AFCRL-65-527

ESTABLISHMENT OF A LONG-PERIOD SEISMOGRAPH NETWORK UTILIZING MAGNETIC TAPE RECORDING

Paul W. Pomeroy

Lamont Geological Observatory
Columbia University
Palisades, New York

Contract No. AF19(604)-8485

Project No. 8652

Task No. 865207

Final Report

Period covered: June 1961-May 1965

1 June 1965

Prepared for

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

WORK SPONSORED BY ADVANCED RESEARCH PROJECTS AGENCY

PROJECT VELA-UNIFORM

ARPA Order No. 292

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ABSTRACT

A worldwide network of long-period seismographs recording on magnetic tape has been established, including stations at Mt. Tsukuba, Japan; Honolulu, Hawaii; Uppsala, Sweden; Huancayo, Peru; College, Alaska; Canberra, Australia; and Palisades, New York. At these stations the amplified outputs of 3-component 15-second transducers are recorded at two gain levels on tape recorders operating at .06 inches per second. These units provide 16 2/3 days of recording time per reel with a bandwidth of DC to 10 cps and a signal-to-noise ratio of 60 db. This worldwide network continues in operation at the present time.

Analysis techniques developed and/or utilized for data analysis in this program include: (a) high-, low- and band-pass filtering; (b) inverse filtering, (c) Fourier analysis, (d) rotation of instrumental axes, (e) cumulative energy, (f) longitudinal-vertical product for particle motion, (g) angles of emergence and azimuth, and (h) direction of microseism approach and beam width. Studies of particular interest to the VELA-UNIFORM program include: (a) contouring of total energy and ratio of high-frequency-to-low-frequency energy for the Hardhat and Gnome underground nuclear events and comparison with data from the New Madrid and Hebgen Lake earthquakes, (b) the determination of experimental radiation patterns for Love and Rayleigh waves (both amplitude and phase) for several underground nuclear explosions and the comparison of the observed data with theoretical models, (c) studies of deep hydrophone and ocean bottom seismometer data using several analog analysis techniques, and (d) the study of PcP arrivals from the BILBY event.

INTRODUCTION

The work statement of this contract reads simply "the establishment of a long-period seismograph network utilizing magnetic tape recording." Specifically, funding was initially provided for the establishment of five (5) stations. Within this funding, a total of seven stations has been established throughout the world. This accomplishment has been made possible by judicious management of available funds and the continued cooperation of the stations of this network. The result has been the accumulation of a large amount of valuable data for the Air Force, the Advanced Research Projects Agency, the cooperating stations and Columbia University. The worldwide network of stations continues in operation today and is producing large amounts of valuable scientific data.

In addition to the recording instrumentation at the network stations, an analog data analysis facility has been established at the Lamont Observatory with the support of this and other contracts. A wide variety of analysis instrumentation is available in the analog analysis laboratory for handling data initially recorded on magnetic tape. The data may be reproduced at high speed and subsequent analysis may be done on analog or digital computers depending upon the particular project. Analog computers available include a 20-operational amplifier general purpose unit, a 48-amplifier general purpose unit, and two special purpose units. A medium speed, automatic digitizing system is available for data transformation to the digital domain for subsequent analyses on an IBM 1620 computer or a 7090 computer available at Columbia University.

The initial renewal proposal for this contract, submitted in 1963, stated the purpose of the renewal as twofold:

1. To secure funding to insure the continuing operation of the magnetic tape recording network and
2. To secure funding to carry out analyses on the magnetic tape seismograph data.

This second purpose is particularly important since the principal purpose of recording seismic data on magnetic tape is to provide data easily adaptable to automatic reduction and analysis. Furthermore, it is only by continuing analysis of the recorded data that deficiencies in the recording system can be corrected and system improvements made.

Several analog analysis techniques have been developed and/or used during the course of this contract. These methods, which will be described in detail in a later section of this report, allow the analysis of large amounts of magnetic tape data in a rapid and efficient manner. Among the operations which may be performed in the analog domain are (a) high-pass, low-pass, band-pass, and inverse filtering, (b) integration of traces, (c) computation of Fourier spectra, (d) rotation of instrumental axes, (e) multiplication of components to separate particle motion, (f) computation of emergence angle and azimuth angle, and (g) computation of microseismic direction of approach and beam width.

Although only a small portion of the funding of this contract was devoted to data analysis, several analyses of significance to the VELA-UNIFORM program have been carried out. These include:

(a) Analyses of the total energy distribution and the variation of the ratio of high-frequency-to-low-frequency energy within the U. S. for the Hardhat and Gnome underground nuclear explosions. These studies, which show a structural control on the energy distribution, were compared with those of two earthquakes in Hebgen Lake and New Madrid.

(b) The determination of the radiation patterns (both amplitude and initial phase) of Rayleigh and Love waves from several underground nuclear explosions in Nevada and several small magnitude earthquakes.

(c) Studies of the foreshock-aftershock sequence of the Alaskan earthquake of 28 March 1964 to observe the variation of magnitude, location and depth; the spectral content of the surface waves; and the spatial and temporal distribution of microaftershocks.

(d) A study of deep hydrophone and ocean bottom seismometer data recorded on magnetic tape to cast some light on the origin of microseisms.

(e) A study of the PcP arrivals from the BILBY event.

These studys, together with many others, are described in detail in a later portion of this report. Further analyses of the tape recorded data are continuing at the present time.

NETWORK STATIONS

The stations listed in Table I are cooperative members of this network and are fully operational at the present time.

Table I

Station	Latitude	Longitude	Date of Commencement of Operation
Mt. Tsukuba, Japan	36 12 39.0°N	14 06 36.0°E	Aug 1, 1962
Honolulu, Hawaii	21 19 18.0°N	158 00 30°W	July 15, 1962
Uppsala, Sweden	59 51 29.0°N	17 37 37.0°E	Sept 7, 1962
Huancayo, Peru	12 02 18.1°S	75 19 22.1°W	Dec 13, 1962
College, Alaska	64 54 00.0°N	147 47 36.0°W	Dec 10, 1963*
Canberra, Australia	35 19 15.0°S	148 59 55.0°E	Apr 12, 1964*
Palisades, New York	41 00 25.0°N	73 54 31.0°W	June 11, 1962

* - The installation of these stations was delayed pending completion of vault construction by the cooperating station.

An outline map showing the locations of the stations listed in Table I is presented in figure 1. At these stations, the instruments are operated entirely by local personnel. Routine maintenance, including cleaning of the recording heads and changing of photographic monitor records and magnetic tapes, is provided, while unusual maintenance and system upgrading is performed by Lamont Observatory personnel in the course of an annual service trip. Records a routinely mailed to Lamont Observatory for analysis and ultimate storage.

INSTRUMENTATION

Since the primary purpose of this ontract was to develop, procure and install instrumentation suitable for recording the output of long period seismometers on magnetic tape, considerable attention to the instrumental details will be given in this report. In the interest of brevity, however, detailed descriptions and circuit diagrams will be presented only for unusual instrumentation developed especially for this contract. Only general descriptions of more standard instruments, such as long-period seismometers and tape recorders, will be presented.

1. Seismometers.

(a) Vertical long period - All of the stations in this network utilize the Columbia-type long-period vertical seismometers manufactured by the Sprengnether Instrument Company. These units have the following specifications:

Transducer: Single coil velocity type
Moving Mass: 11.2 kilograms
Coil Resistance: Approximately 500 ohms
Output: 89 volts/meter/second
Output Non-linearity: $\pm 1.5\%$ in a 3° operating range.
Free Period: 15 seconds. At Canberra, by special arrangement with the local personnel, a free period of 30 seconds is utilized.

(b) Horizontal long period - The stations in this network utilize long-period horizontal instruments manufactured either by the Sprengnether Instrument Company or by the United Geomeasurements Division of United ElectroDynamics Inc. (formerly Lehner and Griffiths). The specifications of these instruments are as follows:

	Sprengnether Type	UED Type
Transducer:	Single coil velocity	Single coil velocity
Moving Mass:	10.7 kilograms	6.9 kilograms
Coil resistance:	Approx. 500 ohms	Approx. 500 ohms
Output:	89 volts/meter/sec	103 volts/meter/sec
Output non-linearity:	$\pm$1.5% over 3° operating range	---
Free period:	15 seconds	15 seconds

At Canberra, a free period of 30 seconds is utilized. The choice between the horizontal instruments was arbitrary since the coupling circuits can be adjusted to provide equivalent operating conditions.

2. Amplifiers. Three channels of preamplification are required to bring the three-component, long-period signals up to a level suitable for driving the record oscillators of the tape recorder. The preamplifiers must be able to accept low impedance inputs (i.e., $\sim$ 5000 ohms) and, of course, the input and output of each preamplifier must be completely isolated to prevent feedback to the photographically recording monitor circuit. The amplifier selected for this purpose was a Minneapolis-Honeywell Deviation Amplifier having the following specifications:

Environmental Limits:

Ambient temperature: 40° to 120° F
Relative humidity: 10% to 95%
Vibration: .03 inches peak-to-peak - 1 to 60 cps - 0.2g

Input:

Minimum span: $\pm$ 25 microvolts
Minimum detectable signal: $\pm$0.5 microvolts - $\pm$0.5x10^{-11} amperes
Resistance: 40,000 ohms at a gain of 10,000
10,000 ohms at a gain of 40,000
Gain: Adjustable 7500 to 100,000
Stability: 2% at a gain of 10,000

Output:

Capability: $\pm$ 4 volts into 2000 ohms or more
Impedance: 250 ohms at a gain of 10,000
1000 ohms at a gain of 100,000

Ripple: 1% RMS of the direct output voltage
Zero Stability: ± 0.5 microvolt for an 8-hour period
Noise: ± 0.5 microvolts peak-to-peak over a 0 to 5 cps band pass. In general, the measured noise level was about ± 0.15 microvolts peak-to-peak over this pass band.

The wisdom of the choice of these amplifiers is indicated by the fact that, aside from a few failures of the mechanical chopper units, there have been no maintenance problems with these units. In addition, these units are of the plug-in type; they have front panel meters; they are rugged and they are rather inexpensive, i.e., approximately $450/channel. For use in this project they could be incorporated directly into the tape recorder units thus making a single package for installation purposes.

The above seismometer-amplifier combination provides a displacement response, which with increasing period falls at 6 db/octave from approximately 5 cps to 15 seconds and then drops at 18 db/octave for periods greater than 15 seconds.

3. Tape Recorders. Minneapolis-Honeywell Model 7400 tape recorders specially modified for this project were selected as the basic recording unit. The specifications of these units are as follows:

(a) Electronics.

Input level: ± 0.7 to ± 35 volts for $\pm 40\%$ carrier deviation
Input impedance: 10,000 ohms unbalanced to ground
D. C. linearity: less than 1% peak-to-peak output deviation from best straight line through zero center
Total harmonic distortion: less than 1.5%
Zero drift: less than 0.5% of peak-to-peak output for an 8-hour period
Sensitivity drift: less than 0.5% of full scale for an 8-hour period
Output level: 0 to 4 volts peak, variable
Output current: 30 milliamperes maximum at 4 volts peak
Output impedance: less than 1 ohm; short circuit proof
Oscillator frequency: 54 cps

(b) Transport.

Reel size: 14 inches
Tape width: 1/2 inch
Number of channels: 7
Tape speed: .06 inches per second with provision for 11 other speeds
Tape thickness: 1 mil
Recording time: 15 days
Monitor lights: to indicate record failure

The signal-to-noise measurements carried out on the above system indicate the following values:

Band pass: 0 to 5 cps	61DB peak-to-peak signal to RMS noise
Band pass: 0 to 1 cps	65DB peak-to-peak signal to RMS noise

The track configurations for these 7-channel systems are given in Table II.

Table II

Channel	Use	Level
1	North-South	High gain
2	East-West	High gain
3	Vertical	High gain
4	Compensation	Unmodulated
5	North-South	Low gain (x 1/5)
6	East-West	Low gain (x 1/5) + time information
7	Vertical	Low gain (x 1/5)

A photograph of the operational tape recorder at Palisades with pre-amplifiers, timing system and real time reproduce system is presented in figure 2.

4. Time. The basic design criteria for the timing system were the following:

(a) Since the recorded time interval on each reel of tape is of the order of 15 days, it is a necessity to have time indications in days, hours and minutes, at least at the beginning, middle and end of the tape.

(b) A constant-frequency, 54 cps carrier with an accuracy of .001% is recorded as a compensation channel. This provides an excellent relative time base.

(c) Readable time marks must be recorded on at least one channel.

(d) The AM bandwidth of the system at .06 inches-per-second tape speed is of the order of 100 cycles so that any time code must have definition within this limitation.

(e) A time mark visible even under a time base compression of 100 is required.

Because of the complexity generally associated with commercial time-code generators and because of the lack of electronic technicians at many of the network stations, the use of time-code generators was precluded. In order to eliminate confusion at the network stations, it was decided not to operate independent clocks or timing systems solely for the magnetic tape systems. Such operation would have meant two timing corrections at one station.

The timing system resulting from the above considerations was the following:

(a) The time marks from the cooperating station's clock are inserted on channel number 6 of the magnetic tape recorders. The time corrections of the station clock are noted on a logbook sheet forwarded to Lamont with each reel of tape.

(b) Time code information, including a station identification number, the year, the month, the day, the hour, and the upcoming minute, is inserted by hand keying on channel number 6 in International Morse Code at the beginning, middle and end of each tape. Two decimal figures are used to indicate each piece of information. In order to obtain a reasonable playback of this information, each dot must be five seconds in duration and each dash 15 seconds in duration. In addition, day, hour and upcoming minute information is inserted on channel number 6 daily by the same means. All of the time code information put on the tape is also recorded in a logbook and one copy of this data is sent to Lamont Observatory with the tape. A schematic of a typical timing circuit is presented in figure 3. Since each station varies the format of its timing (i. e., some have normally closed relay circuits, others normally open) slight variations in this circuitry may be found at the network stations.

Since it has become a tedious task at many of these stations to put the time code information on the tape (the operation requires about twenty minutes of operator time), a simple automatic system has been devised. This system is essentially mechanical in nature and relatively trouble free. It will be installed at the outlying stations under the continuation of this contract. A photograph is included in this report as figure 4 and schematic diagrams are presented in figures 5 and 6.

5. Magnetic Tape. Some problems were encountered in the initial operation of this network due to oxide shedding of the magnetic tape utilized. This "shed" oxide built up on the heads causing a recording head-magnetic tape separation which led to loss of carrier after three to five days of operation. This shedding was primarily due to the nature of the tape used, i. e., Scotch 599 instrumentation tape which has a relatively soft base and coating. The use of Memorex 42J or Ampex 748 magnetic tape completely eliminated this problem and these two tapes are being used exclusively in this network at present.

6. Photographic Recording Monitor Facilities. The outputs from the long-period seismometers are fed in parallel to the tape recorder

and to long-period galvanometers whose oscillations are recorded on drum recorders. The long-period galvanometers are United ElectroDynamics GL 261 operating at a fr e period of 75 to 90 seconds. Although the response characteristics of this system are quite different from those of the tape system, the station operators are (in case of trouble) able to determine if the seismometers are swinging freely and thereby isolate, to some degree, the source of any trouble. The drum recorders used for this purpose are Sprengnether Series F 3-component with a recording speed of 15 millimeters per minute and a translation rate of 1 centimeter per revolution. The photographic monitor records are also forwarded to the Lamont Observatory for use with the magnetic tape records. A schematic presentation of a typical tape and photographic system (College, Alaska) is presented in figure 7.

7. Real Time Reproduce Facilities. This entire recording program is successful primarily because of its cooperative nature. The network stations are free to utilize the records for their own research purposes. However, in the past, they have been able only to use the photographic monitor records for research and system maintenance. The problem of playback of signals in real time when they are recorded at .06 inches/second is unusually severe unless flux sensitive heads are used. However, because of their electronic complexity, flux sensitive heads were not used in this application.

A real time playback system using velocity sensitive heads has been designed and built at the Lamont Observatory. This system, operating at .06 ips, gives a signal-to-noise ratio greater than 34 db (peak-to-peak signal to RMS noise). The system uses a Honeywell reproduce head of either the standard type or a special type with a larger number of windings. The former type gives less output but may be used at reproduce speeds higher than .06 inches per second, but its increased inductance precludes its use at speeds greater than 6 inches per second.

The output of the reproduce head is amplified and subsequently demodulated. The schematic diagram of the circuit designed for this purpose is shown in figure 8 and a picture of a unit is shown in figure 9. Oscilloscope and demodulator outputs are available so that the carrier or the demodulated signal may be observed. A Heathkit 3" oscilloscope and a Sanborn Model 299 recorder are provided to each station for this purpose. All the units are ready for installation and will be included in the stations during the next periodic maintenance trip.

DATA ANALYSIS FACILITY

With the aid of this contract in conjunction with NASA contracts, an analog data analysis facility has been established at the Lamont Geological Observatory. The principal purpose of this facility is to analyze the magnetic tape data obtained under this contract and its successor AF19(628)-5058.

The equipment included in this grouping consists of the following:

1. 1 TR-48 48-amplifier analog computer with high accuracy multipliers and a separate console of five 100-volt, very high accuracy multipliers
2. 1 TR-10 20-amplifier analog computer
3. 1 Technical Products Company spectrum analyzer
4. 1 Kay Electric Corporation sound spectrograph
5. 1 ISAC statistical analog computer with tape loop for power spectra and auto and cross correlation analysis
6. 2 Honeywell Model 7400 tape transports with record/reproduce electronics
7. 1 Honeywell tape loop transport for spectrum analyses
8. 1 Dymec DY6654 medium-speed digitization system with punched card/punched paper tape output
9. 1 hand digitizer, laboratory built, with associated electronics and punched card, punched paper tape and electrical analog output

10. 1 Sanborn 4-channel, hot-pen recorder
11. 3 Krohn-Hite 330 A-4 low-frequency, band-pass filters.

A photograph of the TR-48 computer, the principal data analysis unit, is presented in figure 10. All of this equipment allows the rapid and efficient analysis of data originally recorded on magnetic tape in either the analog or digital domain.

ANALYSIS TECHNIQUES

During the first two years of this contract, the primary emphasis was on the design, assembly and installation of the equipment. By the end of the above period, five stations of this network were operational and data recorded on magnetic tape was being received at the Lamont Observatory. This, in turn, required the development of analog analysis techniques for handling this data. The principal purposes of the second 2-year period of this contract were:

1. To insure the continuing operation of the magnetic tape recording system and
2. To initiate and carry out analyses on the seismic data recorded on magnetic tape.

The following analog analysis techniques have been devised and/or utilized.

1. Simple filtering - high pass, low pass or band pass. The electrical analog output of the magnetic tape systems is particularly useful for simple filtering analysis. Selective and successively longer period low-pass filtering first reduces and then eliminates the intermediate 4- to 9-second microseismic background and effectively isolates long-period features. High-pass and band-pass filtering have been used extensively to isolate higher mode waves from the wide band seismograms.

2. Inverse filtering. The electrical analog output contains the system instrumental response. This response may be easily removed by

inverse filtering using analog computer components. In addition, inverse filtering may be used to shape the system response to any desired characteristic within reasonable limits established by system noise and other factors.

3. Total energy computation. After shaping the electrical analog output from the tape recorders to a flat velocity response, the signal may then be squared and integrated using simple analog computer components to obtain the integrated wide band energy. If the signal is filtered prior to the squaring and integrating operation, a narrow band integrated energy is obtained which is a measure of the energy spectrum of the event.

The use of the wide band method allows the automatic determination of a value similar to the AR value which has been suggested as a diagnostic aid. Automatic compilations of this value can be made from the long-period instruments and compared with similar values derived from short-period records of the same event. The automatic determination of these values could be of significant interest for identifying earthquake and explosive events.

The three-component signals may be added in a simple analog manner to produce total energy at the station.

4. Fourier spectral analysis. The original magnetic tape seismogram, after appropriate filtering, can be multiplied by the output of a multiple phase oscillator to produce the product of the time function (the seismogram) and sin ωt and cos ωt. The product output f(t) sin ωt and f(t) cos ωt is then integrated to produce the Fourier coefficients

$$g(w) = \int f(t) \cos \omega t \, dt$$

$$h(w) = \int f(t) \sin \omega t \, dt$$

Using this method, rapid determinations of the Fourier spectra may be made.

Fourier spectra in the analog domain may be obtained also by the method of Cooper and Broome. Their method eliminates the use of an analog multiplier which is usually the weak link of any analog data handling system.

5. Rotation of instrumental axes. It is often valuable to obtain pure longitudinal and pure transverse horizontal components. When the original seismogram is recorded on magnetic tape, the longitudinal (L) and transverse (T) motion can be obtained by application of the formulas

$$L = N \cos \theta + E \sin \theta$$

$$T = N \sin \theta - E \cos \theta$$

where θ is the azimuthal angle. The azimuth angle may be determined from the epicentral location or the azimuth angle may be scanned to obtain the best separation. Alternatively, the azimuth angle may be determined from the analog technique discussed below. In any event, axis rotation may be accomplished quickly and efficiently using analog computer components and has been extensively applied to many events of interest. SH motion is effectively isolated on the transverse component upon application of this technique.

6. Determination of azimuth angle and angle of emergence. A program for the analog computer has been developed to give the azimuth angle and the angle of emergence as a function of time. The program was originally developed according to the equations:

$$\sin^2 e = \frac{Z^2}{L^2 + Z^2} \qquad \sin^2 \theta = \frac{T^2}{L^2 + T^2}$$

where e is the emergence angle

θ is the azimuth angle

L is the longitudinal seismic trace

Z is the vertical seismic tract

T is the transverse seismic trace

Since the multiplication circuits have a limited dynamic range, the following equations for the desired angles were programed on the computer:

$$\frac{1}{1 + \cot e} = \frac{|Z|}{|L| + |Z|} \quad \text{and} \quad \frac{1}{1 + \cot \theta} = \frac{|L|}{|L| + |T|}$$

7. Phase identification. The use of the techniques discussed in this section separates waves showing compressional-type particle motion from those showing SV-type particle motion and surface wave particle motion. Thus, compressional-type particle motion may be separated from microseismic noise and, therefore, the system is of value for increasing the signal-to-noise ratio in the P wave. Any method which enhances the signal-to-noise ratio is valuable in relation to the detection problem.

The multiplication of the "pure" longitudinal component record by the vertical component record produces the separation of interest. If the directions up and away from the source are defined as positive, then in the product of the longitudinal and vertical compressional-type particle motion will be positive in sense while SV-type particle motion will be negative in sense. Thus, compressional P and SV are separated while SH was separated earlier on the transverse instrument playout.

The multiplication of the signals by one another permits the "aiming" of the instruments at a certain specified area. This allows the monitoring of areas of interest with a resultant increase in signal-to-noise ratio.

8. Direction of approach and beam width. For studies of microseisms, the following system has been programed on the analog computer.

Assuming a simple Rayleigh wave, if we filter the electrical analog outputs of the tape recorders, we have

$$N = A \cos\theta \sin\omega t$$

$$E = A \sin\theta \sin\omega t$$

$$Z = Ap \cos\omega t$$

where A is the amplitude of the horizontal component of the Rayleigh wave

θ is the azimuth angle

p is the polarization constant

t is the time and

ω is the angular frequency.

Integrating the Z component with respect to time, we obtain

$$Z_i = \frac{Ap}{\omega} \sin\omega t$$

Multiplying Z_i by the two horizontal components separately and integrating the products, we obtain two quantities which yield the azimuth providing the integration time includes several cycles of the signal.

$$\frac{I_{EZ}}{I_{NZ}} = \frac{\int_0^T E Z_i \, dt}{\int_0^T N Z_i \, dt} = \frac{\sin\theta \frac{A^2 p}{\omega} \int_0^T \sin^2 \omega t \, dt}{\cos\theta \frac{A^2 p}{\omega} \int_0^T \sin^2 \omega t \, dt} \approx \tan\theta$$

To obtain an estimate of the spreading or beam width of the signal, the following quantity B was programed:

$$B = \frac{I^2_{EZ} + I^2_{NZ}}{I_{ZZ}^2} \quad \text{where } I_{ZZ} = \int_0^T Z^2 dt \text{ and B is the beam width}$$

parameter. This parameter decreases with increasing spread and interference. For two or more interfering sources of the same frequency but different azimuth, the above method gives an intermediate direction depending on the relative intensity of radiation at the recording site. The method is capable of resolving the multiple source problem if the spectra of the sources are different. Finally, the method may be used to determine the direction of approach of Rayleigh waves and to study lateral refraction. Love waves, body waves, and random noise tend to be eliminated by this method.

DATA ANALYSES

1. Analog Analysis Techniques. One of the first studies carried out under this contract was that entitled "Analog Analyses of Seismograms Recorded on Magnetic Tape," by Sutton and Pomeroy of the Lamont staff. That paper described many of the analysis techniques together with applications to different seismic phenomena. In particular, analog analyses of seismic waves from eight distant earthquakes, a large nuclear explosion, and a microseism storm were used to illustrate some of the advantages of analog magnetic tape recording. Inverse and selective filtering, with and without filter phase shift, were used to remove instrumental effects, to improve signal-to-noise ratio and to emphasize desired phases. Fourier, energy, and power spectra were obtained by several analog methods. Comparison of the result of an analog Fourier analysis of the Palisades record of a large Soviet nuclear explosion near Novaya Zemlya in 1961 with digital analyses of two smaller explosions of 1958 in the same area as recorded at Palisades showed remarkably similar spectra. The only significant difference between the two sets of data is that the larger event was richer in long-period energy. Plots of frequency vs. time and of cumulative energy, in different frequency bands, vs. time, showed that seismic data could be presented in a form more convenient for certain studies than could the conventional record. Various combinations of the original three-component signal not only indicated the ease of identification of certain types of waves but also aided in the detailed study of near-station effects. Results of the rotation of apparent instrumental axes to longitudinal horizontal, transverse horizontal, and vertical were used to demonstrate the advantages of these types of data transformation.

2. Surface Wave Radiation Patterns. One of the most exciting studies, which was carried out partially under the support of this contract, was the investigation of surface wave radiation patterns for underground nuclear explosions and small-magnitude earthquakes. Initially, in this study the surface wave radiation patterns (both initial amplitude and initial phase) were determined for several of the larger underground nuclear explosions in Nevada. Initial phases of the surface waves were obtained by performing a Fourier analysis of the record and equalizing the phase to the source, using long-period records from the temporary, long-range seismic measurements (LRSM) stations. The results showed that Rayleigh waves from explosions in tuff and alluvium appeared to have nearly the same initial phase at all azimuths, indicating an explosive force acting as a step function in time as a possible source mechanism. However, the presence of Love waves, together with the same asymmetry in the Rayleigh wave amplitudes, indicated that some asymmetrical forces were also acting at the origin. The collapses which followed these explosions generated Rayleigh waves with polarities apparently reversed from those of the explosions. The collapses generated much weaker Love waves, relative to the Rayleigh waves, than the explosions and, therefore, the Love waves must be generated at or near the source. The Hardhat explosion in granite gave a radiation pattern with double-couple symmetry in both amplitude and phase and such a radiation pattern cannot be explained by a simple symmetric explosive force. Brune and Pomeroy considered several explanations including the possibilities that the surface waves were generated by cracking or force motion along pre-existing cracks, that there was tectonic strain release resulting from cavity formation, or that there was triggering of tectonic motion. The latter hypothesis appeared to be the most probable since an aftershock sequence occurred, outside the cavity zone, in a manner similar to that common for earthquakes.

Several analyses of earthquakes were carried out, also, and, in general, the earthquake sources appeared more complicated than the explosions. The study of earthquake sources is continuing. Haskell's equations for Rayleigh wave radiation patterns have been programed for the IBM 1620 so that theoretical radiation patterns may be computed for comparison with the observed data. All of Haskell's cases have been computed. In addition, patterns for vertical dip-slip faults at depths of 0 to 100 km in 10 km steps have been calculated at periods of 16, 25 and [illegible] seconds. The information obtained from the long-period waves about the source is, of course, of fundamental importance to the problem of identification of explosions and earthquakes.

3. Analyses of the Hardhat and Gnome Underground Explosions and the New Madrid and Hebgen Lake Earthquakes. We have defined the "energy" E as $E = \int_{0}^{\infty} s^2(t)\,dt$ where s(t) is the signal amplitude in microns for a given station and component for a given event. Contour maps of the exponent of the resultant E in terms of micron^2 seconds have been computed along several profiles from these events. The Q values show an azimuthal dependence which is probably related to the particular tectonic provinces involved. Typical values obtained for Q are between 200 and 400.

If we divide the spectra of the short-period signals from these events arbitrarily at 1.4 cps, we can then define a $\Delta f = f_H - f_L$ where

f_H is equal to the center frequency of the high-frequency band and

f_L is equal to the center frequency of the low-frequency band.

Contour maps of the ratio of high-frequency energy-to-low-frequency energy content have been prepared and these maps also show evidence for tectonic control. Also, typical values for Δf are around 0.4 cps so that f_H = 1.8 cps and f_L = 1.0 cps. This is a narrow concentration of the energy. A closer examination of the Δf values indicates an azimuthal dependence. Examination in detail of the particle motion at the LRSM stations from these events is currently under way and will be continued under AF19(620)-5058.

4. Direction of Approach of Microseisms. A study of the direction of approach of microseisms and the beam width of the source was carried out utilizing the methods outlined in the analysis section above. Basically, one-hour samples of microseismic data recorded at the network stations were used. All three components of the tape recorded signal were filtered sharply using Krohn-Hite band-pass filters. The calculations of the azimuth angle and the beam width parameter were carried out on an Electronics Associate, Inc. (EAI) TR-10 analog computer. As noted above, the results are far more precise than those of earlier studies and the computed azimuth angles are not influenced appreciably by Love waves or by random noise. For extratropical cyclones, the bearings obtained lag behind the storm center, while for hurricanes the bearings tend to follow the areas where the storm is over the continental shelf. For single sources, the directions obtained using different filter settings are the same, while, in certain cases, the multiple source problem can be solved using these techniques.

5. Spectrograph Analyses of Earthquake Dispersion and Microseism Periods. A particularly powerful method of handling large amounts of data is the combination of magnetic tape seismograms and the Kay Electric Company sound spectrograph. The spectrograph produces a plot of frequency vs. time in the frequency range from 5 to 500 cps. In addition plots of amplitude and power vs. frequency may be obtained. A magnetic tape record is re-recorded in the analysis drum

and the results are produced by a spark recording on sensitized paper. Spectral analysis of several microseism storms has led to the identification of several storms which generate seismic waves in the 14- to 18-second period range, as well as those in the 7- to 9-second range. This identification is made from the coincidence of the azimuth of approach of the different periods and from the simultaneity of the beginning of the microseisms in the two period ranges. Earthquake analyses with the spectrograph unit have been centered on examining the dispersion in surface wave trains of modes whose dispersion is not well known, for example, the higher shear modes from southern Alaska earthquakes.

6. Analog Analyses of Deep Hydrophone Data. These studies, which were carried out partially with the support of this contract, were particularly useful for demonstrating the power of certain analog analysis techniques while at the same time providing information of interest to the VELA-UNIFORM ocean bottom projects. Data from six hydrophones situated in about 3000 fathoms of water were analyzed to determine the power spectral density of the microseismic background during the passage of a hurricane over the recording area in the Caribbean. Signals were converted from visible records to magnetic tape records. Eight-minute intervals of data recorded at six-hour intervals over a 4-day time period were utilized. Once the signals were recorded on magnetic tape, they were passed through a one-third octave (passive) band-pass filter and then were squared and averaged using a Ballantine RMS voltmeter. Forty-five separate filter settings or frequency points were used in the analysis and specific results were checked using a digital computer.

The primary energy recorded was at a period of 2.6 seconds. The analysis results show that the peak power on a given hydrophone occurs at the time of the closest approach of the storm center to the hydrophone. This maximum energy is predominantly in the .5- to 1-cps frequency range. The highest power of the longer period noise, i.e., in the 4- to 15-second period range, occurs approximately 12 hours after the passage of the storm.

7. PcP from the Underground Nuclear Explosion BILBY. PcP arrivals from the BILBY explosion were well recorded at a number of the Worldwide Standardized Seismograph Network (WWSSN) and the Long Range Seismic Measurements (LRSM) stations. Upon analysis of these PcP arrivals, the need for additional PcP information from this event became apparent. A program was initiated at the Lamont data analysis facility to examine the magnetic tape records from the LRSM stations for additional arrivals using analog analysis techniques. The particular technique utilized the product of the longitudinal and vertical component records. This involved passing these two short-period signals through band-pass filters and then multiplying the two traces together on either the TR-10 or the TR-48 analog computers. This product was used to detect longitudinal-type particle motion in the short-period wave train in the presence of other signals and background noise. Several additional PcP arrivals were located. Of course, at epicentral distances less than 17° this particular method fails, since the radial component of PcP is too small to produce a readable signal upon multiplication.

8. Foreshock-Aftershock Sequence of the Alaskan Earthquake of 28 March 1964. Several studies of this foreshock-aftershock sequence have been carried out since this set of events provides an unusually compact set of data from a restricted source area. Studies of the magnetic tape records from College, Alaska, and Palisades, New York, for this sequence, were particularly fruitful. Amplitude and phase spectra of 60 aftershocks, which occurred during the first three days after the event, were obtained. These spectra were then correlated with depth of occurrence, the location and the magnitude of the event. A plot of the maximum raw amplitudes of the surface waves as a function of magnitude from m = 3.7 to 5.3 (m_b=USCGS) has been made and no abrupt change in surface wave generation around magnitude 4.0 was observed. In addition, multiple filtering techniques were used to obtain a picture of the high- and low-frequency excitation. Additional data on the depth of occurrence were

obtained from the short-period array stations at Eskdalemuir, Scotland, and Yellowknife, Canada, for some of the larger aftershocks.

The magnetic tape records from College were reproduced to determine the magnitude and number of the foreshocks which occurred prior to the main shock in 1964. Thirty small shocks were located in the region where the main shock occurred. These studies were carried out to determine the b value in the formula

$\log N = a + b\,(8 - m)$ where m is the magnitude and a and b are constants.

Detailed field studies of the aftershock sequence were also carried out partially under the support of this contract. Two tripartite arrays with 1 kilometer and 30 kilometer spacings, respectively, were temporarily established in Alaska during April and June 1964. These arrays, utilizing high-gain, high-frequency equipment, recorded large numbers of microaftershocks, that is, those too small to be recorded by standard seismological stations. During the April period of operation over 1000 aftershocks and microaftershocks were recorded each day, while in June the number decreased to around 400 per day. The distribution of aftershock magnitudes shows variations for shocks from different areas. These data provided a comparison of the spatial and temporal seismicity within the epicentral region for the two periods covered. The data were initially recorded on magnetic tape and the analyses were carried out at the Lamont Observatory.

9. <u>Analyses of Ocean Bottom Seismometer Data.</u> The analysis of ocean bottom seismometer data is, of course, of great interest to the VELA-UNIFORM program. The use of facilities provided by this contract to study these data provides the maximum possible efficiency in data handling. During May 1964, ocean bottom data from a three-component long-period seismograph system were recorded on magnetic

tape from a site near Bermuda. Five-minute samples of this data were taken every 6 hours, reproduced and passed through an RMS voltmeter whose output represented the total microseismic energy on the bottom at this site. Results of this study showed that:

(a) The microseismic power vs. time curves show two peaks each associated with the passage of a storm center, at the time of the closest approach of the center to the recording station.

(b) The time history curves of the microseisms at the ocean bottom site and at the Bermuda seismograph station are qualitatively the same.

(c) The peak power in the horizontal component particle motion is approximately 9 times that of the vertical on the ocean bottom, while on Bermuda the power on the vertical component instrument is slightly greater than that on the horizontal components. The particle motion ratio on the ocean bottom is approximately that of the first shear mode.

A study of the ocean bottom data obtained on magnetic tape at the site off Point Arena, California, is currently in progress. The particle motion on the horizontal instruments at this site is somewhat greater than that on the vertical, but the ratio of horizontal-to-vertical motion is not as great as that obtained at the Bermuda site.

10. Spectrograph Studies of Microbarometric Waves. The Kay Electric Company sound spectrograph is useful for studying various geophysical phenomena. Partially under the support of this contract, this device was used to plot dispersion curves (frequency vs. time) for observed and theoretical microbarograms of acoustic gravity waves in the atmosphere. The observed microbarograms were obtained from large, near-surface nuclear explosions. The dispersion curves obtained from the sound spectrograph have been compared with those obtained from analysis on a digital computer and the two methods give consistant results.

11. Analog Studies of Distant Earthquakes. A study of 15 earthquakes recorded at several stations of the magnetic tape network has been carried out. Analysis techniques employed on the records of these events include:

(a) Band-pass filtering

(b) Axis rotation

(c) Multiplication of the longitudinal and vertical to determine particle motion

(d) Determination of angle of emergence

(e) Determination of azimuth angle.

The principal purposes of this study were to determine the angle of emergence as a function of distance and focal depth and to check the operation of the recording network, particularly for compatibility of amplitude and phase response characteristics between stations.

12. Many of the larger Lake Superior explosions were well recorded on the short-period magnetic tape system at Palisades, including all those of 2000 pounds or more. Multiple filtering analyses were performed on these records to determine the optimum playback filters for these events.

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FIGURE CAPTIONS

Fig. 1. Outline map showing the locations of the cooperative stations operating long-period seismometers and slow-speed magnetic tape recorders under this contract.

Fig. 2. Photograph of slow-speed tape recorder with associated pre-amplifiers, timing system and real time reproduce system as utilized in the performance of this contract.

Fig. 3. Schematic diagram of a typical timing system utilized throughout this network. Slight variations of this unit will be found at different stations depending on the local timing format.

Fig. 4. Automatic time code keying unit to be supplied to stations of this network.

Fig. 5. Schematic diagram of automatic time keying unit.

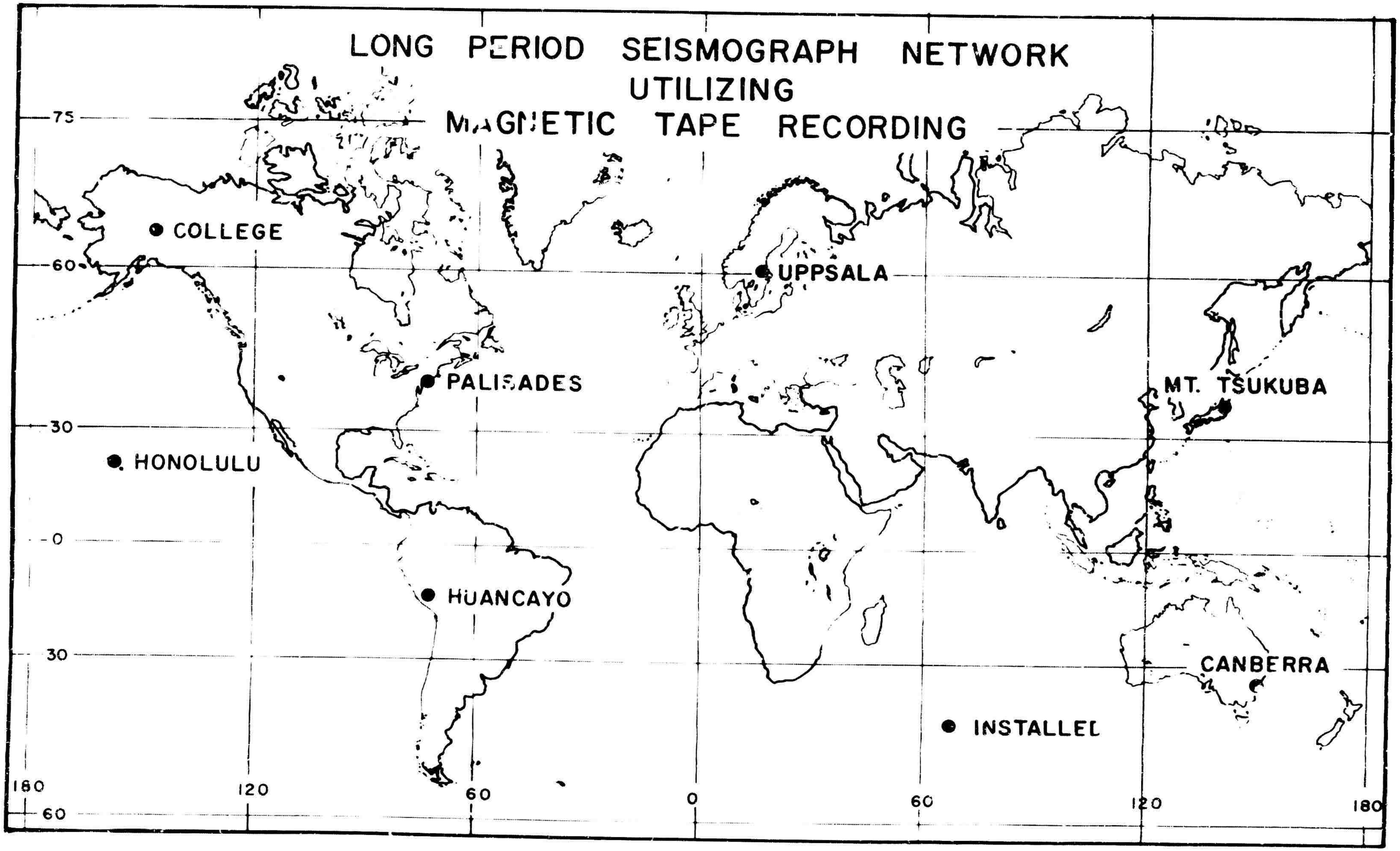
Fig. 6. Schematic diagram of automatic time keying unit. Details of figure 5.

Fig. 7. Schematic presentation of a typical magnetic tape and photographic recording system. In this diagram, calibration is performed using the second coil on the seismometer.

Fig. 8. Schematic diagram of the real time reproduce system using velocity sensitive heads designed for use at .06 inches-per-second tape speed.

Fig. 9. Photograph of the real time reproduce system designed for .06 inches-per-second operation.

Fig. 10. Photograph of the EAI TR-48 general purpose analog computer and its associated 100-volt, high-accuracy multiplication circuitry.



LONG PERIOD SEISMOGRAPH NETWORK
UTILIZING
MAGNETIC TAPE RECORDING
COLLEGE
UPPSALA
PALISADES
MT. TSUKUBA
HONOLULU
HUANCAYO
CANBERRA
INSTALLED
75
60
30
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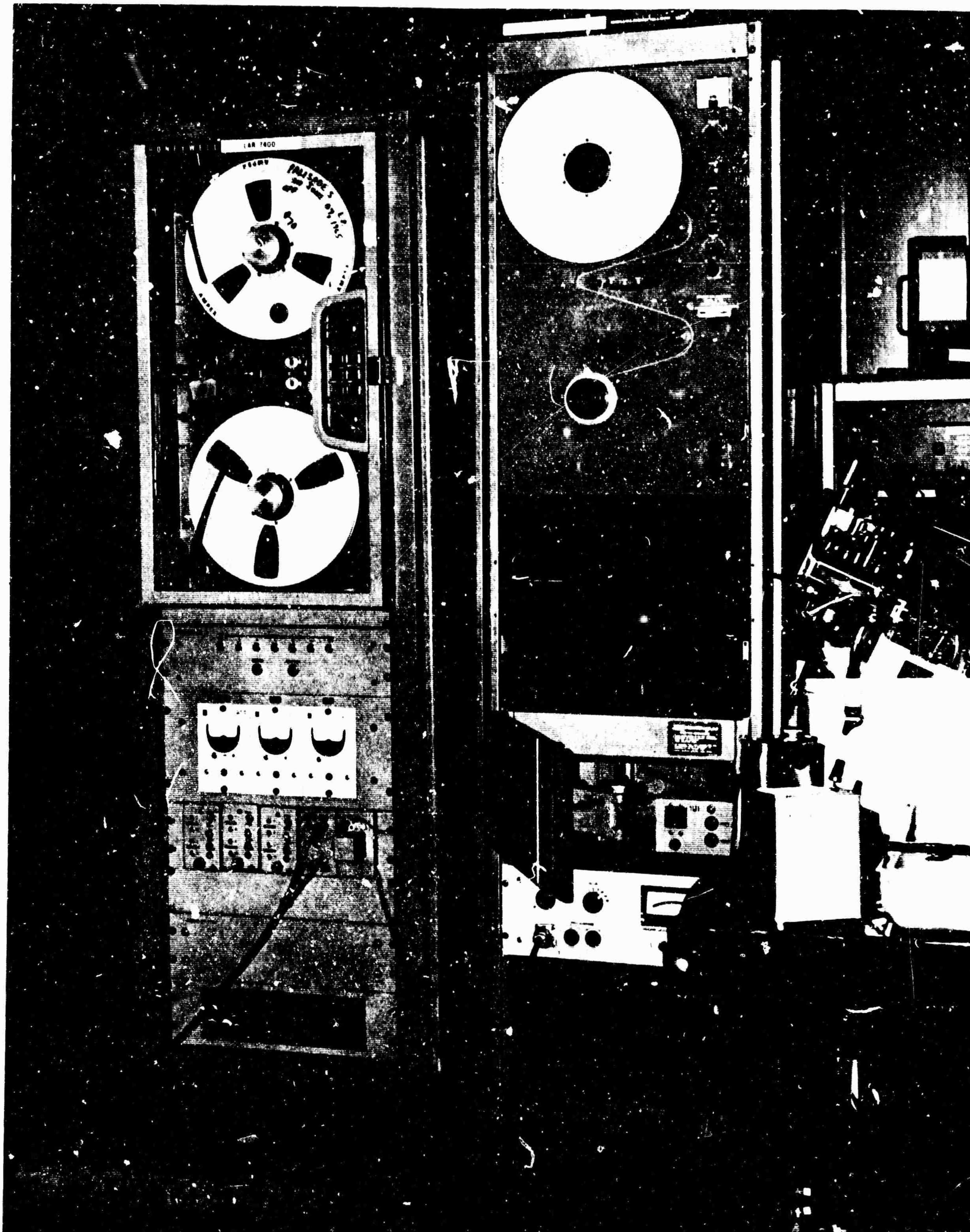
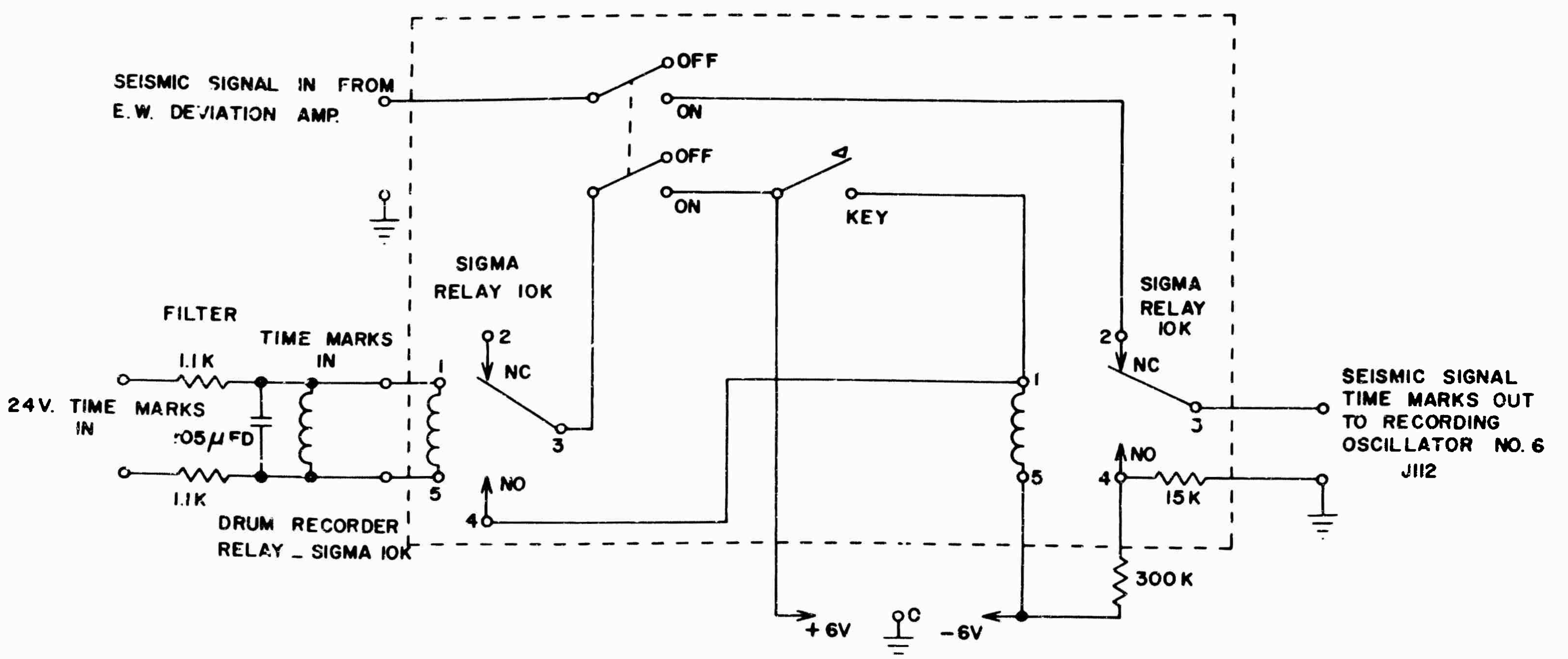
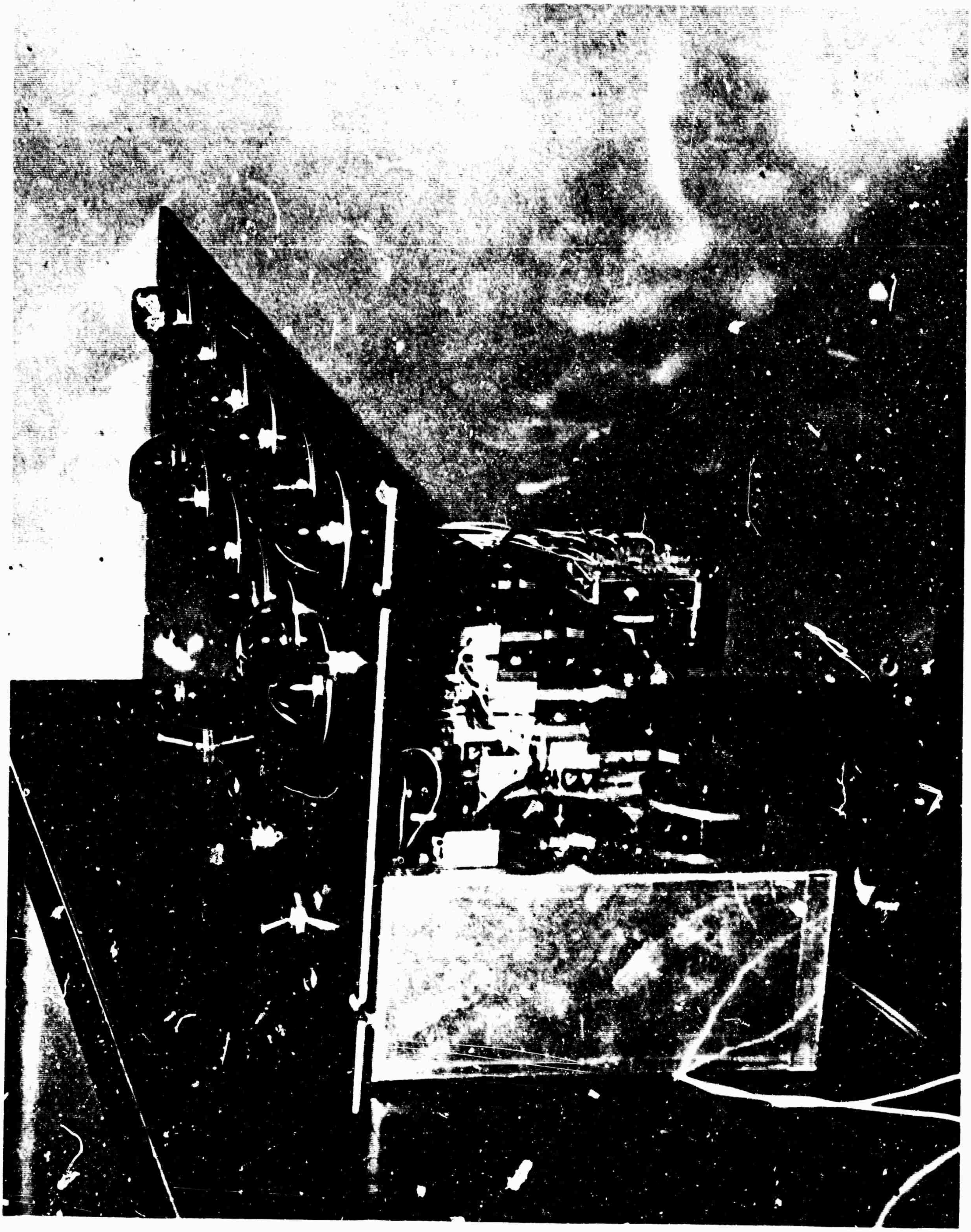
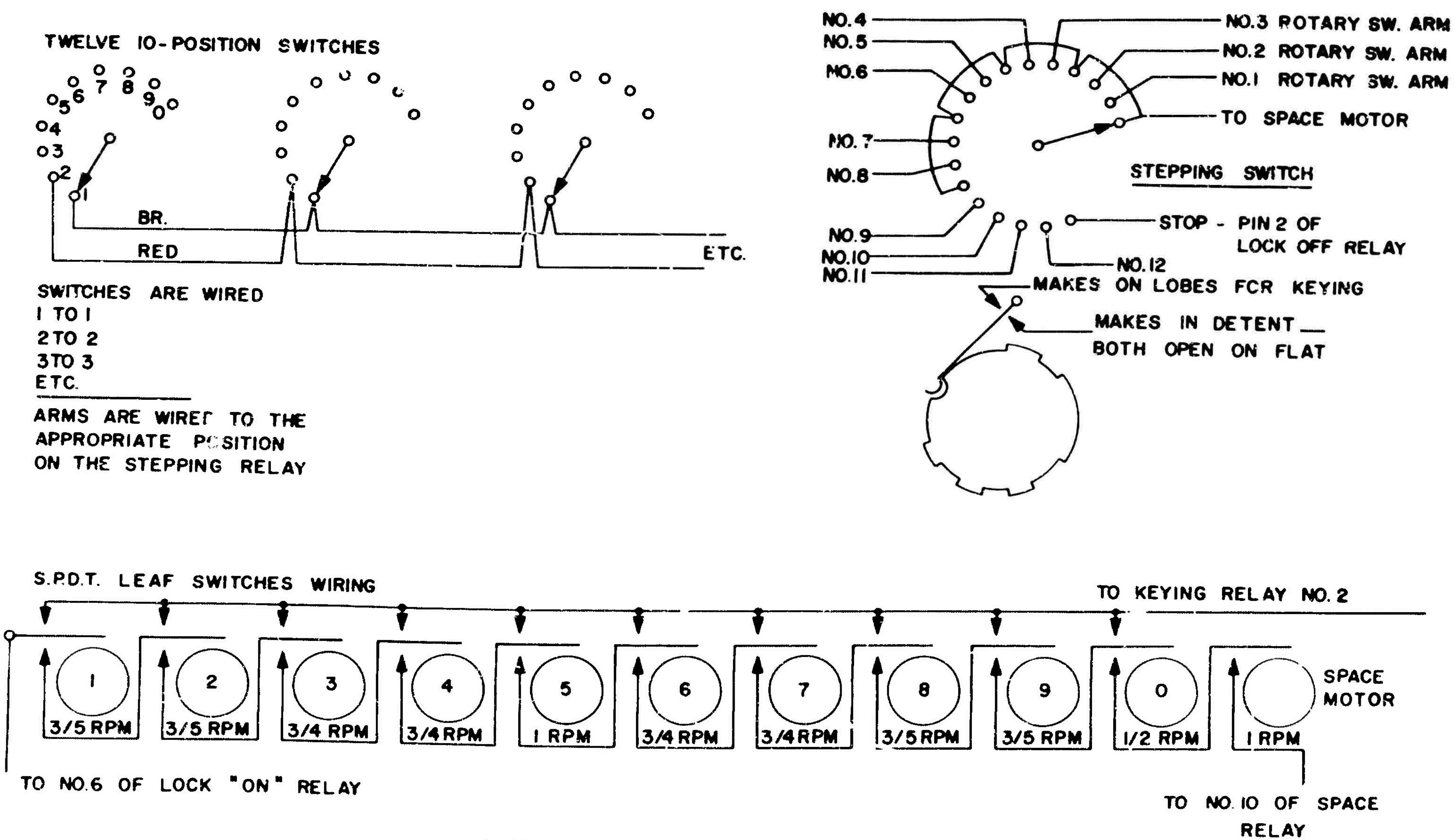


TIME MARK CIRCUIT

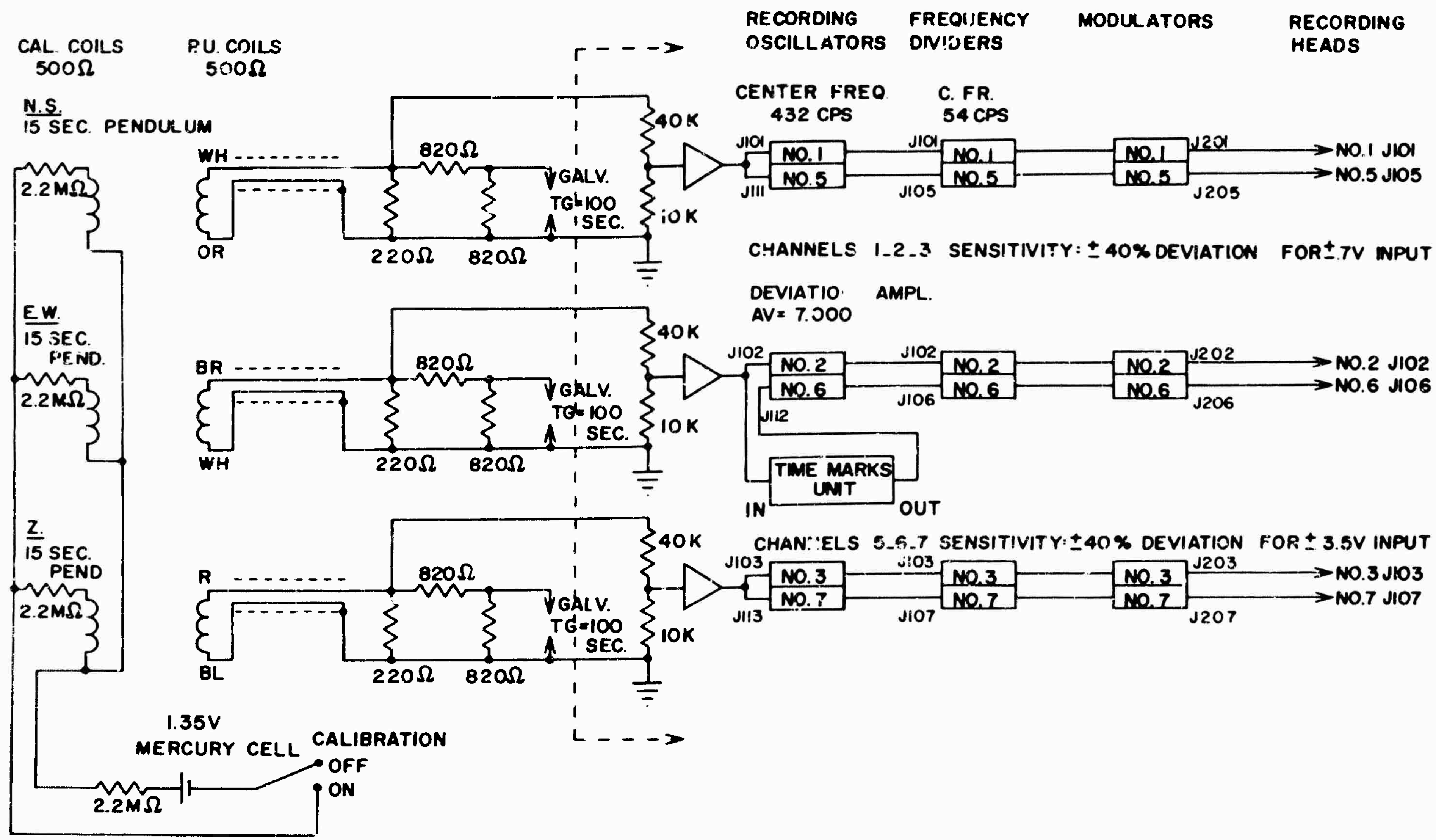


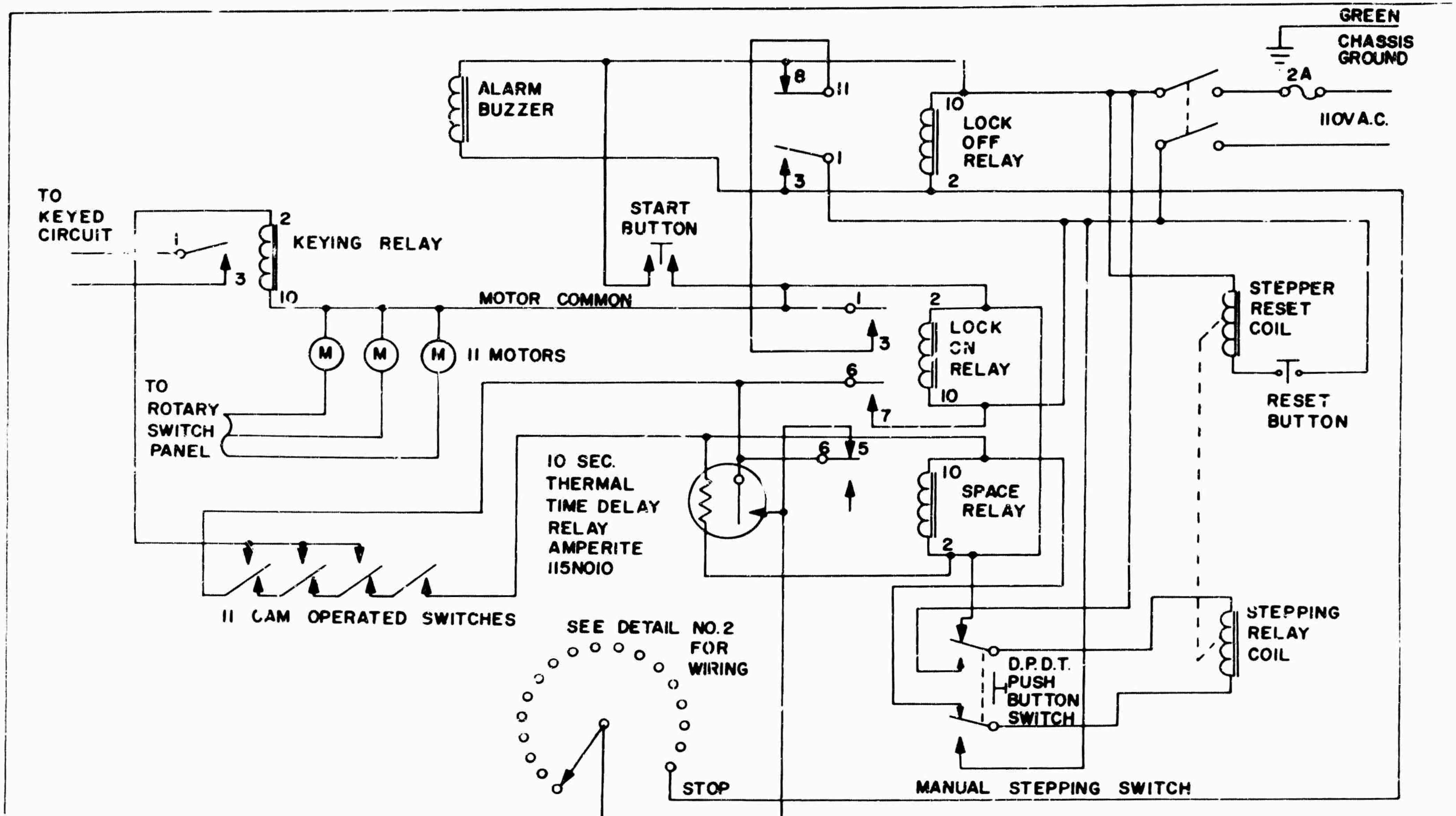




LOW SPEED ENCODER

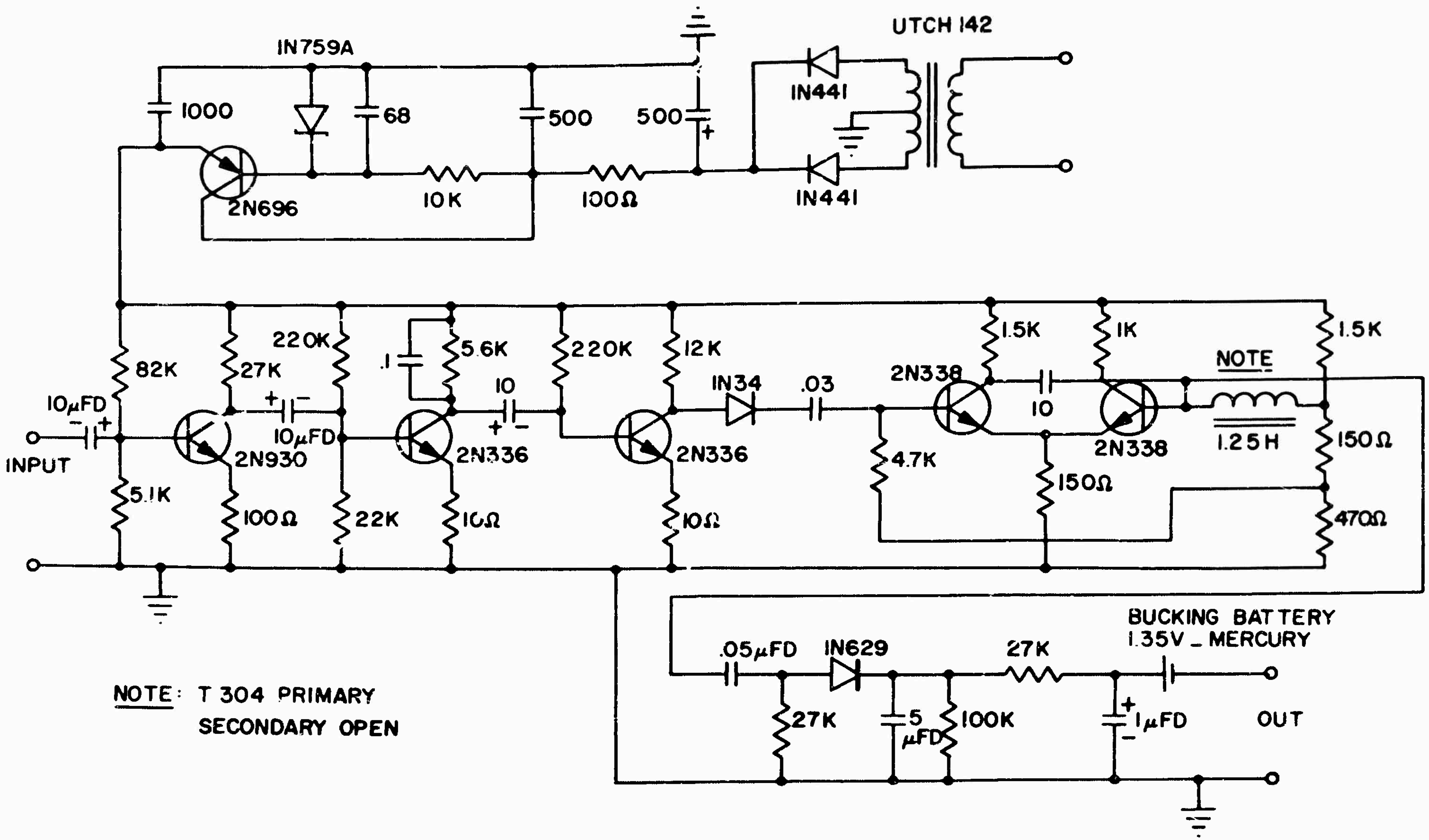
TAPE RECORDER SYSTEM





LOW SPEED ENCODER

REAL TIME PLAYBACK SYSTEM



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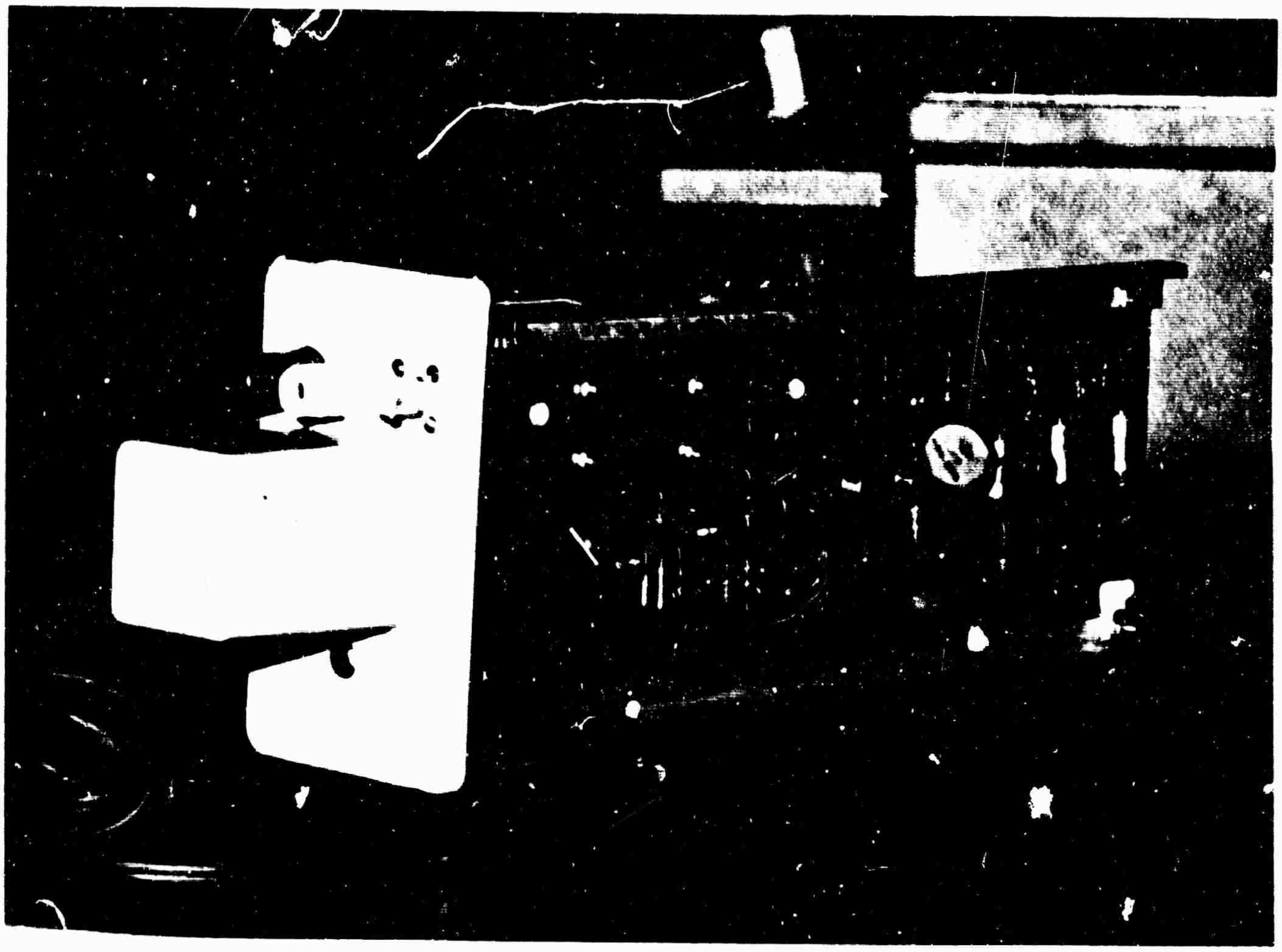

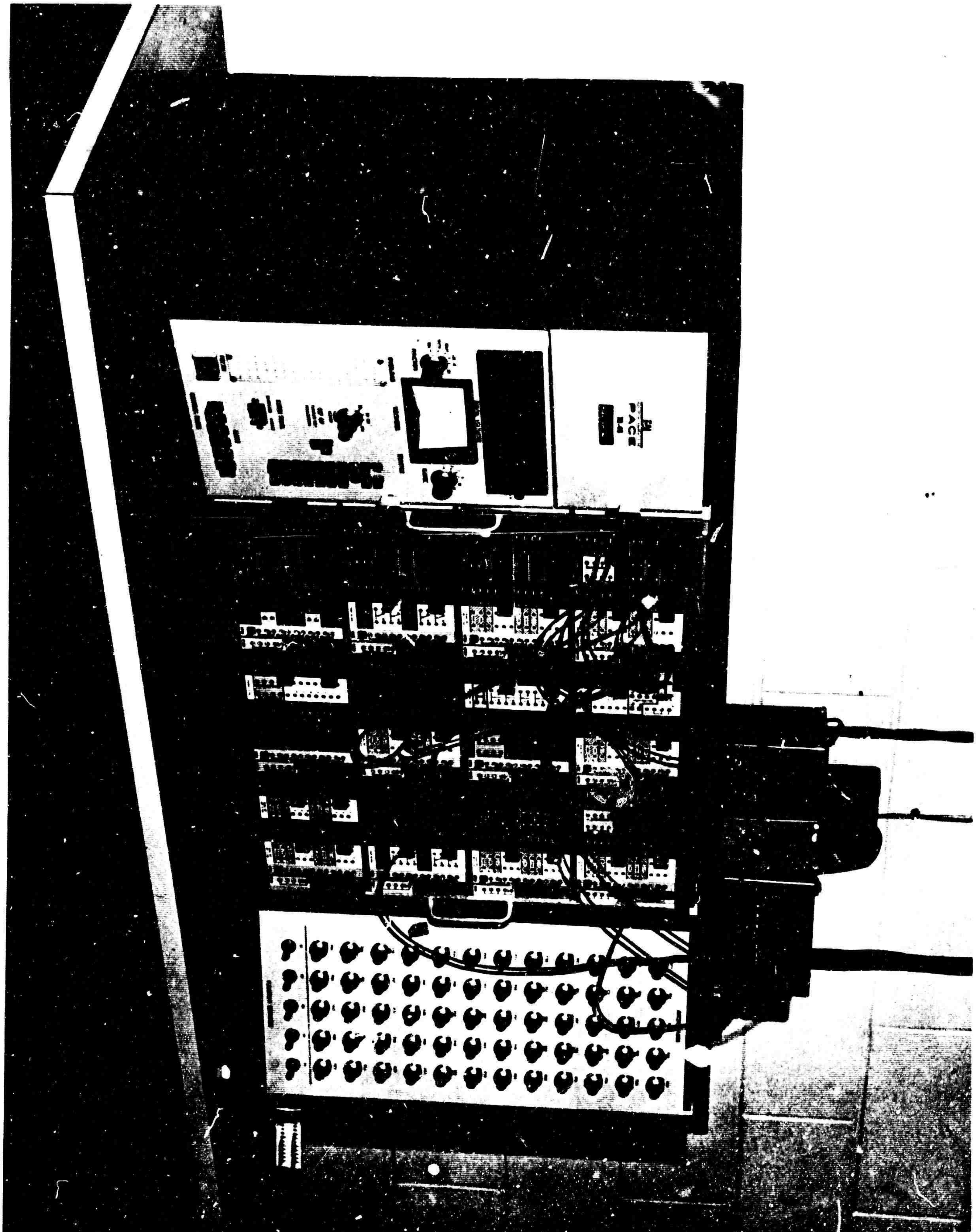

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13. ABSTRACT

A worldwide network of long period seismographs recording on magnetic tape has been established, including stations in Japan, Hawaii, Sweden, Peru, Alaska, Australia and Palisades. At these stations the amplified outputs of 3-component 15-second transducers are recorded on tape recorders operating at .06 inches per second. These units provide 16 2/3 days of recording time with a bandwidth of DC to 10 cps and a signal-to-noise ratio of 60 db. This worldwide network continues in operation at the present time.

Analysis techniques developed and/or utilized for data analysis in this program include (a) high-, low- and band-pass filtering, (b) inverse filtering (c) Fourier analysis, (d) rotation of instrumental axes, (e) cumulative energy, (f) longitudinal-vertical product for particle motion, (g) angles of emergence and azimuth, and (h) direction of microseism approach and beam width. Several studies of particular interest to the VELA-UNIFORM program are discussed, including (a) contouring of total energy and ratio of high-frequency to low-frequency energy for the Hardhat and Gnome underground nuclear events and (b) the determination of experimental radiation patterns for Love and Rayleigh waves (both amplitude and phase) for several underground explosions.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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slow-speed magnetic tape recording						
analog data analyses						
cumulative energy distribution						
Fourier analysis (amplitude and phase) studies						
longitudinal-vertical product						
particle motion studies						

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