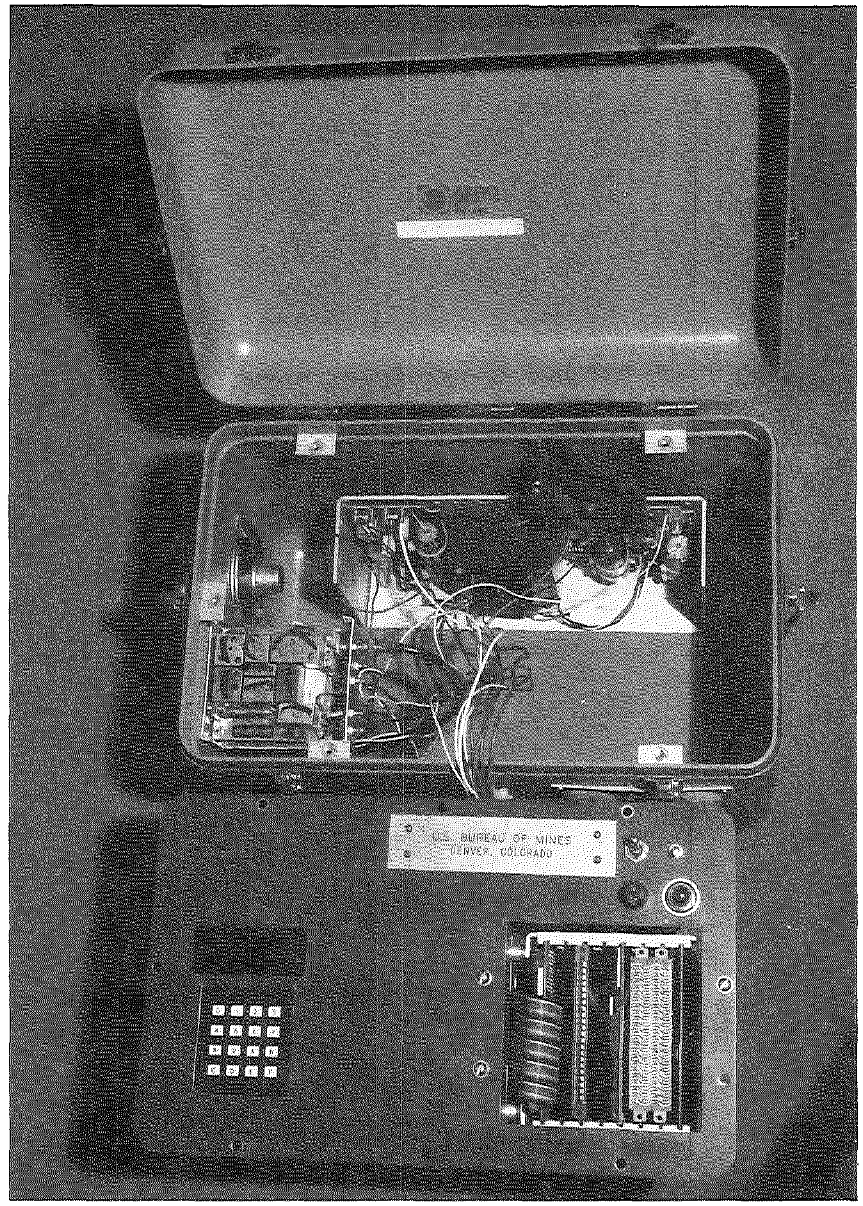


FIGURE 47. - Interior view of receiver unit showing power supply and receiver device.

voltages are obtained from a Power One model HCBB 75W variable-level, triple-output power supply operated from a standard 120-V a.c. source. The Power One regulated power supply incorporated into the microseismic system receiver provides +5 V at 6 A, +12 V at 1.5 A, and -12 V at 1.5 A. This available power is well in excess of the manufacturer's recommendations for the microprocessor, but is necessary for operation of the I-O keypad with readout and the RF receiver device. The essential features of such a power supply as used in this system are that it be regulated, provide adequate power, and have the necessary voltage sources. Any power supply that meets these criteria may be used.

Antenna

The receiver utilizes an antenna and mast assembly identical to that used for the transmitter. For reference, figure 19 and table 4 in the "Transmitter System" section give pertinent information on this antenna assembly. Attention is directed to the coaxial cable options listed in that section since often the receiver antenna will need to be placed a greater distance from the unit than is necessary for the transmitter. This

```
----------------------------------------
        GEOPHONE COORDINATES

    NO.     N-S      E-W      ELEV.

    1 :     11485    15584    4950
    2 :     11476    15468    4900
    3 :     11532    15501    4901
    4 :     11601    15584    4900
    5 :     11578    15471    4899
    6 :     11611    15536    4900
    7 :     11540    15262    4850
    8 :     11493    15451    4850

    AVERAGE VELOCITY =  10000

42:42:42   1   5   X   X   0   X   X   X
42:42:42   1   0   X   3   6   X   X   1.
    LOCATING!!
SOURCE--  11466   15559   4850
 (      11 LOOPS)
 ( .625000        20.0251        )
42:42:42   2   3   X   X   7   0   X   1
    LOCATING!!
SOURCE--  11531   15866   4460
 (     100 LOOPS)
 ( 5.00000        34.8625        )
42:42:42   X   X  14   0   X   X  11   X
42:42:42   X   0  15   X   X   X  16   X
```

```
42:42:42   X   X   X   0  12  16   X   X
42:42:42   X   2   3   0   X   X   X   X
42:42:42   X   X  12  16   X   X   0   X
42:42:42   X  11   6   X   X   0   3   X
    LOCATING!!
SOURCE--  13591   15536    3110
 (      100 LOOPS)
 ( 20.0000        7.25034       )
42:42:42   X   X   X  12   X  12  21   0
    LOCATING!!
SOURCE--  11493   15451    4819
 (        8 LOOPS)
 ( .625000        59.6018       )
42:42:42   X   X   X   X   1  21   X   0
42:42:42   X   X  14   X   X   0   X  12
42:42:42   X   X   1   X   X   0  16   X

----------------------------------------
              DAILY SUMMARY
----------------------------------------

  DAY  043
  TIME 00:00:00
     13  EVENTS
      4  LOCATABLE

 GEOPH.   TOTAL  UNIQUE  FIRST   MAXIMUM
 NUMBER   RESP.  RESP.   ARRIVAL DELTA T

   1 :       3       0       0        2
   2 :       6       0       2       11
   3 :       7       0       0       15
   4 :       6       0       3       16
   5 :       5       0       1       12
   6 :       7       0       4       21
   7 :       6       0       1       21
   8 :       5       0       2       12

SOURCE LOCATION ON
```

FIGURE 48. - Printer output formats.

results from the desirability to place the receiver in a suitable indoor monitoring location, but good FM reception will usually require outdoor placement of the antenna. Thus, coaxial length should be a consideration when selecting the type of lead-in cable that will be used.

Printer

The system permanent record is provided by a 40-column line printer using the electrosensitive print method. The printer used in the Bureau system is a model EX-801S built by Axiom in Glendale, Calif. The printer requires only a 120-V a.c. power source and an RS 232 data input. Electrosensitive roll paper (12.7 cm (5 in) wide x 60 m (196.85 ft) long) is used for the data presentation. The sample printout in figure 48 is typical of the data and output format produced by this printer.

System Software

The Motorola M6800 based microcomputer in the receiver manages the collection, analysis, and printing of data. Communications between operator and microcomputer are achieved through the system console, consisting of a keypad and LED display. Thus the microcomputer appears to be doing different tasks at same time. This seeming concurrency is achieved using the microprocessor's interrupt capability. As a result the system software breaks into three pieces that will be described separately. These are the system power-on reset handler and main operational logs, the system NMI handler, and the system IRQ handler. From the point of view of the programer, these three are essentially independent programs that communicate only through shared workspace in memory.

Power-on Reset Handler and Main Operational Wait Logs

When the microcomputer power supplies come on, the hardware will automatically generate a hardware reset signal after a few milliseconds. This signal is generated by the heartbeat circuit shown in figure 36. As a result the microcomputer is forced into the power-on reset handler program (fig. 49).

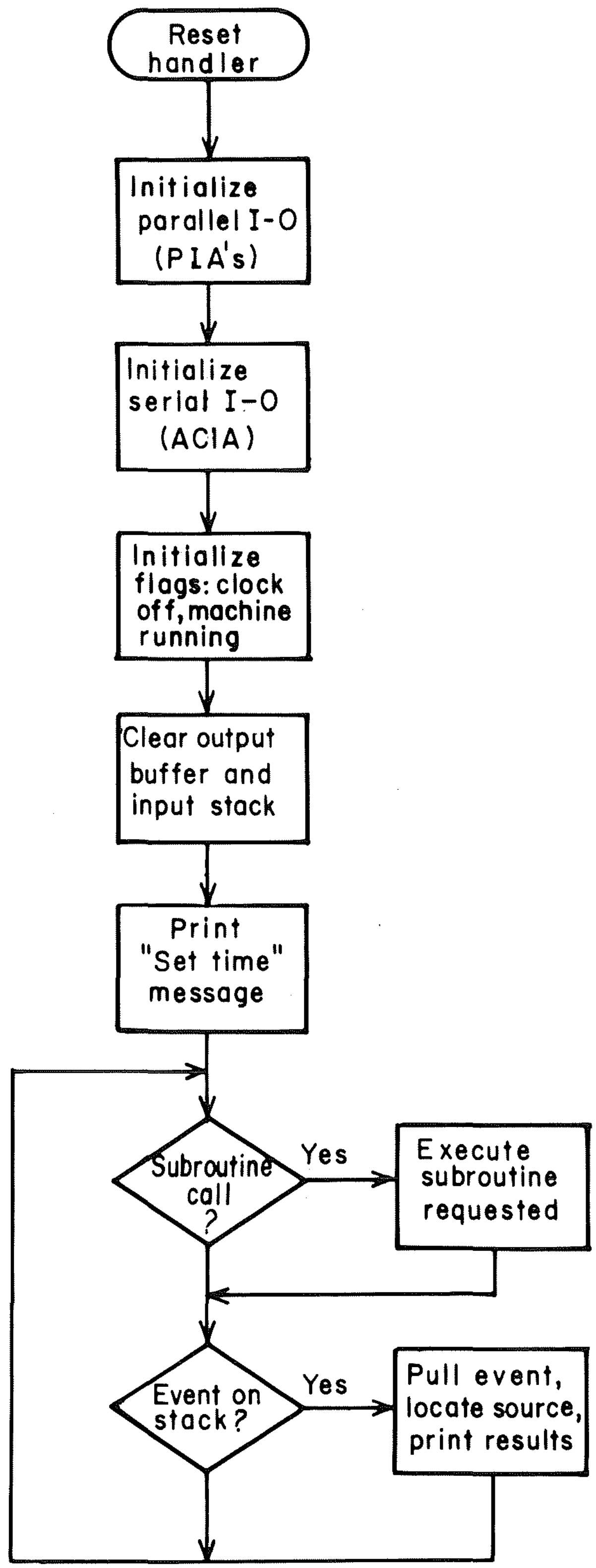


FIGURE 49. - Power-on reset flow diagram.

The reset program performs the major system set up and initialization. For example, the system I-O channels use Motorola special purpose devices that must be programed by writing into certain registers. Also certain "flags" (memory locations) that define the status of the system must be initialized. Thus the system comes "up" with the console display turned off as a result of the initialization of one of these flags.

The major memory data buffers must be defined upon initialization. These two buffers are the output buffer, which stores American Standard Code for Information Interchange data that are to be dumped to the printer; and the event stack, which stores information received over the telemetry link. Since the initial condition of these buffers, which is established during the reset initialization, is the empty condition, a power failure will result in the loss of any data that had not been processed or summarized before the power failure.

The final function of the reset program is to announce that a reset has occurred by printing the message "set time" on the printer. The operator should respond by entering the current time through the system console. The memory that contains present time is volatile; its contents are not destroyed if the power supplies are turned off.

After all initialization tasks are completed the system enters the main operational loop, where the system waits until a task is available. There are two kinds of tasks that may become available.

First the system checks to see if a subroutine request has been made by the operator. Such a request can be made from the system I-O console that is supported in software by the handler described in the "Maskable Interrupt (IRQ) Handler" section. If a request has been made, the system performs the specific job that has been requested. Such jobs include a current summary, a printout of geophone locations, and a command to enable or disable the source location subroutine.

Second, the system monitors the event stack. If this is not empty, then an event is pulled from the stack and processed. (Events are placed on the stack by the NMI handler.) If source location is enabled, the location subroutine is entered, and the results will be placed in the output buffer.

Nonmaskable Interrupt (NMI) Handler

The NMI handler flow charted in figure 50 supports the telemetry input, enabling transmitted data of a microseismic event to be decoded and placed on the event stack. When the microprocessor NMI signal makes a negative transition, the system will suspend execution of its current task and enter the NMI handler program.

The NMI signal is generated by circuitry on the interface board, shown in figure 46. When a transmission is initiated, a tone detector on this board fires. This first signal detection triggers the NMI generator that produces 600 interrupts per second. The NMI handler program counts these and automatically generates an output signal that will turn off the NMI generator when it times out.

The NMI handler will perform one pass for each of the several hundred transitions of the NMI generator that occur during a transmission. The time spent for each pass is only a few microseconds. During these passes the NMI handler detects the synchronization transition (see the timing diagram, fig. 10) and decodes each of the 64 data bits by majority vote. Not shown on the flow chart are consistency checks that can cause a premature termination of the NMI generator with subsequent loss of the event. For example, if either tone detector fails to indicate a valid tone present over a period in which a tone should be present, then the sequence will be terminated.

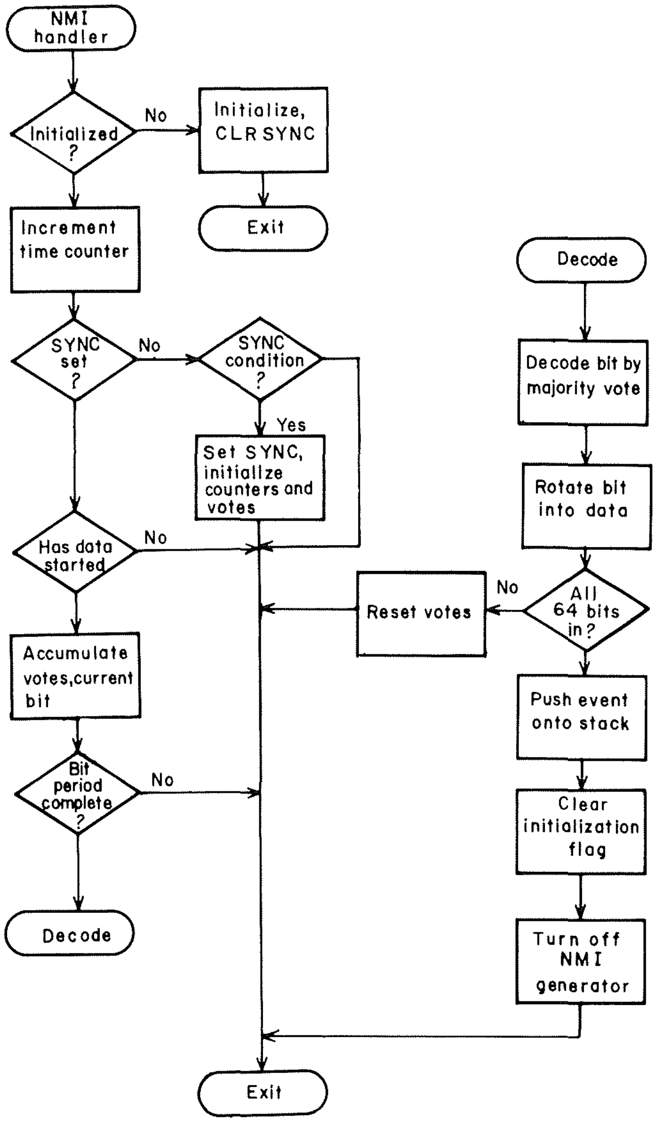


FIGURE 50. - NMI (nonmaskable interrupt) flow diagram.

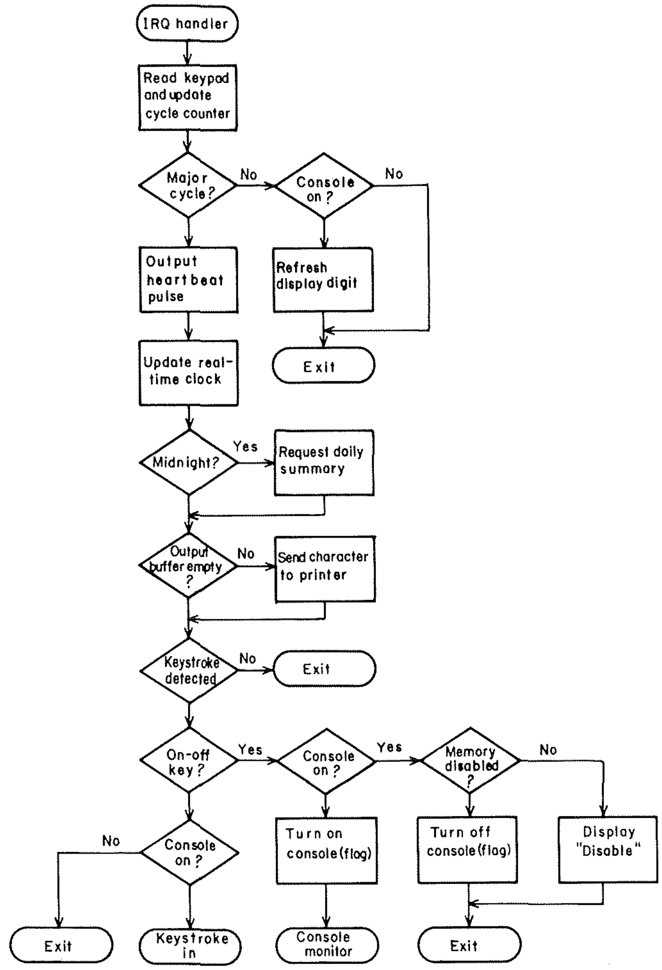


FIGURE 51. - IRQ (maskable interrupt) flow diagram.

Maskable Interrupt (IRQ) Handler

The IRQ handler that is described in part by the flow chart in figure 51 supports the system console and real-time clock. The hardware signal that generates the maskable interrupt is given the mnemonic IRQ (for interrupt request) by Motorola. It is so designated in figure 36. The IRQ generator is a crystal oscillator located on the system I-O console PC board. For technical reasons, it is connected to the microprocessor through a parallel I-O port.

The IRQ generator produces 1,200 interrupts per second; this is the rate at which the IRQ handler is entered. If the console LED display is on, one digit of the display is refreshed during each interrupt. Since there are 15 digits, each is refreshed 80 times per second--well above the flicker rate. Ninety percent of the passes through the IRQ handler terminate after such a refresh, consuming only a few microseconds of CPU time.

On every 10th interrupt (or 120 times per second) the IRQ handler program also makes a pass through a "major cycle." During the major cycles, several other activities occur.

For example, the system generates a heartbeat pulse during major cycles. This pulse is sent to the heartbeat circuit on the interface board. Should the heartbeat pulse fail to occur at regular intervals, this circuitry will generate a reset signal to revive the system by forcing it into the power-on reset initialization sequence described previously. This should not happen under normal operation.

The real-time clock is updated during major cycles and at midnight a software request is made for a daily summary subroutine execution by the main system program. The output buffer is also checked during major cycles, and if not empty, a character may be transmitted. Finally, a check is made to see whether a keystroke has been detected. If there are none, the major cycle terminates.

If a keystroke is detected, it is first determined whether this key pressed is the on-off key, which will turn the display and the system console monitor program on or off. If it is the key, the appropriate response is made. If not, and the system console is on, the system branches to some point in the console monitor program at a point that had "requested" a keystroke. This is done by a dummy return from subroutine and the use of two different machine stacks. The description of this mechanism and all the functions of the console monitor program require more detail than is warranted by this report.

Source Location Programs

Of the several source location programs and models that have been developed, two are in current use during field tests of this system. The first was developed and written the Bureau (3). This program, known as the seven-point approximation method, provides an indirect solution employing a successive approximation procedure using relative times of arrival of microseismic energy at a minimum of four detectors. The procedure, as given in reference 3, is to optimize data through an "ordered search routine, in which trial microseismic data are generated for a hypothetical source and compared with the original [true] data." Average location time using this technique is about 60 seconds.

The second source location routine was developed and written as a part of the work under this project. This algorithm also uses relative arrival times as raw data, but provides a direct solution in an extremely short time frame (1 to 3 sec). This feature substantially reduces the possibility of lost data (though some storage is provided) during periods of high rock noise rates because processing time is more nearly equal to the maximum data telemetry transmission rate.

Published literature is not available on the direct solution method described here. Where further information is required, inquiries should be made directly to the authors.

The relative accuracy of either of the described location methods is very dependent on the care taken during the detector coordinate location survey. Of even greater importance is the accurate determination of sonic velocity, which is necessary as a parameter in both location routines. This is a site-specific variable that can (if a poor velocity survey is done) cause a very large relative error in source location results. The importance of accurate coordinate and velocity surveys cannot be overemphasized.

Operating Instructions

Power-on Reset

The microprocessor system is automatically reset when the receiver unit power is switched on. (There is no reset button.) The system may also be reset by the heartbeat circuit if an abnormal timing situation occurs. System reset causes the message "POWER-ON RESTART" to be sent to the printer. The real-time clock is maintained in non-volatile memory, but the current date and time should be verified after this prompt is given.

System Console

The system console is shown in figures 43 and 44. It consists of a calculator style keypad and LED display. The console is the only means of communicating commands to the system. When the system has been reset, the console will be off; with nothing on the display. The console may be turned on by toggling the on-off key on the keypad. The message "CONSOLE ON" will be displayed. The operator may now store or recall geophone coordinates, velocity, and time; or request a variety of system status printouts.

Entering Geophone Coordinates and Velocity

Before the velocity or a geophone coordinate can be defined, the special memory must be enabled by setting the small toggle-type memory protect switch on the top panel.

Geophone coordinates and velocity are entered as signed integers (no decimal point). The units are feet and feet per second, respectively. The operator may enter signed integers into the display in the normal way using the keys "0" through "9" and "-" and "CLR." The negative sign changes the sign of the number displayed, while the clear command will clear the display and enter a zero. The keypad decimal point should not be used for entering coordinates or velocity data. To define a geophone coordinate, the value is entered in the display and "STO," "GEO," and two indices are keyed. The indices describe the position that the data will assume an eight by three matrix. The eight matrix rows represent the eight available channels. The three columns represent the X (north-south), Y (east-west), and Z (elevation) coordinates (fig. 48) in that order, which uniquely define the geophone position for any given channel. For example, to define the value of geophone number three, X coordinate, to be 1091, the operator should

1. enter the number 1091, and

2. key "STO," "GEO," "3," and "1."

To read the value of a geophone coordinate the operator keys "RCL," "GEO," and two indices. If a coordinate is defined and then recalled, and the recalled value is in error, then the status of the memory enable switch should be checked.

The velocity is defined by entering the numerical value and then keying "STO," "SPEED," and any integer index.

If an illegal store or recall sequence is attempted (such as "RCL," "GEO," "5," "5") the message "ERROR" will appear in the display. The operator must clear the error condition by keying "CLR."

After the velocity and geophone coordinates are entered, the operator should return the memory enable switch to the "protected" position.

Real-Time Clock

The current time may be displayed by keying "RCL," "TIME." The format is day, hours, minutes, seconds; with the fields separated by decimal points as shown in figure 44. The display will be updated every second. To set the time, the current time is entered in exactly the same format and then the keys "STO" and "TIME" are struck. Note that the day number must be entered as three digits including possible leading zeros. The real-time clock keeps military time, with hours in the range 00 to 23. Since the time is entered approximately 1 second after the keys "STO" and "TIME" have been struck, the operator should compensate by entering the time a little prematurely and then striking the "TIME" key at the proper second.

System Status Reports

The operator may request a small number of status printouts from the keyboard. The procedure is to

1. enter a one-digit report code, and

2. key "STO" and "SUBR."

The available status reports with codes are as follows:

CODE 1 print time of day,

CODE 2 print a current summary of all geophone activity since the previous midnight,

CODE 3 print a table of geophone coordinates and velocity,

CODE 4 disable source location, and

CODE 6 enable source location.

For example, to request a current summary, key "3," "STO," and "SUBR." (A summary is automatically printed each night at midnight.) It will itemize by geophone the total number of responses, the number of responses for which a geophone responded uniquely, the number of responses in which a geophone was the first to respond (closest to the event), and the maximum arrival time difference recorded for this geophone.

Automatic Status Reports

The system will automatically record on the printer each event as it occurs. The data format is time of day followed by up to eight arrival time differences (fig. 48). (If a particular geophone did not respond, an "X" will be printed for its arrival time difference.) For example, an event is received at 11:00 a.m. in which geophone four responds first, and geophone five responds 13 units later. The audio data transmission may be heard on the receiver's speaker and the printer will print the following message:

11:00:00 X X X 0 13 X X X.

If four or more geophones respond, the event is classified as locatable and a source location will be attempted automatically by the microprocessor. The printer will print the message "LOCATING !!," and the results of the location routine will be printed a short time later.

Each night at midnight the system will also automatically print a daily summary of the statistics of the geophone responses for the previous 24-hour period.

Terminating Console Commands

When the operator is finished with the console, it should be turned off by toggling the on-off key. (The system will spend less time in overhead activity with the console off.) If the memory enable switch is on and an attempt is made to turn the console off, the message "DISABLE" will appear on the display. The operator should return the memory enable switch to the protected position and then turn off the console. It is important that the memory should not remain enabled since a power failure could cause loss of system parameters. In the protected state, this memory is nonvolatile and, therefore, immune to power failures.

Miscellaneous Related Data

Velocity Survey

The velocity of the earth media through which sonic signals propagate has significant effect on the operation of a microseismic detection system. In the normal earth structure, near-surface materials exhibit low velocities while deep rock formations are characterized by high velocities. This gradational velocity characteristic must be taken into consideration when installing a monitoring system, analyzing energy arrival times, and calculating source locations.

As mentioned earlier, there are few large-scale homogeneous geologic formations. As a result of this fact, tests at specific locations are necessary to establish the sonic velocity for a particular site. The normal procedure for determining earth velocities is the seismic refraction method. The velocities determined by a refraction test are used to insure understanding of variations in first arrival times and for use in calculations of the source of microseismic energy. The information is also useful in determining how deep the detectors are placed, the array configuration, the probable signal attenuation, etc. For the purpose of the source location program calculations, an average velocity for the media is used. This velocity figure is determined from the refraction test data and is entered into the program through the keyboard on the receiver top panel. Refraction seismics is an area of considerable size in itself and no attempt will be made here to cover the subject in sufficient detail to enable an investigator to become proficient in the method. It is sufficient here to make the reader aware of the method and the necessity to obtain reliable velocity figures for use in microseismic applications. For those who want more information on the subjects of velocity determination and refraction methods, most texts on geophysical investigations should provide adequate coverage of the subject.

Phone Array, Phone Installation, and Location Survey

It has been well established in previous work that the parameters involved in the attenuation of acoustic energies are important considerations in the capture of microseismic data. One method by which some of these problems may be minimized is in the thoughtful layout of the array of geophones (or other detectors), with proper regard for likely sources of rock noise. An eight-channel system, such as the one described in this report, can be installed in an infinite variety of patterns. Though this is a distinct advantage in view of the infinite types and shapes of slope failure zones which may be encountered, some guidelines are essential to effective monitoring (fig. 2).

1. Anticipated noise source areas should be within the outer boundaries of the array whenever possible.

2. Geophone spacing should be as wide as possible, but not to the extent that data might be lost due to distance attenuation.

3. Three-dimensional areal (multiple bench) arrays offer more accurate source data, and should be used whenever possible; planar arrays have a greater inherent error owing to aperture angles.

4. Drill holes should be kept as vertical as possible to maintain the geophone in its maximum sensitivity orientation.

5. Survey of the coordinate positions and elevations of each geophone should be made to (±0.5 ft) and plotted on an up-to-date mine topography map. The microseismic system utilizes these data and prints out locations based on the mine coordinate system.

6. Locate the transmitter for the geophones so that periodic checks and maintenance of it can be as convenient as is feasible.

As stated, these are only guidelines, and it is recognized that all will not always be met. Beyond these suggestions, experience and understanding of the specific area will be important considerations. Educated trial and error is a valid recourse in many situations.

Geologic Analysis for Array Orientation and Limitations

Unstable areas in pit walls will nearly always be evident for some time before complete failure occurs. Such is generally the nature of failing rock. It will not, however, always be possible to identify exactly how large a failure area may be or just what shape or form it may take without extensive investigation. Except in isolated cases, a mine will already have available most of the necessary lithological and petrographic information to provide a basis for an educated guess of the nature of incipient failure. Where it is desired to monitor such an area, the choice is available to utilize an initial geophone array based on the educated guess or to spend the time and effort to delineate the hazard zone before monitoring begins. Under the educated guess method, the source location capability of the system can be used effectively to identify the actual failure area. This allows the operator to reorient the array based on actual knowledge, rather than through guesswork, for further monitoring.

A direct and immediate resolution of the educated guess system is not always possible, however, due to the error probability associated with the initial array. This electronic equipment is not without limitations and usable range. As the noise source location moves out from within the outer boundary of the selected geophone array, error in locations increases in an exponential relationship to this distance. The source location algorithm depends on reasonably accurate data to produce source coordinates, and as the data available to the algorithm become less accurate, the location yielded will be less reliable. Another possible problem may also arise is that as the source-to-array distance increases, the possibility is reduced that four geophones (a minimum for locatability) will be able to capture the source noise.

Error Analysis Program

A computer graphics program has been developed by the Bureau that models the source location algorithm and analyzes the error associated with any selected source for any selected array pattern and orientation. The essential component of this system is an error function that, when given certain probable traveltime errors, can evaluate the range and direction of possible error for a specific location problem by two-dimensional plot of an ellipse. Through a complex system of weighted averaging, the ellipse is made to represent the locus of function solutions of a variable vector that changes in magnitude as the directional component is rotated about the source point. This, in effect, permits the user to select a source-to-array relationship that will give location solution coordinates in which there can be a known level of confidence.

The advantages of modeling an array arrangement in this manner are obvious. If error can be minimized prior to drilling even the first geophone installation hole, the economic benefit is maximized. Also, if it is possible to know the degree of confidence that can be expected from any array before any data are recorded, there can be little doubt about the validity of data that are taken when monitoring begins.

CONCLUSIONS

The results of studies by the Bureau have led to the development of a slope stability monitoring system using microseismic techniques. Two units of the state-of-the-art instrument system were designed, constructed, and tested.

The monitoring system consists of a transmitter and a receiver, and some peripheral equipment. The transmitter unit, battery pack, solar charging equipment, and a telemetry antenna are located near the suspected problem area in an open pit mine. Geophones are installed in shallow drill holes in an areal array and are connected to preamplifiers that deliver conditioned signals to the transmitter unit. The receiver unit and a line printer are normally installed in an office or mine shack where 120-V a.c.

power is available. The receiver unit is connected to an antenna that is erected outside the building and pointed toward the transmitter site. All data coming from the pit wall are transmitted from the transmitter site to the receiver location over the data telemetry link, thus eliminating hard wiring between transmitter and receiver.

The monitoring system is portable, reliable, and easy to operate and maintain. Precautions have been taken to insure protection against the harsh mine environment.

Installation at two open pit mines allowed field tests to be conducted to provide information on system performance. To date, about 1 year of total operating time has been accumulated on the system. Over this time span, improvements have been made in the electronics and support equipment so that no problems are being experienced with environmental extremes. Rough handling and severe temperatures and weather can be tolerated with no degradation of system performance.

A source location program resident in the microcomputer in the receiver unit provides printed X, Y, and Z coordinates of the source of acoustic energy originating in the pit wall due to rock fracturing. A warning device such as a horn can be attached to the receiver unit to provide audible notification of movement in the pit wall slope.

The system is currently useful for other similar geologic monitoring applications and can be adapted to still others of varying complexity. Such structures as dams and quarry highwalls may be monitored for stability through direct surface attachment of the geophones to the structure. Underground work such as block caving mining, shallow longwall mining, and even possibly some solution mining may be monitored from surface drill hole installation of geophones similar to that used for the slope stability work.

The cost to duplicate the instrument system, as shown in table 8, is presently about $7,630.

TABLE 8. - Estimated cost of hardware to duplicate system

Transmitter unit	$950.00
Batteries, solar panel, and regulator	900.00
Receiver unit and microprocessor	2,200.00
Preamplifiers (8 required at $90.00 each)	720.00
Geophones (8 required at $115.00 each)	920.00
Printer	750.00
Cables	1,000.00
Special tools	190.00
Total	$7,630.00

Minimal field testing has been accomplished as of this report preparation. Extensive tests on open pit mine slopes (and possibly other geologic problems) are planned to fully evaluate the potential of this technique.

BIBLIOGRAPHY

1. Blake, W., F. Leighton, and W. I. Duvall. Microseismic Techniques for Monitoring the Behavior of Rock Structures. BuMines Bull. 665, 1974, 65 pp.

2. Broadbent, D. C., and C. W. Armstrong. Design Application of Microseismic Devices. Proc. 5th Can. Symp. on Rock Mechanics, Toronto, Canada, Dec. 6-7, 1968. Mines Branch, Department of Energy, Mines and Resources, Ottawa, 1969, pp. 91-103.

3. Dechman, G. H., and M. C. Sun. Iterative Approximation Techniques for Microseismic Source Location. BuMines RI 8254, 1977, 23 pp.

4. Dix, C. H. Seismic Prospecting for Oil. Harper & Brothers, New York, 1952, 414 pp.

5. Dobrin, M. B. Introduction to Geophysical Prospecting. McGraw-Hill Book Co., Inc., New York, 1960, 446 pp.

6. Hamilton, E. Compressional-Wave Attenuation in Marine Sediments. Geophysics, v. 37, No. 4, August 1972, pp. 620-646.

7. Lancaster, D. CMOS Cookbook. Howard W. Sams & Co., Inc., Indianapolis, Ind., 1980, 414 pp.

8. Lepper, C. M. Guidelines for Selecting Seismic Detectors for High Resolution Applications. BuMines RI 8599, 1981, 42 pp.

9. Lepper, C. M., and F. Ruskey. High-Resolution Seismic Reflection Techniques for Mapping Coal Seams From the Surface. BuMines TPR 101, October 1976, 17 pp.

10. Merrill, R. H., and D. W. Wisecarver. Factors That Influence the Design of Slope Walls in Rock. Paper prepared for presentation at XXII Congresso Brasiliero de Geologia, Belo Horizonte, Minas Gerais, Brazil, Sept. 1-7, 1968, 21 pp.; available from A. P. Poland, Denver Research Center, Denver, Colo.

11. Mooney, H. M. Handbook of Engineering Geophysics. Bison Instruments, Inc., Minneapolis, Minn., 1973, 121 pp.

12. Paulsen, V., R. B. Kistler, and L. L. Thomas. Slope Stability Monitoring at Boron. Min. Cong. J., v. 53, No. 9, September 1967, pp. 28-32.

13. Sheriff, R. E. Encyclopedic Dictionary of Exploration Geophysics. Society of Exploration Geophysicists, Tulsa, Okla., 1974, 266 pp.

14. Stateham, R. M., and J. S. Vanderpool. Microseismic and Displacement Investigations in an Unstable Slope. BuMines RI 7470, 1971, 22 pp.

15. Telford, W. M., L. P. Geldart, R. E. Sheriff, and D. A. Keys. Applied Geophysics. Cambridge University Press, New York, 1976, 860 pp.

16. United Geophysical Corp., Staff. Seismic Energy Sources 1968 Handbook. 57 pp.

17. Wintek Corp. (Lafayette, Ind.). Reference Manual, Wince Micromodules. 1977, 141 pp.

18. Wisecarver, D. W. Changes in Stress, Strain, and Displacement With Change in Slope Angle. Pres. at Ann. Meet., AIME, New York, Feb. 25-29, 1968, 24 pp.; available from A. P. Poland, Denver Research Center, Denver, Colo.

19. Wisecarver, D. W., R. H. Merrill, D. O. Rausch, and S. J. Hubbard. Investigation of In Situ Rock Stresses, Ruth Mining District, Nevada, With Emphasis on Slope Design Problems in Open-Pit Mines. BuMines RI 6541, 1964, 21 pp.

20. Wisecarver, D. W., R. H. Merrill, and R. M. Stateham. The Microseismic Technique Applied to Slope Stability. Trans. Soc. Min. Eng., AIME, v. 244, 1969, pp. 378-385.

APPENDIX.--PREAMPLIFIER AND LINE DRIVER SMALL PARTS LIST

Resistors[1]

	Kilohm		Kilohm
R1.....	10	R11.....	10 (20-turn trim pot)
R2.....	330	R12.....	2.7
R3.....	1	R13.....	330
R4.....	330	R14.....	3.3
R5.....	10	R15.....	33
R6.....	100	R16.....	330
R7.....	330	R17.....	4.7
R8.....	1	R18.....	1
R9.....	10	R19.....	4.7
R10....	1	R20.....	1,000

[1]All resistors are 1/8 watt.

Capacitators	Microfarad	Composition	Capacitators	Microfarad	Composition
C1.............	[1]22	Tantalum	C7.............	[2]4.7	Tantalum
C2.............	.1	Mica	C8.............	[3]39	Mica
C3.............	.1	Mica	C9.............	.1	Mica
C4.............	[2]10	Tantalum	C10............	.001	Mica
C5.............	.1	Mica	C11, C12.......	[2]68	Tantalum
C6.............	.001	Mica			

[1]At 6 V.
[2]At 25 V.
[3]Picofarad.

Other components	Manufacturer and model
Operational amplifiers A1 and A2	Signetics SE5534
Silicon rectifiers D1 and D2....	Texas Instruments 1N4001
Transistor Q1..................	Motorola or RCA 2N3904
Schmitt trigger................	Motorola or RCA 4093BE
Quad miniswitch S1.............	Grayhill
Printed circuit board..........	Custom

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