

EQUIPMENT FOR DEEP ELECTROMAGNETIC SOUNDINGS

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Equipment for Deep Electromagnetic Soundings

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FORWARD

These reports* of our methods for the acquisition and analysis of electromagnetic sounding data are from B.K. Sternberg's Ph.D. thesis. In total, the system consists of an analogue transmitting and receiving system, a computer-controlled digital recording system and its programs, and numerical methods for analyzing the data. Most of the individual parts are fairly standard. Even so, the system represents a lot of effort in gathering pieces from many sources and adapting them to work together. Since the programs are specific to our system, we give the theoretical equations and their conversion to forms for numerical evaluations. Listings of computer programs follow and are in either BASIC or FORTRAN.

The equipment and programs are research gear and are not elegant. Our technology ranges from about 1970 to 1976 and our cost is describable as low budget. I believe that the material can be useful in two ways to people who wish to do geoelectric measurements. First, if you like the experiments, you can use our system for the basis of an advanced system. Second, chunks such as a program or circuit here and there may be useful and save a bit of work.

C.S. Clay
Weeks Hall
February 1978

- * Sternberg, B.K., Electrical resistivity structure of the crust in the southern extension of the Canadian Shield -- layered earth models.
- * Sternberg, B.K., Interpretation of electromagnetic data -- numerical methods and computer program listings.
- * Sternberg, B.K., and L.R. Stanfield, Equipment for deep electromagnetic soundings.

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* Page numbers start at 143 as this is Appendix A of:

Sternberg, B.K., 1977, Electrical Resistivity Structure of the Crust
in the Southern Extension of the Canadian Shield, Ph.D. Thesis,
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A1. GENERAL EXPERIMENTAL LAYOUT

Figure A1.1 shows the general layout of the long-range deep-sounding experiment. The Navy's Wisconsin Test Facility (Sanguine) antennas near Clam Lake were used as transmitter dipoles. Direct current pulses with periods ranging from 2 s to 100 s and amplitude of 70 or 140 A were transmitted on the 22 to 24 km long dipoles. The dipole moment of this antenna is about 1.6×10^6 A-m.

A signal is received at the recording site which consists of an electromagnetic wave that has propagated through the air at a velocity of about 3×10^8 m/s plus a number of waves which have travelled through the earth at velocities ranging from 10^4 m/s to 10^7 m/s and have been reflected from various earth layers. Typically, we received 2 components of the electric field (E_{NS} and E_{EW}) with a grounded electric dipole plus the derivative of the magnetic field (H_z) with an induction coil.

The reflections from layers within the earth arrive at overlapping times and form a complicated transient. Some examples of transient waveforms are shown in Figure A1.2. In practice, there is a substantial amount of noise present which we attempt to minimize by signal averaging and digital filtering (see Appendix B). The shape and amplitude of the transient is dependant on the measurement configuration and on the earth structure. The signal will also be distorted by the various filters in the equipment and this must be deconvolved from the signal.

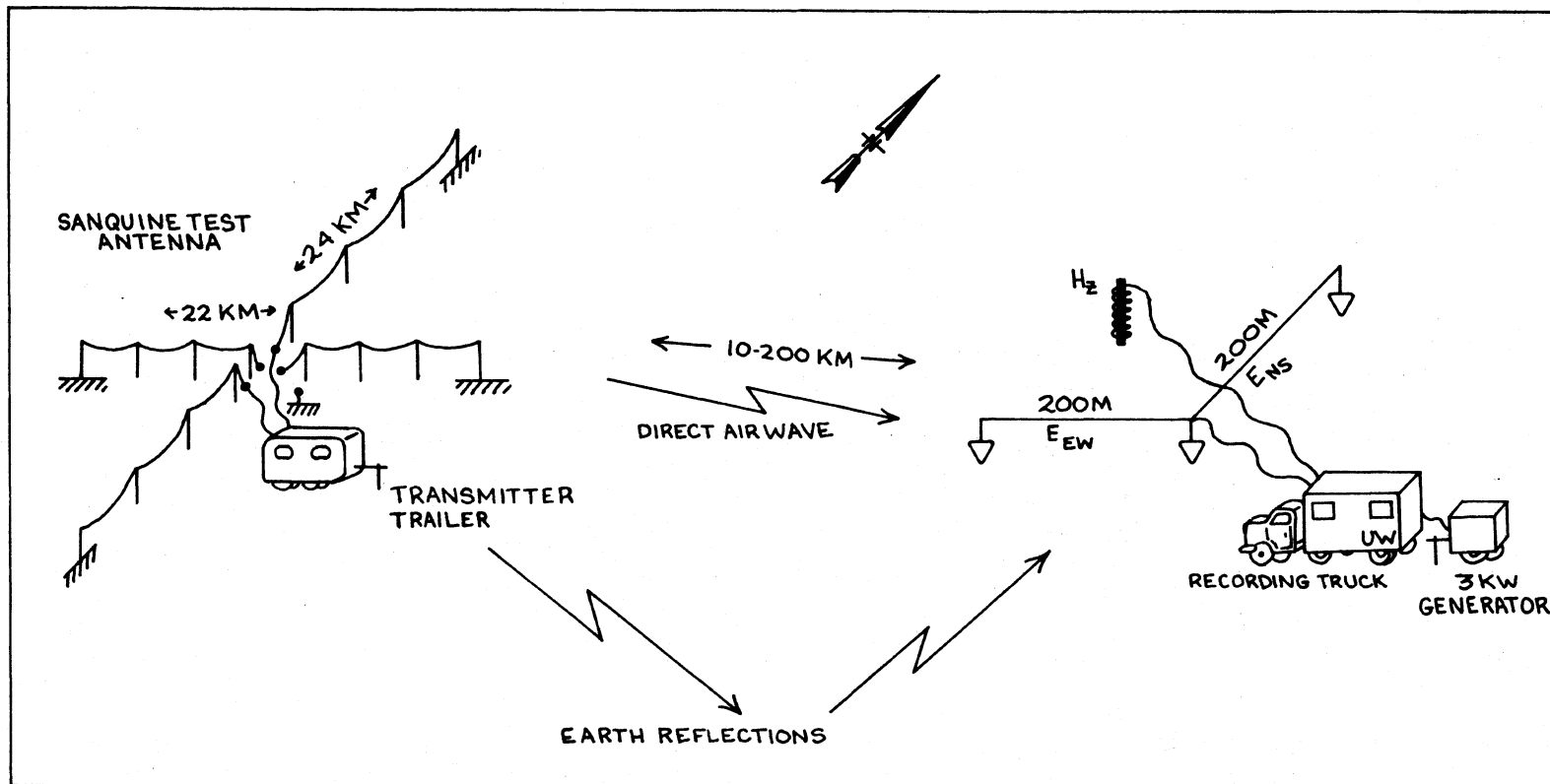
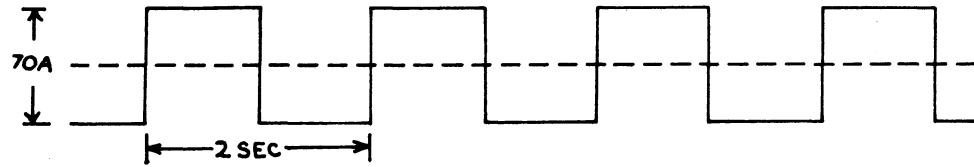
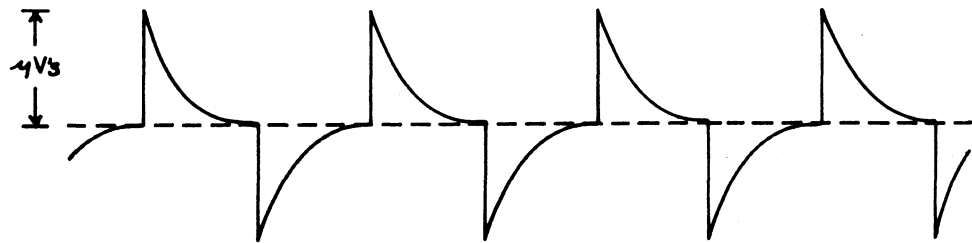


Fig. A1.1 General layout of deep sounding experiment.

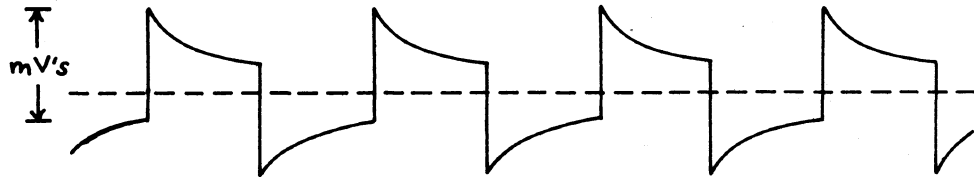
a) Transmitted wave:



b) Vertical magnetic field (Hz) - NS antenna:



c) Electric field - NS antenna, NS receiver dipole (E_{NS}) -
Equatorial (broadside) dipoles:



d) Electric field - EW antenna, EW receiver dipole (E_{EW}) - Polar
(inline) dipoles:

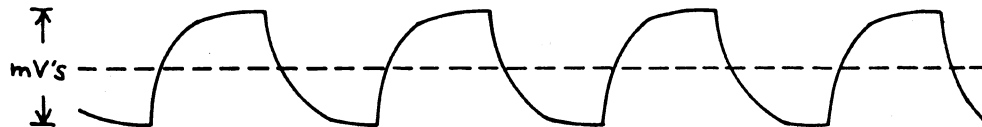


Fig. A1.2 Transmitted and received waveform examples.

The receiver site is assumed to be east of the antennas.

We calculate theoretical responses for various assumed earth models using the computer programs in Appendix B, and then compare these to the observed transients. The best match gives an estimate of the gross earth structure.

A simplified block diagram of the equipment used for deep EM soundings is shown in Figure A1.3. The alternating current is converted to direct current by a rectifier bridge. A precision clock controls a contactor which interrupts the current to form square wave pulses. The receiver consists of amplifiers and analog filters which condition the signal for further digital processing. A receiver clock which is precisely synchronized with the transmitter clock indicates to the computer when pulses are transmitted. The computer averages successive pulses in order to improve the signal-to-noise ratio. The averaged (stacked) signals are stored on magnetic tape for later analysis.

For shallow earth soundings we use the same receiver but analyze the frequency band from roughly 100 Hz - 10 KHz. The transmitter dipole is a grounded cable about one km long and the separation between transmitter and receiver is typically 100 m to 10 km.

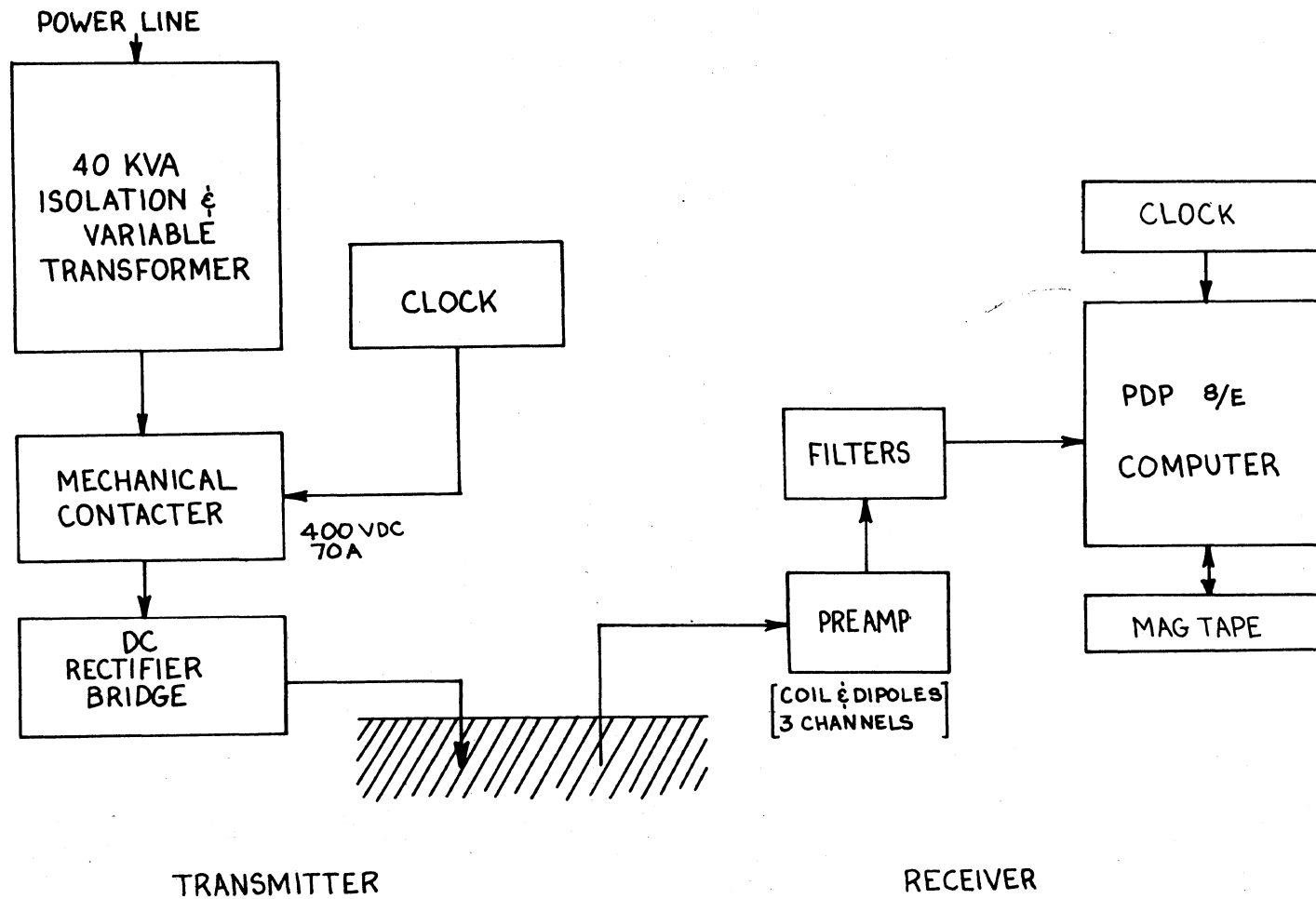


Fig. A1.3 Simplified block diagram of the equipment used for EM deep soundings.

In the next sections we discuss the details of the transmitting and receiving equipment which were constructed for this experiment. We also give some of our experience in the techniques of measuring microvolt earth signals in the presence of a large background noise.

A2. TRANSMITTERS

A2.1 SANGUINE ANTENNA

The Navy's Sanguine test antennas in northern Wisconsin were used as the current dipoles for the long-range transmissions. A description of the antennas and test facility is given in Naval Electronic Systems Command (1971). The location of the center of the antennas is about 8 km south of Clam Lake, Wisconsin, and is at $46^{\circ}5'$ N latitude, $90^{\circ}55'$ W longitude. Two 22 to 24 km long antennas run roughly north-south and east-west. The station ground at the intersection of the two antennas can be used to split the array into four separate dipoles. The construction of the antennas is similar to a standard power line. The ground terminals are 2 to 3 km long.

The DC resistance of the N-S antenna was 3.1 ohm, that of the E-W antenna was 5.0 ohm, and that from station ground to each of the far electrodes was about 7 ohms. These resistances were found to be independent of period (2 to 100 s) and current (15 to 70 A).

A2.2 40 KVA TRANSMITTER

For deep earth sounding in the time domain, we use DC pulses which last from 2 to 100 s. We supplied our own source because the Navy's 1.2 megawatt Sanguine transmitters were designed to operate in a narrow frequency band (45 ± 5 and 75 ± 5 Hz) and were unsuitable for our DC pulse studies. We used instead a mechanical contactor to commutate a DC current. The transmitter was constructed using available components from Federal Surplus Property.

Two transmitters were used. A single polarity transmitter (70 A peak-peak) which had a precisely reproducible turn-off pulse was used for the deep vertical-sounding experiments in the Clam Lake region in 1973 and 1974. An alternating-polarity transmitter (140 A peak-peak) was used for the long-range transmissions across the Flambeau anomaly in 1975.

A block diagram of the transmitter which was used during the 1973 and 1974 field seasons is shown in Figure A2.2.1. The clock and current monitor are described later. A 90 A, 600 VAC relay switched the current on and off. The relay driver consisted of a single transistor and a small relay. The capacitor was placed across the output to partially absorb high-level, short-duration spikes. Spikes of up to 1000 volts, lasting a few microseconds to a few milliseconds and due to spherics were fairly common on the line. The ripple voltage was essentially unfiltered.

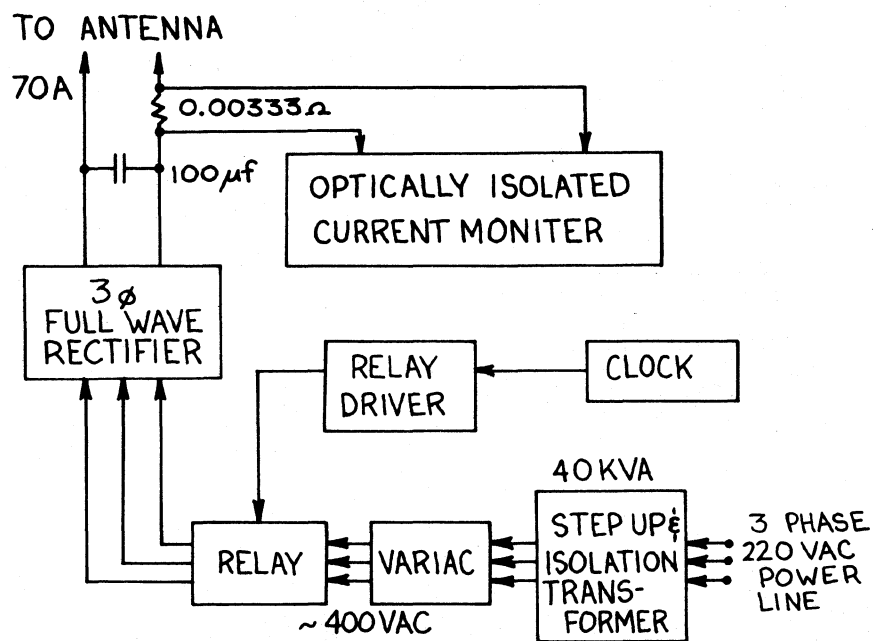


Fig. A2.2.1 40 KVA Transmitting System -- single polarity.

The transmitted current pulse is not an ideal square wave. The antenna has about 50 mh distributed inductance associated with it so it acts like a low-pass filter. The effect of this filter must be deconvolved from the data along with the receiver filter response. The current waveform was digitized and Fourier transformed. The magnitude and phase of the antenna response are shown in Figure A2.2.2.

The current was not regulated. We monitored the current waveform continuously on a strip chart recorder and found that the current was constant to within about 1 to 10 percent.

An advantage of the single-polarity transmitter is that the turn-off pulse provides a very reproducible waveform. A constant pulse amplitude is necessary to make precise measurements of the late-time transient. At all of the sites which were used to determine the layered earth structure in the Clam Lake region, we analyzed the turn-off pulse.

During the 1975 field season we made measurements at very long ranges and we needed maximum signal strength. We were looking for large effects in the transient field and a 1 to 10 percent variability in the pulse shape was acceptable. By alternating the polarity of the transmitted waveform, the dipole moment was increased by a factor of two.

A block diagram of the alternating-polarity transmitter is the same as the single-polarity transmitter (Figure A2.2.1) except for

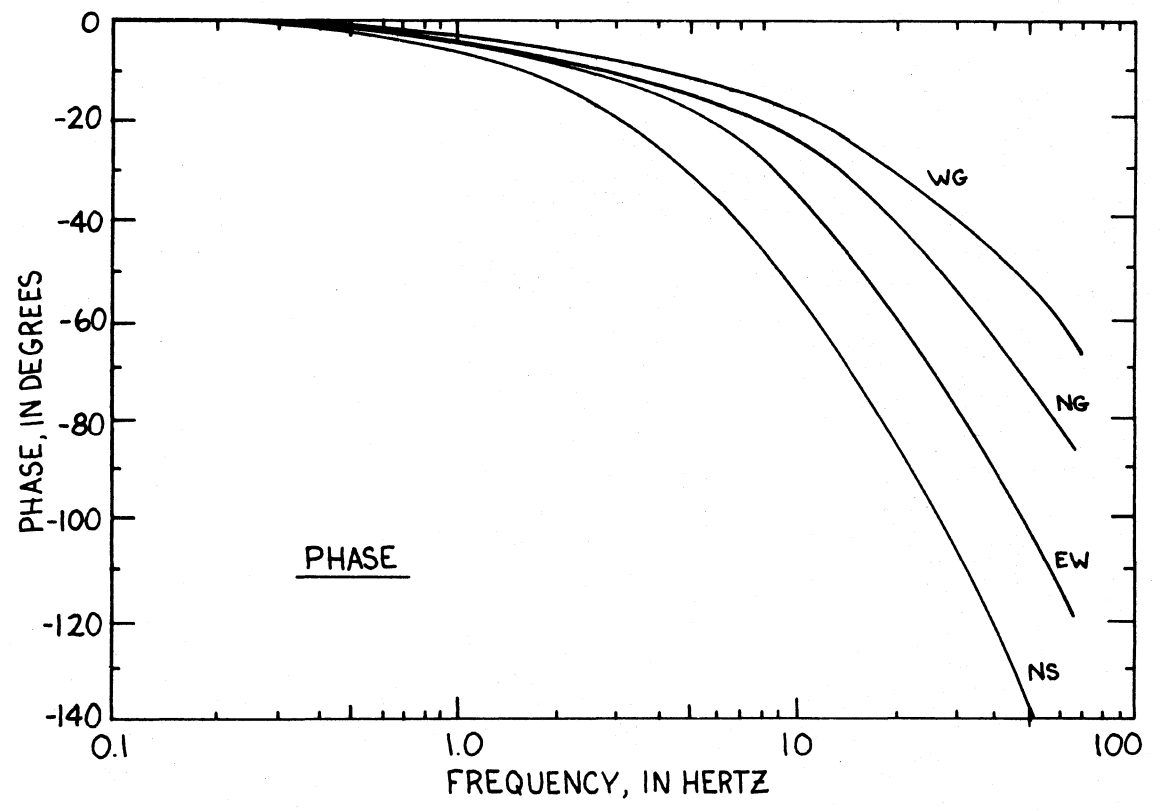
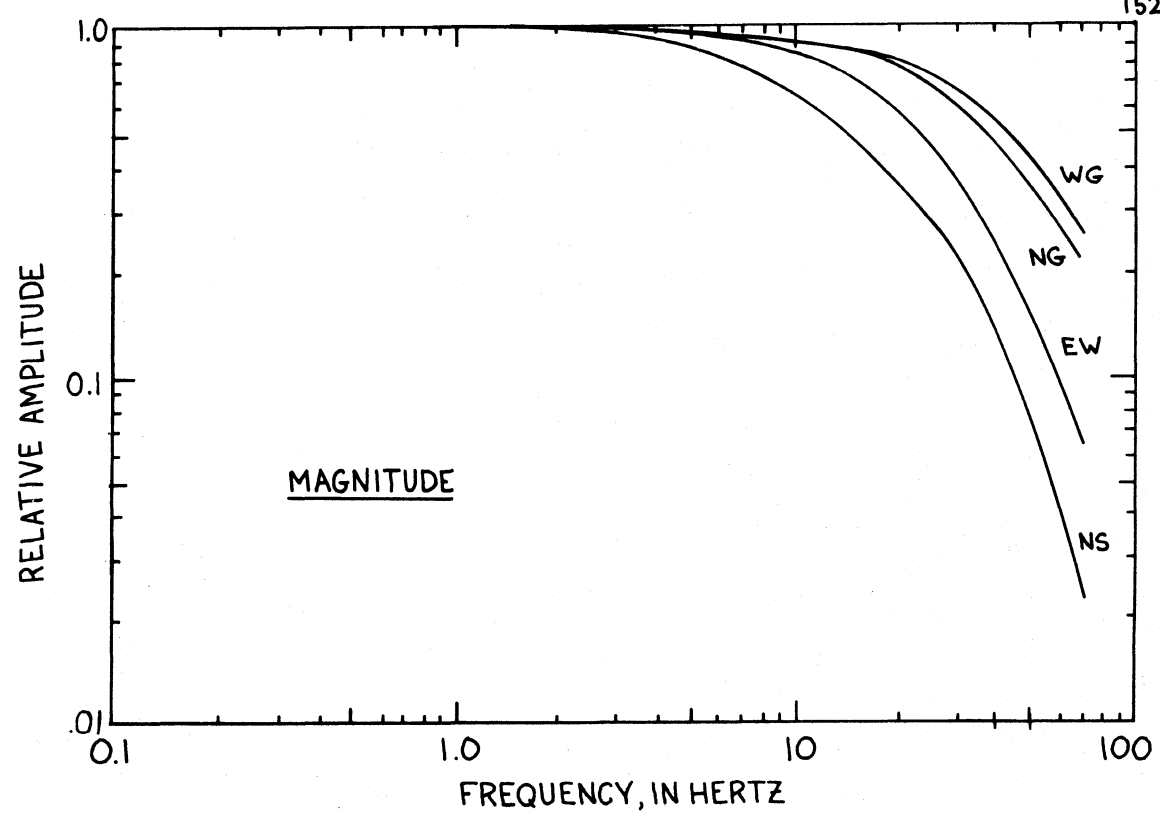


Fig. A2.2.2 Antenna response. NS - North South Antenna; EW - East West Antenna; NG - North to Station Ground Antenna; WG - West to Station Ground Antenna.

the details of the contactor and the rectifier bridge. In Figure A2.2.3 is a circuit diagram of the modifications. An AC contactor alternately connects a rectifier bridge with one polarity and then connects the opposite polarity rectifier.

This scheme avoids the necessity of switching the polarity of the DC current. If we try to switch the DC current, an arc forms which is difficult to extinguish, so we would have to use very large, special-purpose contactors. It is much easier to switch AC since the arc is automatically extinguished every 1/60 sec.

Two 150 A, 600 VAC contactors were mechanically linked together so that one rectifier was always off before the other was turned on. The contacts on the relay were rewired so the bridge rectifier would be made an open circuit when power was turned off to the rectifier.

When we first tried the alternating-polarity contactor, we found that when the polarity changed, a large voltage spike exceeded the ratings of the diodes and burned them out. It was necessary to tune the antenna by placing a capacitor across the antenna to absorb the energy stored in the antenna inductance. The value of capacitance required is found by equating the energy stored in the capacitor and in the inductor (see e.g., Word, D. and F. Patrick, 1964).

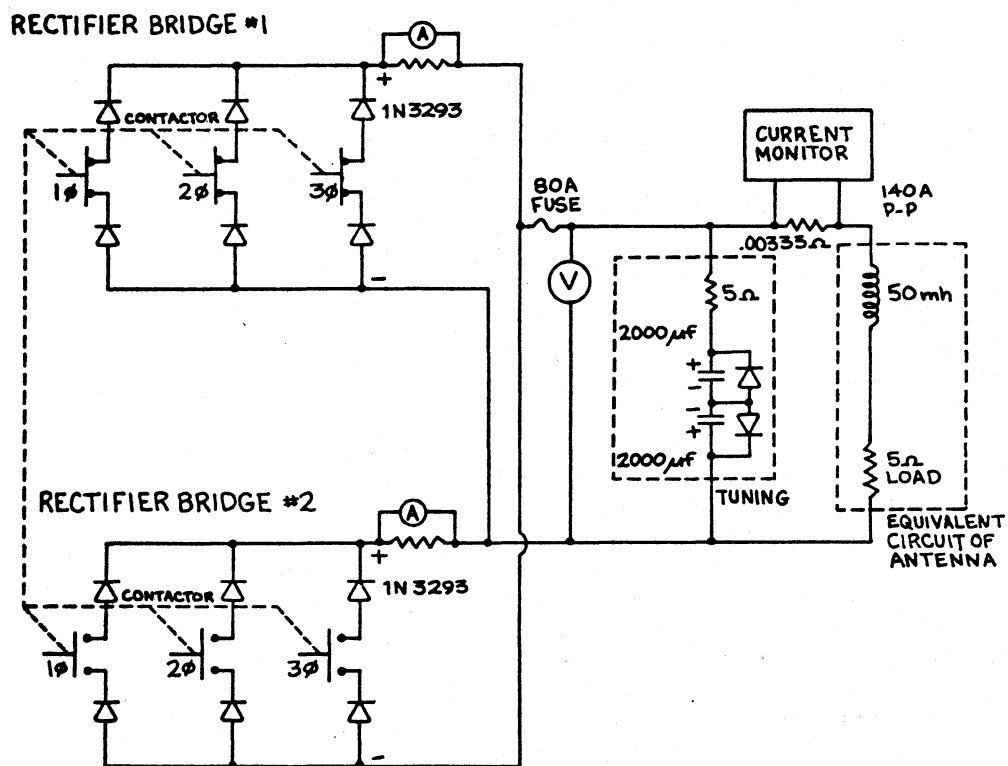


Fig. A2.2.3 Alternating polarity bridge rectifiers and contactors.

$$1/2 CV^2 = 1/2 I^2L$$

or $RC = L/R$

We used an R in series with the capacitor which is equal to the antenna resistance (5 ohms). The antenna inductance is about 50 mh (from Naval Electronic Systems Command, 1971). The required capacitance is about 2000 μ F. This large capacitance was formed by placing electrolytic capacitors back to back to form a nonpolarized capacitor (see circuit diagram in Figure A2.2.3).

The alternating-polarity transmitter has the same filter function as shown in Figure A2.2.2.

The voltages and currents in the system are large enough to be hazardous. All parts of the equipment which the operator could contact were isolated from the transmission circuit and grounded. The isolation system for monitoring the current is described in section A2.5.

A2.3 TELEPHONE INTERFERENCE TESTS

Measurements were made to determine if our DC pulse transmissions would interfere in any way with telephone service in the Clam Lake area. Two possible sources of interference were considered: radiation from the antenna and radiation from the harmonics fed back through the power line.

The measurements were conducted by personnel from General Telephone and ITT Research Institute. A narrow-band wave analyzer was used to measure the noise at harmonics of our transmitted square wave, while a broad-band noise measurement set gave a measurement of the average noise within the normal telephone bandwidth. Measurements were made at several sites which would most likely show signs of interference. No interference was detected with a two-second square wave at 70 A.

A2.4 MOBIL TRANSMITTER

A small (10 A) transmitter was constructed for short-range (1 m to 20 km) measurements. A power transistor was used to interrupt the DC current and to form square-wave pulses. Except for the electronic control circuitry, the mobil transmitter system was assembled from available Federal Surplus Property parts. A block diagram of the transmitter is shown in Figure A2.4.1. Circuit diagrams are in Figures A2.4.2 to A2.4.5.

A 10 KW generator mounted on a 1 1/2 ton cargo trailer supplied the power. The DC power supply consisted of two 200 VDC, 15 A power supplies wired in series to give about 400 VDC output. The power supply was originally voltage and current regulated. The regulation circuitry was not reliable and not very efficient, so it was

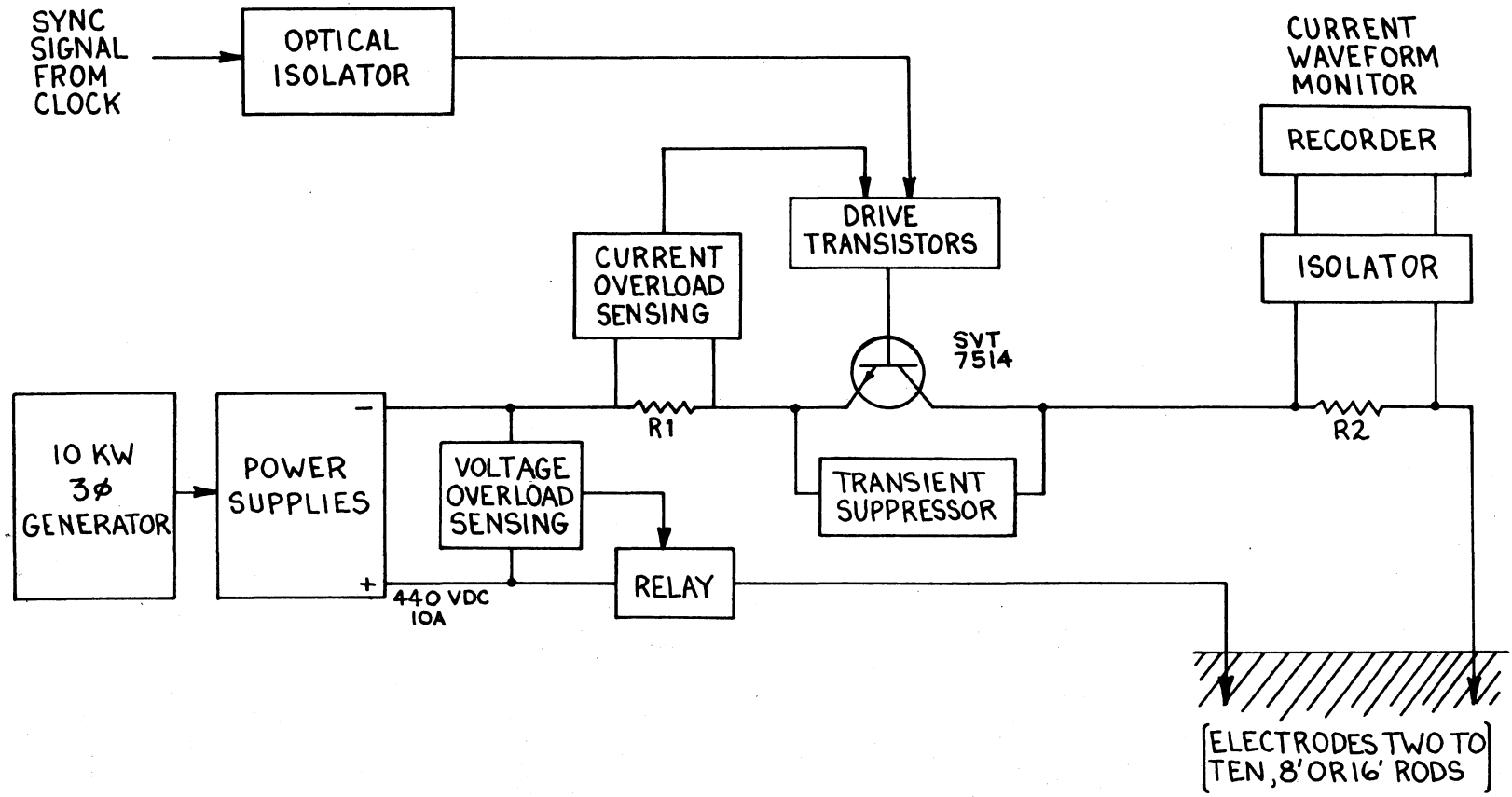


Fig. A2.4.1 Block diagram of mobil transmitter.

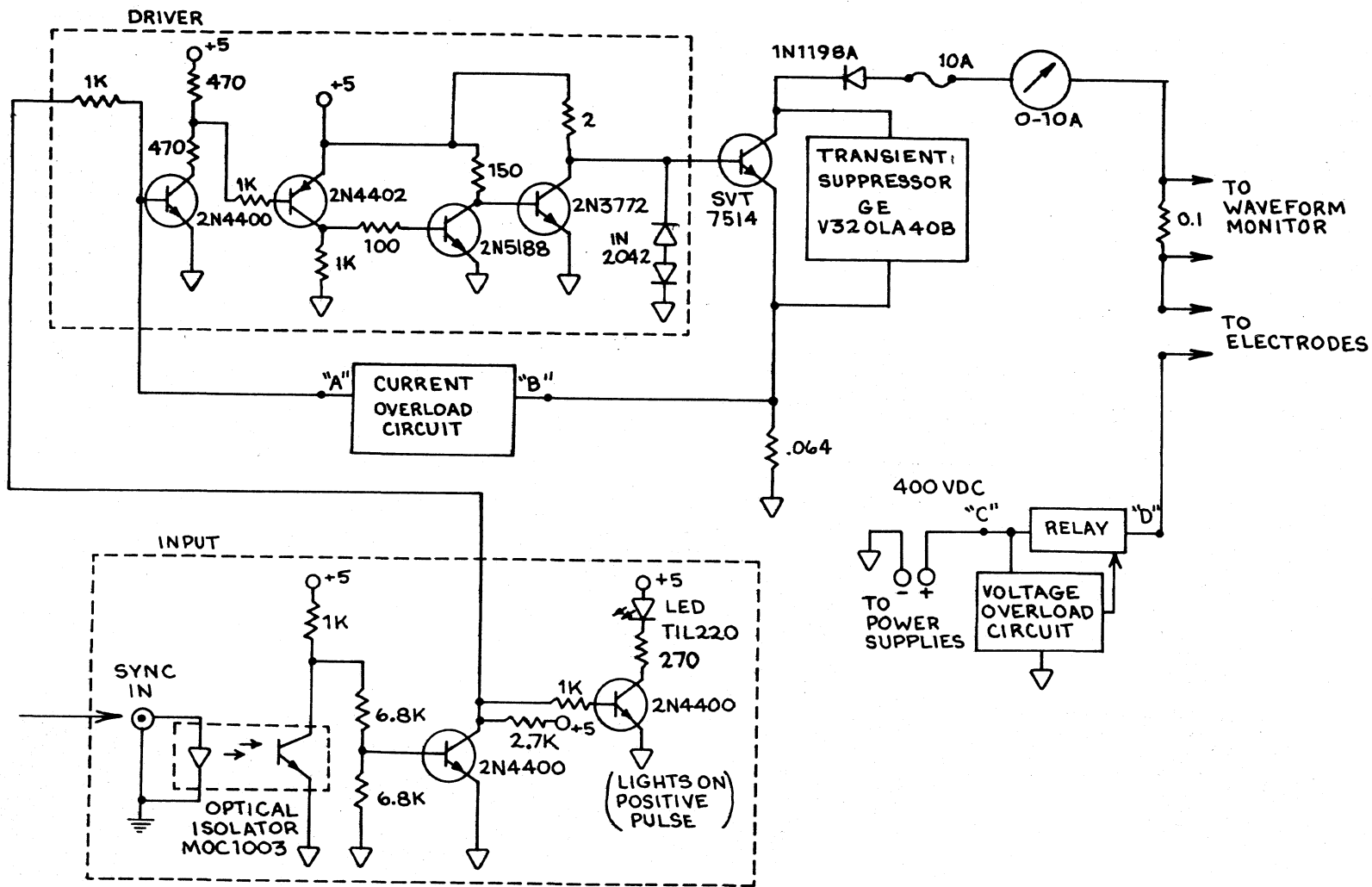


Fig. A2.4.2 Mobil transmitter 1) Common (∇) is isolated from chassis.
 2) Ground (\perp) is equipment and earth ground.

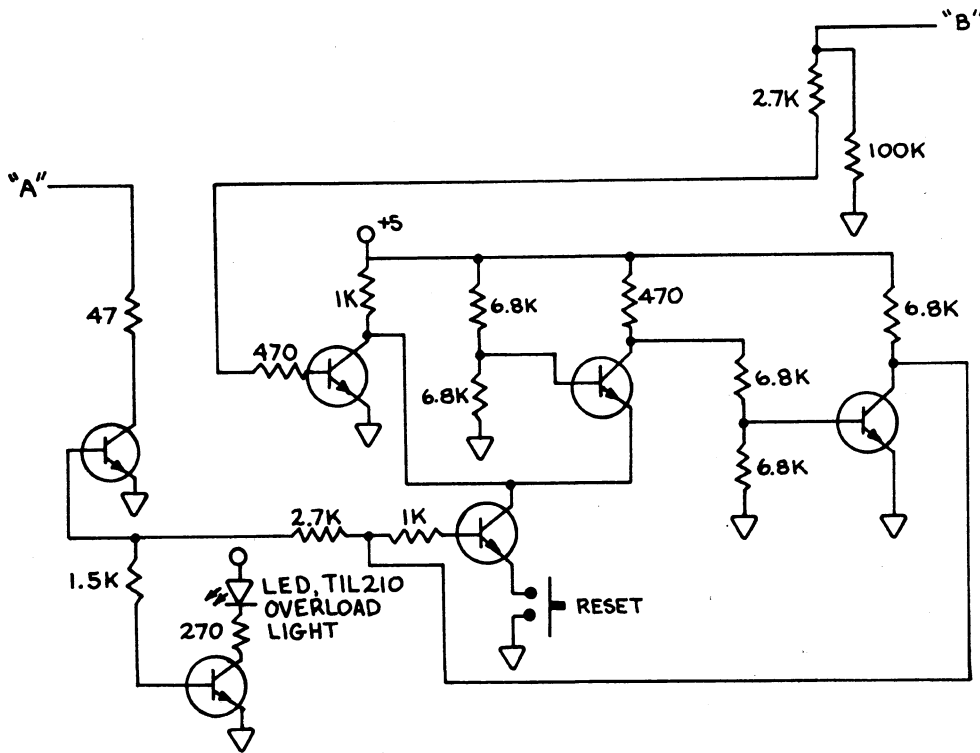


Fig. A2.4.3 Current overload circuit.

- 1) All transistors are 2N4400.
- 2) Circuit trips at 12.4 A.

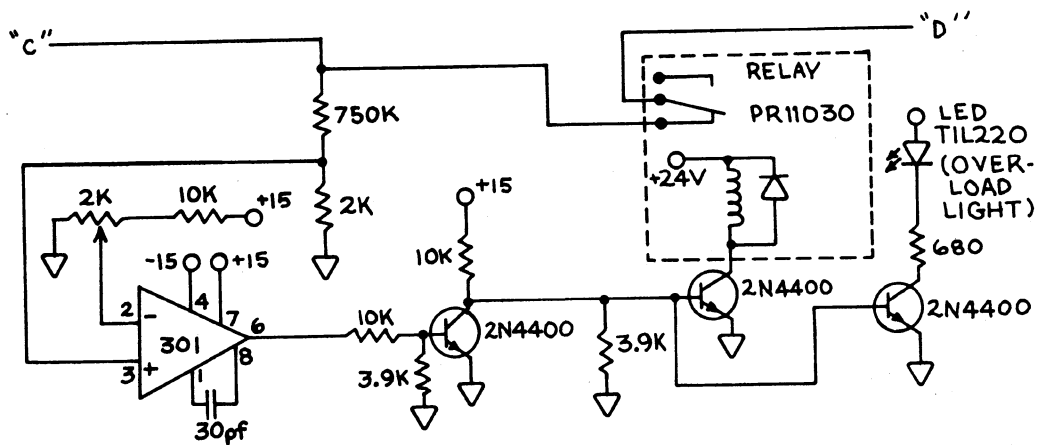


Fig. A2.4.4 Voltage overload circuit.

- 1) Circuit trips at 425 V.

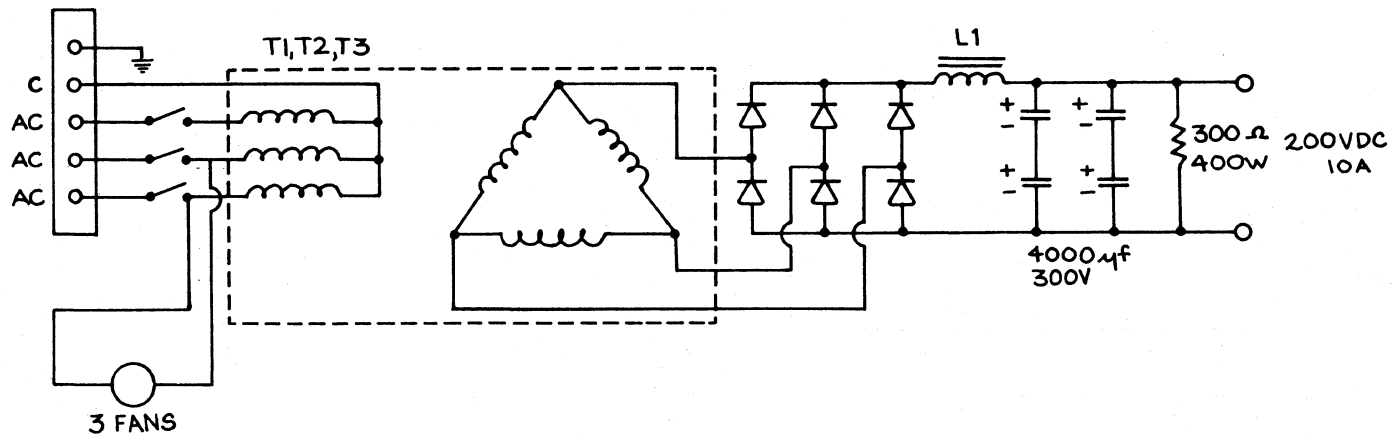


Fig. A2.4.5 Power supplies.

- 1) Power supplies are Mid Eastern Industries MS-128-15A with voltage and current regulation removed.
- 2) Two units used in series for 400 VDC.
- 3) Diodes are RCA 40212.
- 4) No specs for T1, T2, T3, L1.

removed. Since we analyze only the turn-off pulse, regulation does not improve the quality of the data very much.

The power transistor is turned on and off by a clock which is in precise synchronization with the receiver clock. The sync signal is isolated from the transmitter circuitry by an optical isolator. The sync pulse is amplified by a series of transistors and drives the base of the switching transistor (SVT 7514).

If the safe current limit for the power transistor is exceeded, the voltage across R1 rises and at 12.4 A the high-speed sensing network turns off the base of the transistor. The transistor is also sensitive to voltage overloads. The maximum collector-to-emitter sustaining voltage rating for these units was about 500 V. If the voltage rises above 425 V, the voltage sensing circuit turns off the relay.

There is always some inductance in the dipole antenna, and this causes a voltage spike when we turn on or turn off the transistor. A transient suppressor was used to protect the transistor from this high amplitude spike. The transient suppressor (which is basically a very fast zener diode) conducts at 450 volts ($\pm 5\%$).

During the 1973 to 1975 field seasons we did not have zener diodes which were fast enough to protect the transistor. We instead absorbed the energy from the antenna inductance by tuning the antenna with a 14 μF capacitor in series with a resistor of value

equal to the electrode resistance. This was placed across the output leads.

A current monitor senses the voltage across resistor R2. This circuit is described in section A2.5.

The strength of the received signal is proportional to the transmitter dipole moment (dipole current times dipole length). The contact resistance at the electrodes plus the resistance of the cable must be reduced to 40 ohms in order to get the full 10 A current with a voltage of 400 VDC. In northern Wisconsin, the only place we can easily get a sufficiently low contact resistance is in a swamp. Eight foot grounding rods were used for the electrodes. The rods could be connected together for extra depth if the water table is deep. Several adjacent rods may be connected together to reduce the effective contact resistance. If the rods are spaced apart more than about $3/2$ times their lengths, the effective resistance will be the parallel combination of each rod's contact resistance. Where they are available and where they can be safely used, metal culverts and pipes which have been buried a long time make ideal electrodes. If the ground immediately surrounding an electrode is saturated with a brine solution, the contact resistance can be lowered significantly.

In northern Wisconsin, because of the dense forests and brush, the dipole line is usually restricted to roads. A dipole length of about a mile is a practical limit. The cable used was 4-conductor

field-telephone cable (spiral four). Each of the four conductors is #20 gauge giving a total resistance for the cable of about 6.4 ohms per km. Laying out and picking up the cable was facilitated with a motorized cable reel mounted on the generator cargo trailer. There was 1330 feet per reel and a total of about 5.3 km of cable was available.

All the equipment with which the operator comes in contact is fully isolated from the electrode circuit by insulators, isolation transformers and optical isolators. Failure to isolate any part of the system would lead to the equipment acting like a third electrode with a dangerously high step potential near it.

The generator, transmitter truck, and all the equipment are grounded using heavy duty wire connected to an electrode placed within a few tens of meters from the equipment. This ground electrode should have a contact resistance comparable to the dipole electrodes (i.e., less than a few tens of ohms).

A2.5 CURRENT WAVEFORM MONITOR-ISOLATOR

A variety of instruments may be used to monitor the transmitted current waveform: a strip-chart recorder, an oscilloscope, a meter, or the computer. Generally, these instruments have single-ended inputs. For those with differential input, the isolation may not be

adequate for voltages up to 500 V. If a recorder (with one side of the input grounded) was attached to the electrode circuit, the recorder box would become a third electrode. The large step potential existing around the instrument could be very dangerous. A modulator-optical isolator-demodulator was used to isolate the equipment from the electrode circuit.

Figure A2.5.1 shows a block diagram and Figure A2.5.2 is a circuit diagram of the current monitor-isolator. The center frequency of the modulator and demodulator was set at 43.3 KHz. The components after the optical isolator were powered by a ± 15 VDC regulated supply and all components before the optical isolator were powered by a separate, isolated power supply. The circuit was low-pass filtered to about 10 Hz to minimize noise. The frequency response of the isolator is shown in Figure A2.5.3.

In order to monitor the high-frequency transmissions a Triad HS-56 isolation transformer was used (bandwidth = 10 Hz - 30,000 Hz).

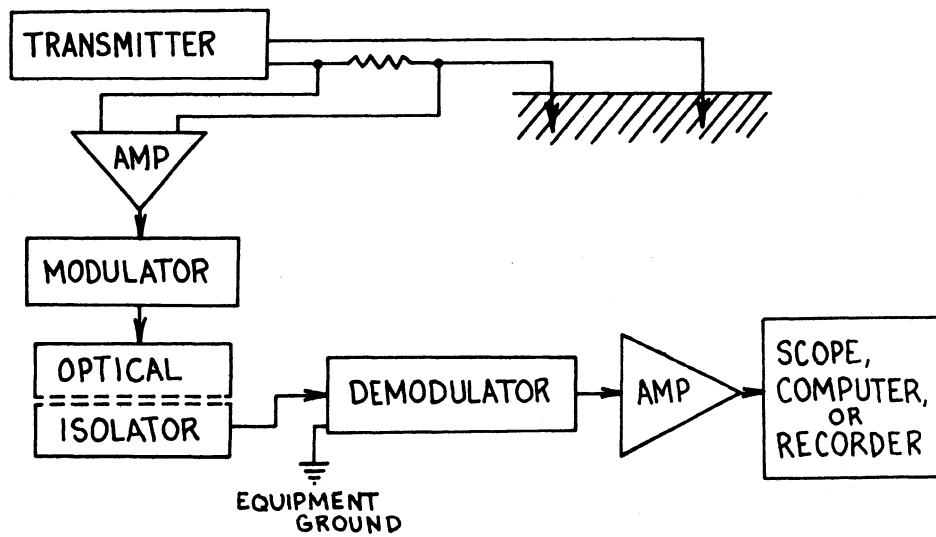


Fig. A2.5.1 Optically isolated current monitor.

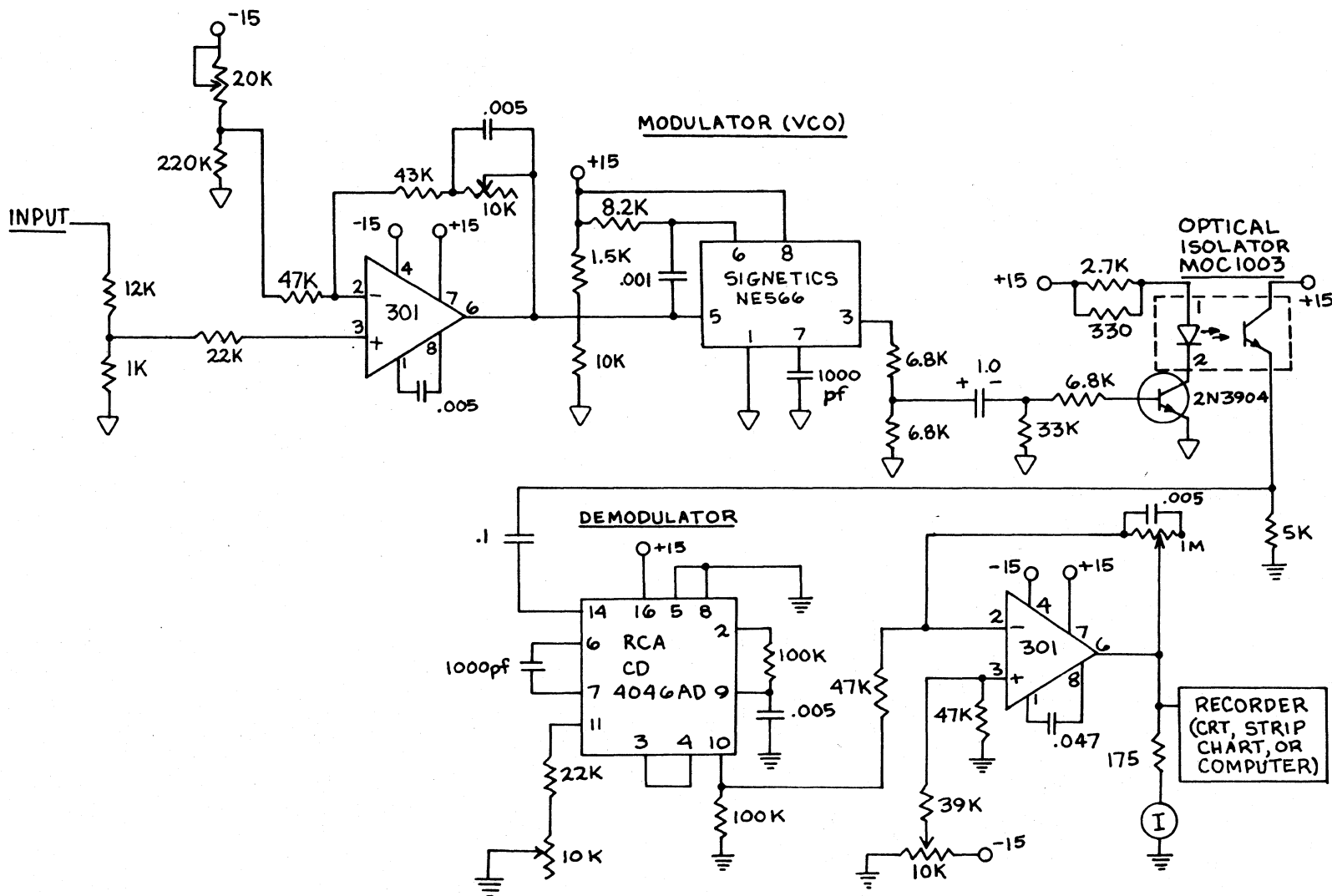


Fig. A2.5.2 Current monitor-isolator.

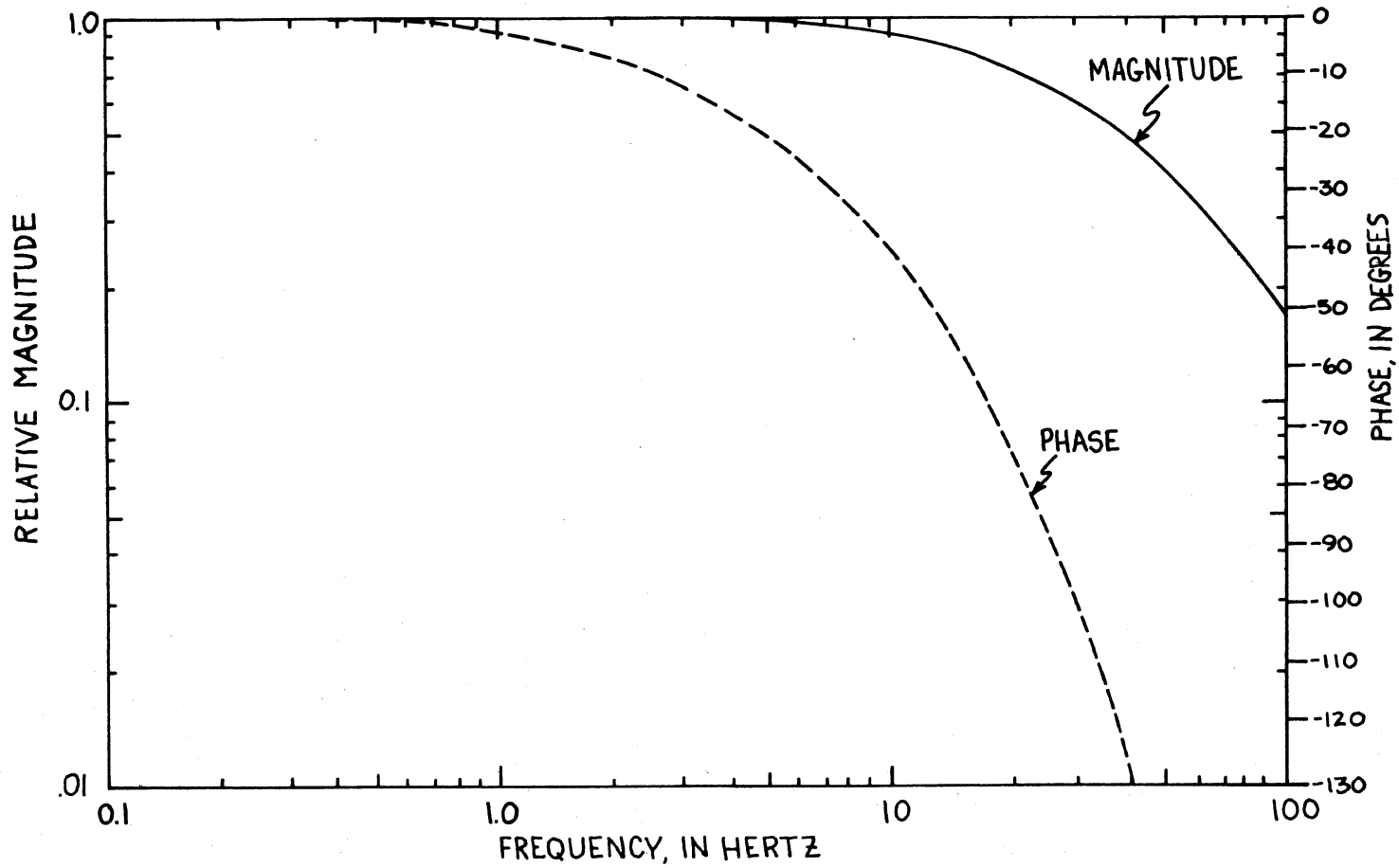


Fig. A2.5.3 Current monitor-isolator response.

A3. RECEIVERS

A3.1 COMPUTER RECEIVER

During the 1973 field season, the receiver consisted of amplifiers and filters which had been built in 1965 by Applied Research Austin (ARA) for the University of Wisconsin magnetotelluric (MT) project. A complete description of this equipment is given in Dowling (1968). Mechanical choppers and vacuum tubes were used in this system. The filter calibration curves which are applicable to all data taken during this season are shown in Figure A3.1.6.

We made a number of tests on this receiver system and found that the equipment generally had adequate specifications for this experiment. We found, however, that when we reversed the polarity of the electric channel input wires, the signal from a controlled source changed by up to a factor of two. We discovered that one terminal of the differential-input electric-channel amplifiers had been internally wired to the equipment (and truck) ground. This led to errors in the measurement of the electric field between the sensor electrodes. The ground was removed and this equipment was successfully used for the sites reported in this thesis.

For the 1974 and 1975 field seasons, a new receiver system was constructed using low-noise, solid state devices. A block diagram of this system is shown in Figure A3.1.1. We discuss the electric channels first.

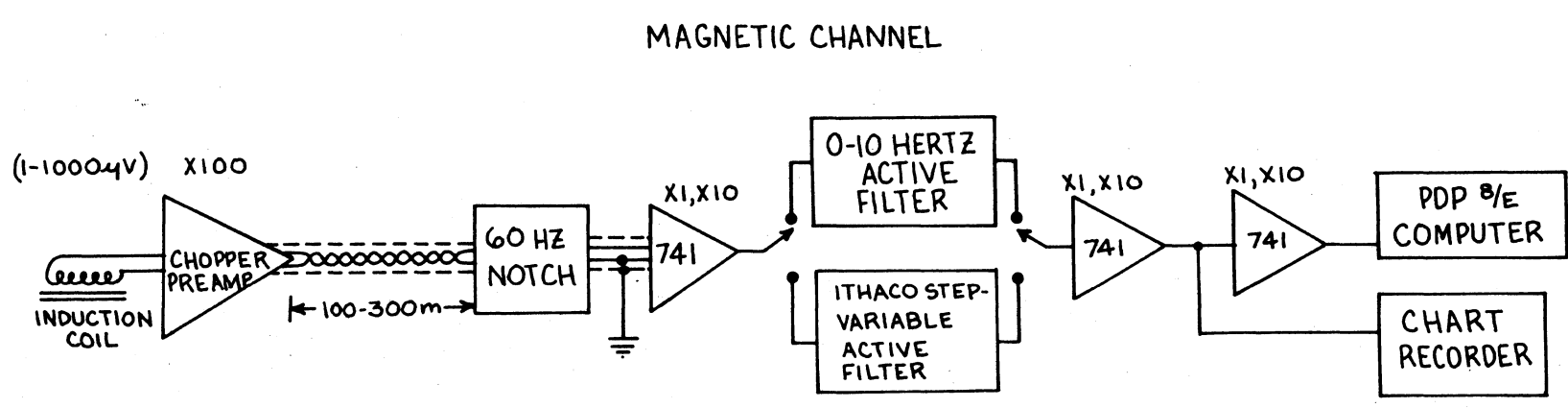
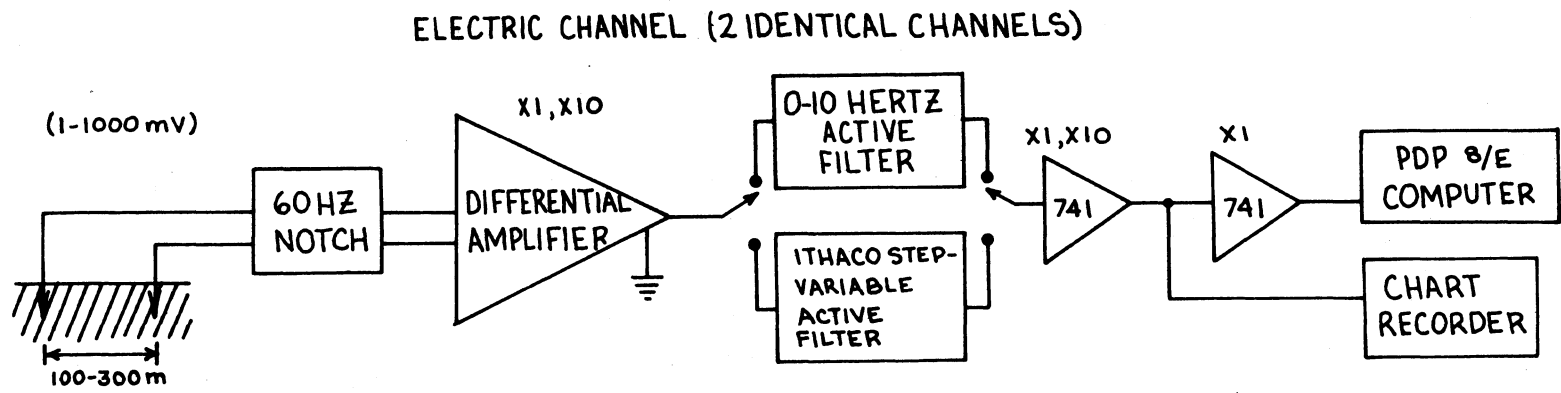


Fig. A3.1.1 Computer receiver, block diagram.

The electric channel sensors are two porous-pot electrodes separated by 100 to 300 m. The porous pots consist of a copper rod immersed in a saturated CuSO_4 solution which is allowed to make contact with the ground through a porous clay pot. The CuSO_4 solution acts as a buffer between the copper rod and the ground and minimizes the development of chemical potentials at the electrode which could be a major source of low-frequency noise (drift). Light, single-conductor wire was used to convey the potential difference between the electrodes to the truck amplifier. Small animals love to eat this wire, and we had to periodically check the resistance of the wire to see if it had been eaten through.

A 60 Hz twin-T notch filter was used to suppress power line noise. We found that it is important that a passive notch filter precede any active amplifier or filter stage. Power line interference can be up to a million times larger than the desired signal. This interference signal can react with the slight nonlinearities in the electronics and produce a noise signal over a wide frequency band and with an amplitude comparable to the desired signal. Passive band-reject filtering around 60 Hz also reduces any beat-frequency interference due to mixing in an active stage of the power line 60 Hz and the local generator frequency.

A twin-T with input and output resistance of 27000 ohms was chosen. This was sufficiently larger than the usual electrode resistance (less than a few thousand ohms) and yet sufficiently

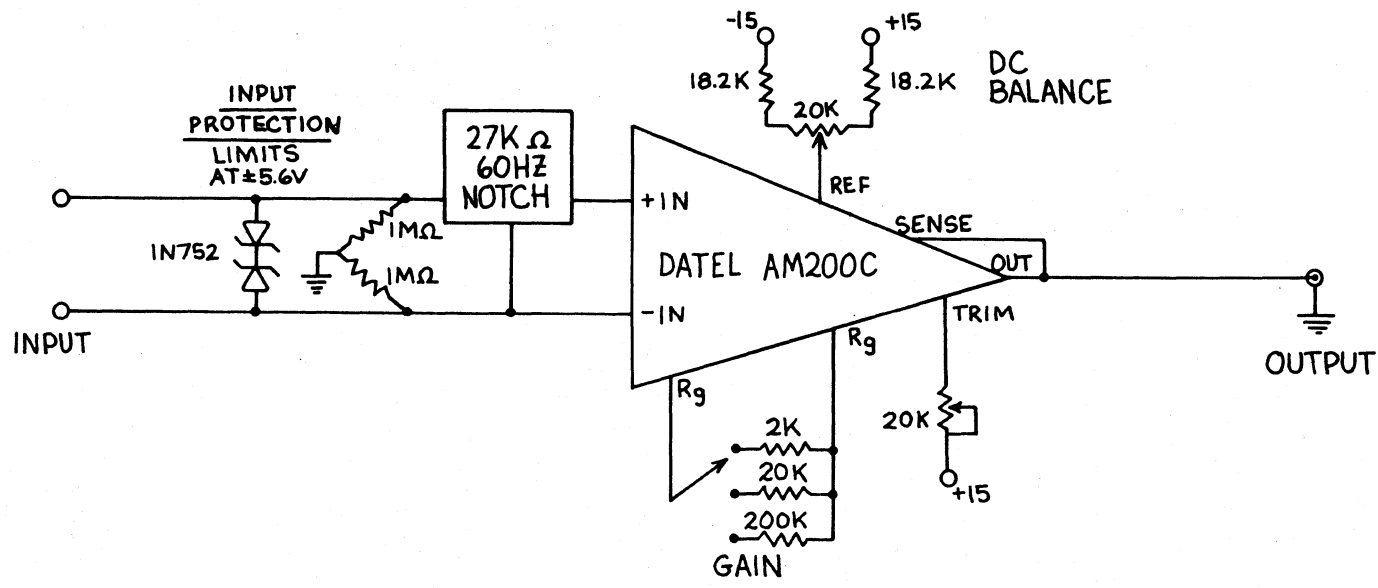
small so as to present a relatively small source impedance to the differential amplifier.

Following the notch filter is a low-noise, low-drift, differential amplifier. It is a DATEL AM200C module with a drift specification of $1 \mu\text{V}/^\circ\text{C}$. The circuit diagram is shown in Figure A3.1.2. The differential amplifier isolates the truck and equipment ground from the electrode grounds.

A stage of active filtering follows the differential amplifier. For the low-frequency, long-range sounding experiments, a 307 operational amplifier active filter was used (Figure A3.1.3). It was wired for Butterworth response and for 0 to 1 or 0 to 10 Hz bandpass. For other bandwidths and for the high-frequency, short-range soundings, an Ithaco model 4214 step-variable active filter could be used with any of the 3 channels.

Several stages of gain amplifiers were used before recording with a chart recorder and the PDP8/E computer. These stages are 741 operational amplifiers (Figure A3.1.4).

Test points were brought out to the front panel at each stage of the receiver so we could check for saturation at any stage. Considerable flexibility was built into each stage (such as a wide selection of gains, bandwidths, etc) in order to adapt to widely varying noise conditions. The gains and bandwidths given on Figure A3.1.1 are the most used values for the long-range, low-frequency transmissions.



POWER SUPPLY

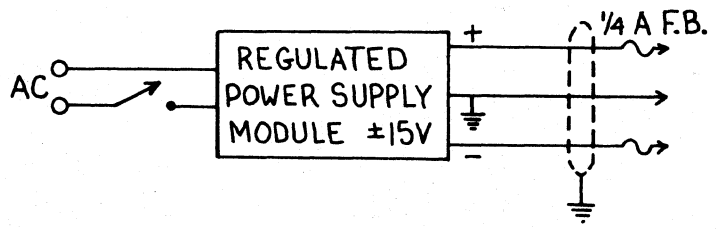


Fig. A3.1.2 E channel differential amplifiers.

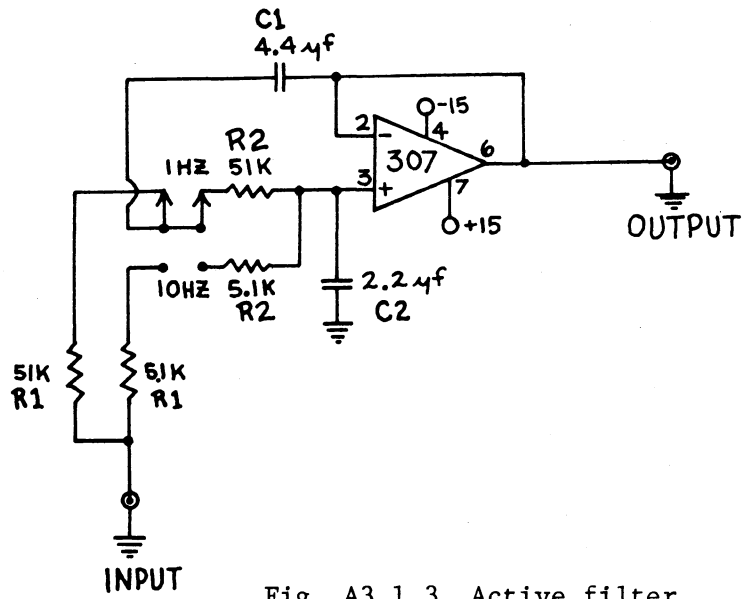


Fig. A3.1.3 Active filter.

- 1) 1 Hz or 10 Hz low pass filter.
- 2) Butterworth response.

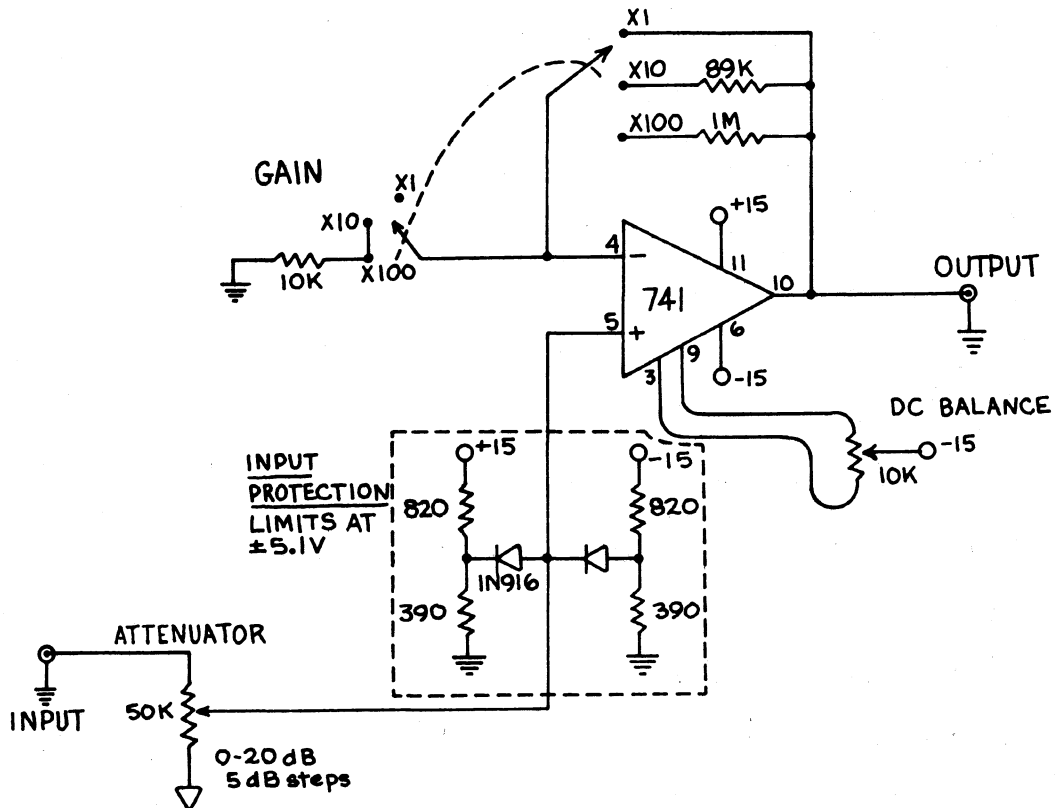
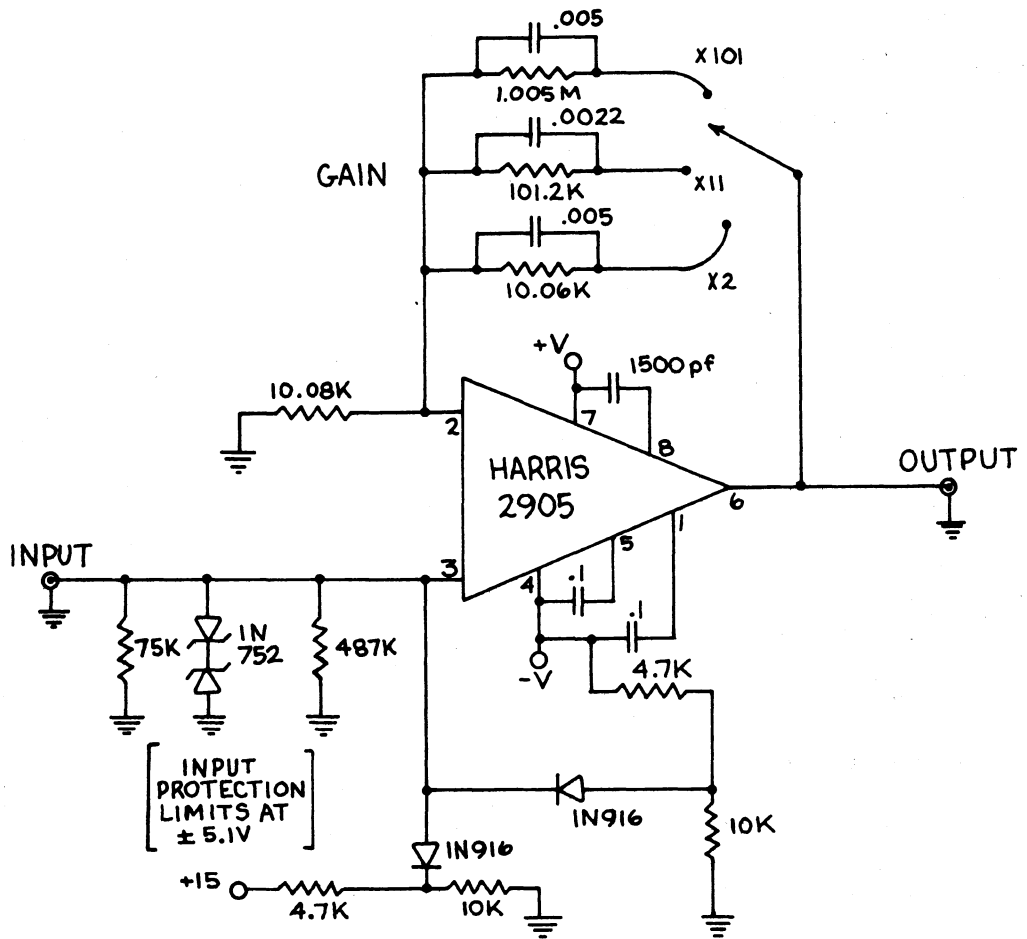


Fig. A3.1.4 Gain amplifiers.

The magnetic channel is very similar to the electric channel with the exception of the input. An induction coil produces a signal proportional to the derivative of the magnetic field. The coil consists of 30,000 turns of copper wire wrapped around a mumetal core 1.2" diameter and 6 ft long. The sensitivity of the coil is nominally $150 \mu\text{V}/\gamma\text{Hz}$ and it weighs about 200 pounds. Movement of the coil in the earth's magnetic field can be a major source of noise. When the signal level was low, the coil was always buried to avoid any wind motion. It is physically difficult to bury a 6 ft long coil vertically in northern Wisconsin glacial drift. When wind noise was low and signal strength high, a portable frame was used to hold the coil.

We found that it is important that a preamplifier be placed close to the coil before the signal is sent to the truck. A low-drift, battery-powered, chopper-stabilized, operational amplifier was built into a waterproof box and placed about 20 feet from the coil. A Harris Semiconductor HA2900 operational amplifier was used (drift = $0.2 \mu\text{V}/^\circ\text{C}$), Figure A3.1.5. The box containing the amplifier is heavily insulated, painted white, and covered with a small umbrella or buried, in order to reduce thermal drift. The gain was usually X100 for the low-frequency measurements (0 to 10 Hz) and X10 for the high-frequency (100 to 10,000 Hz). The 75000 ohm resistor at the input of the amplifier is used to broaden the resonance peak of the coil and provides a fairly flat response from about 100 Hz to



POWER SUPPLY

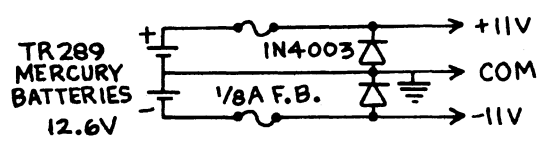


Fig. A3.1.5 H channel chopper stabilized amplifier.

several KHz. The response is directly proportional to frequency from 0 to a few tens of Hz. The low-pass filter capacitors in the feedback loop are needed to avoid oscillation of the amplifier when used with the high-inductance (630 henry) coil.

We found that noise levels were lower when the input amplifier in the truck had a single-ended, rather than a floating input. The coil and nearby chopper amplifier are carefully isolated from the surrounding earth, but one of the inputs to the 741 amplifier in the truck is grounded to the earth.

With the exception of the magnetic-channel chopper preamplifier, which was battery powered, all parts of the receiver were powered with standard commercial ± 15 VDC power supplies. The frequency-response curves for the electric and magnetic channels, which apply to the low-frequency (0 to 10 Hz) measurements, are shown in Figures A3.1.7 and A3.1.8. Although other bandwidths were used on occasion when special noise problems developed, these curves apply to all the transient data tabulated in Appendix C. The filter response curves do not include the induction coil effect which causes the magnitude to be multiplied by the frequency and adds $+90^\circ$ to the phase.

The natural micropulsation and spheric noise levels are larger than the input noise specification for the receiver components more than 90 percent of the time. Care must be exercised when operating the receiver to insure that the specified noise levels are attained.

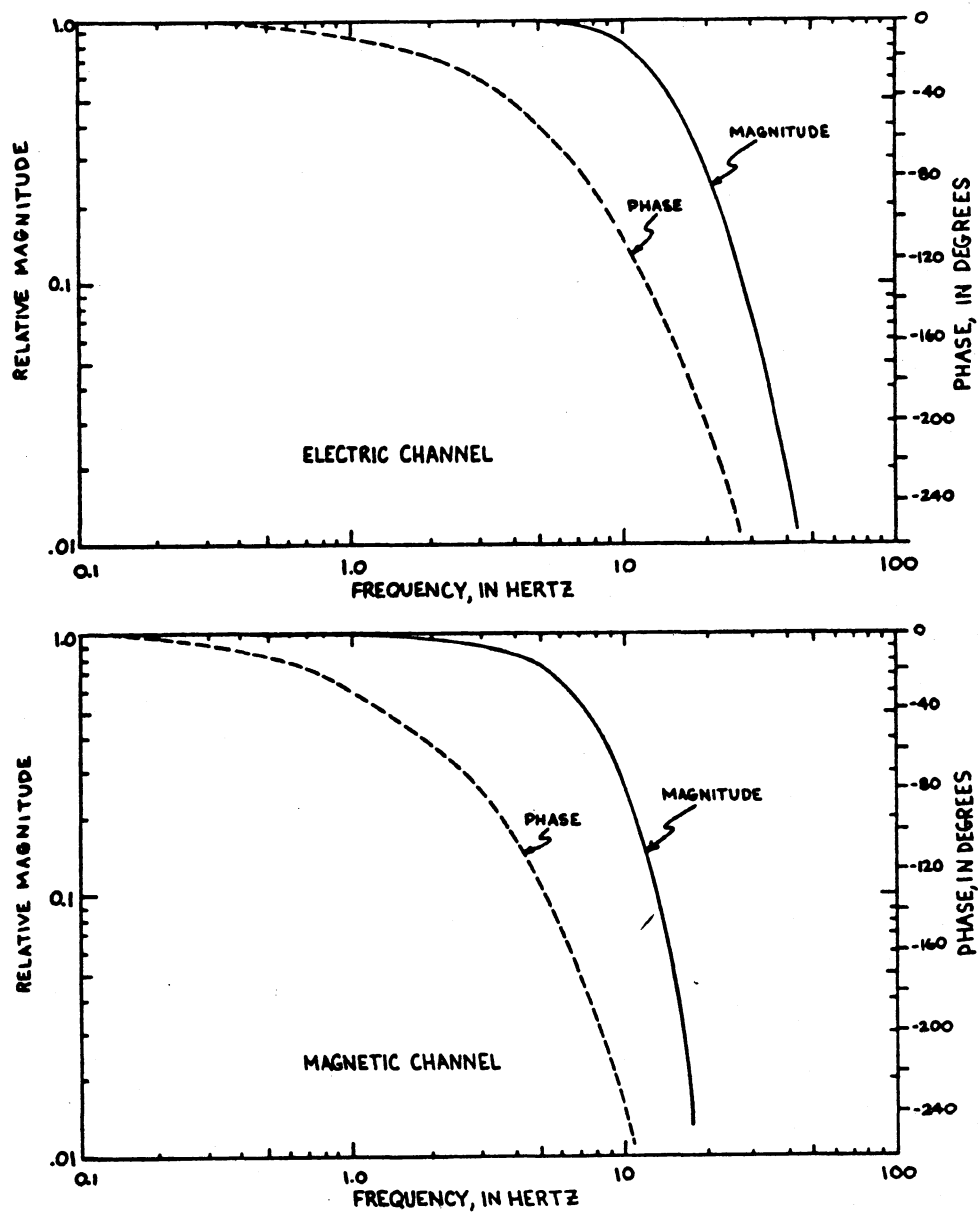


Fig. A3.1.6 1973 Receiver response.

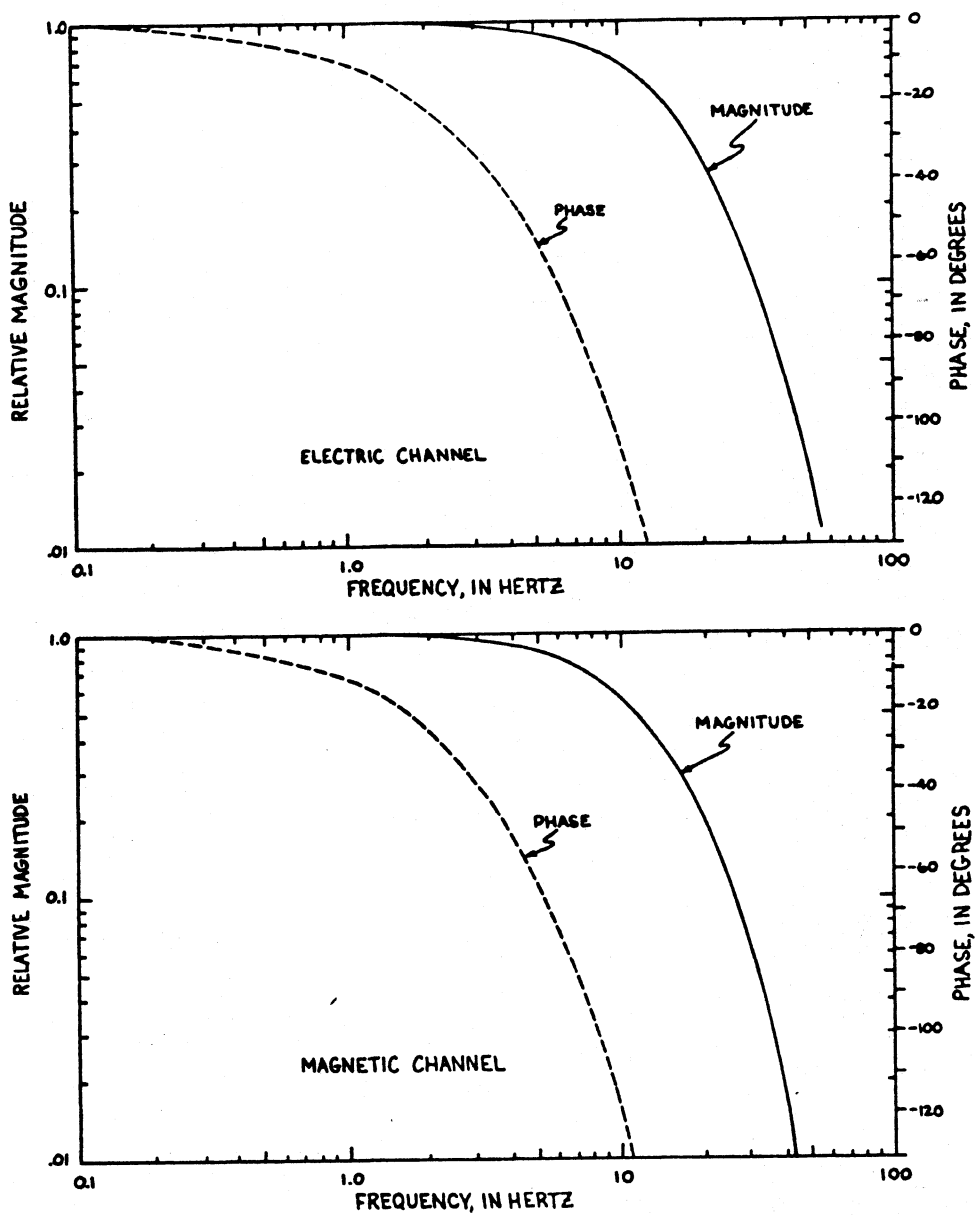


Fig. A3.1.7 1974 Receiver response.

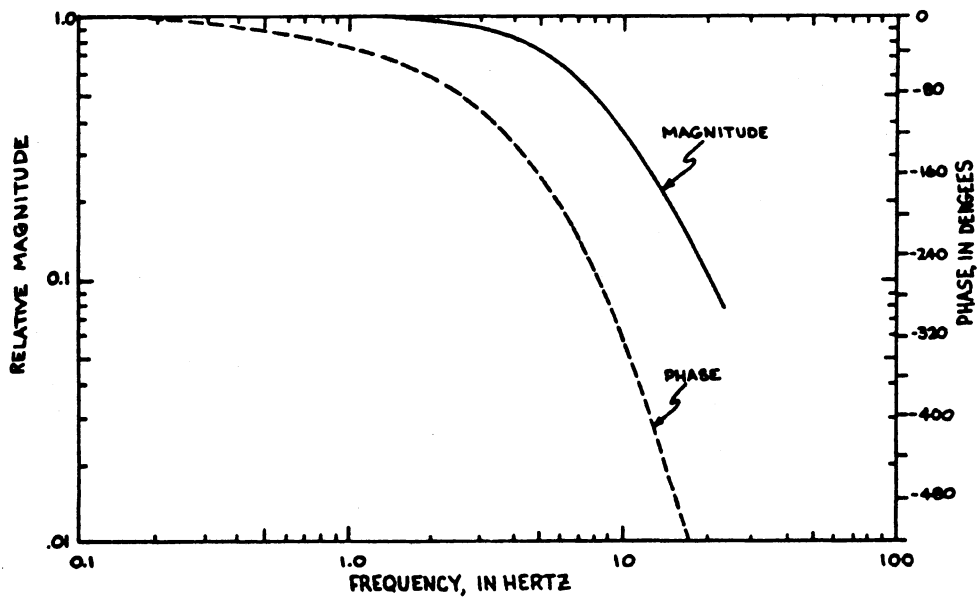


Fig. A3.1.8 1975 Receiver response.

The most common problem is grounding. There must be a single ground point for the entire system. The equipment rack is isolated from the truck and grounded to a porous pot placed a few meters from the truck. The ground around the porous pot should be soaked with brine solution so that the contact resistance is low. The truck body and the generator are then grounded to this same porous pot electrode. Heavy gauge wire or braid is used for all ground connections. The generator trailer is usually just 10 m or so from the equipment truck and must be electrically isolated from the immediately surrounding earth.

When selecting a receiver site, every effort is made to avoid cultural noise problems such as power lines, farm machinery, and cars. Such noise sources should be preferably no closer than one-half mile.

A3.2 RECEIVER CALIBRATION

A complete system calibration was made at least once at each site. We found that this procedure avoided many "anomalies" due to equipment problems. We were also able to account for any drift in the gain or frequency characteristics of the receiver system. A block diagram of the calibration equipment is shown in Figure

A3.2.1.

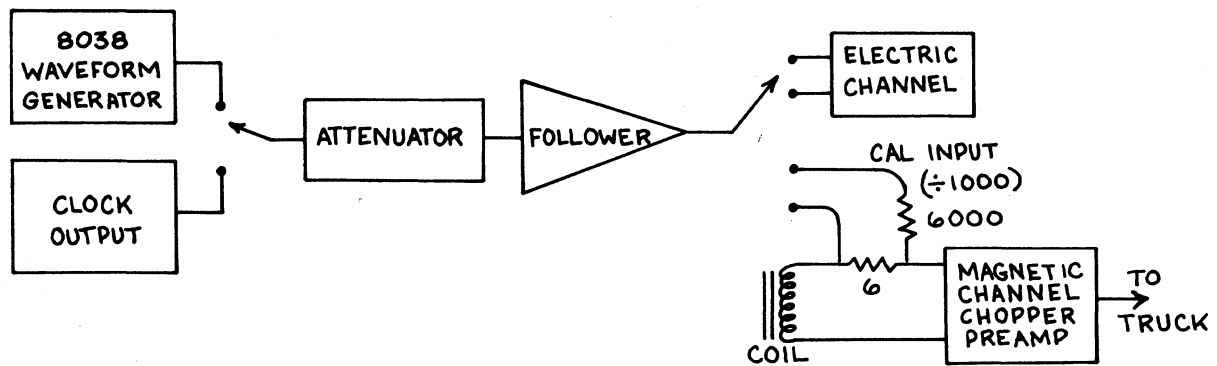


Fig. A3.2.1 Receiver calibrator, block diagram.

The waveform generator circuit diagram is shown in Figure A3.2.2. It is powered by mercury batteries. Both sine and square wave outputs are available, and the frequency is step-adjustable from 0.1 Hz to 31.6 KHz.

Although the small battery-powered waveform generator was very convenient, it was often desirable to use one of the high precision clocks as the waveform generator. When this clock and the receiver clock were synchronized, the precision of the calibration could be increased by stacking.

The attenuator-follower (Figure A3.2.3) provided adjustable voltages from 1 μ volt to 1 volt in 5 dB steps and had a low-impedance output.

The calibration signal was normally injected directly into the electric channel circuitry with the dipole connections removed. For the magnetic channel, the signal was injected into the circuit in series with the coil. This procedure simulated a signal which would be induced in the coil by a time-varying magnetic field.

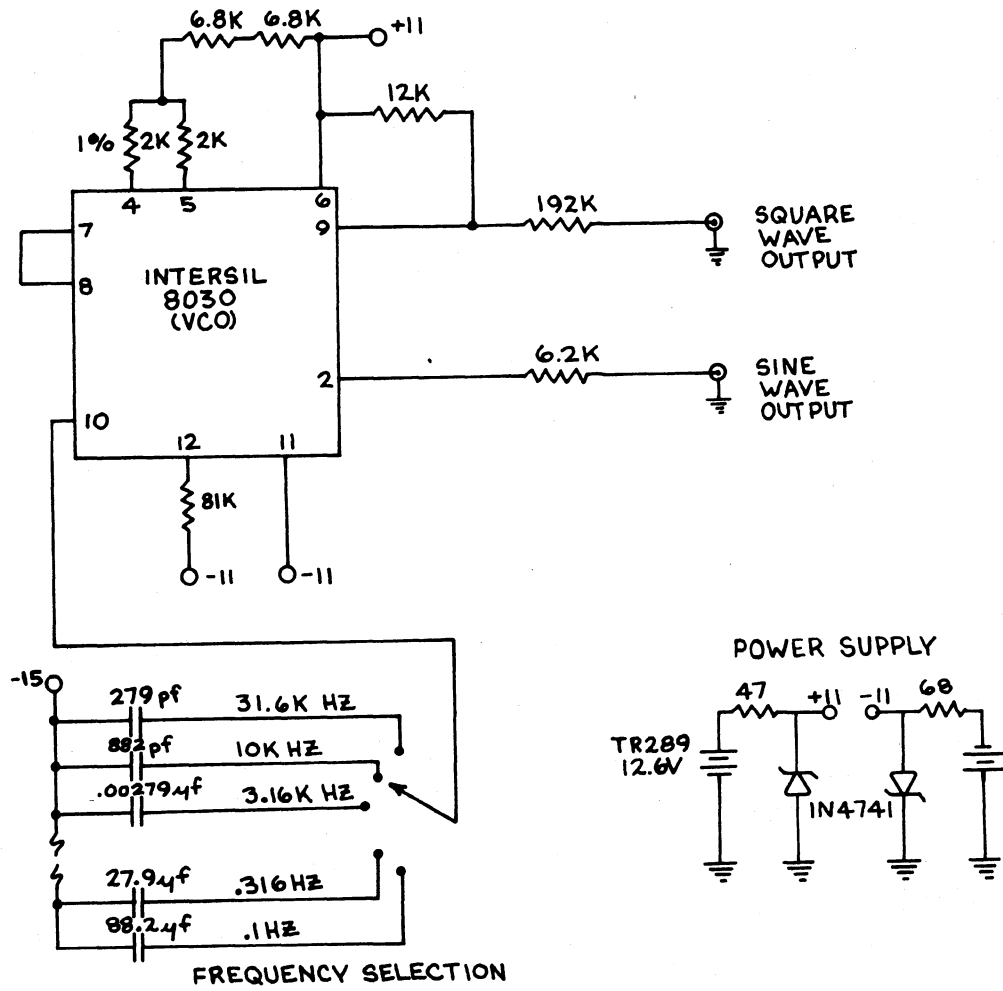


Fig. A3.2.2 Waveform generator.

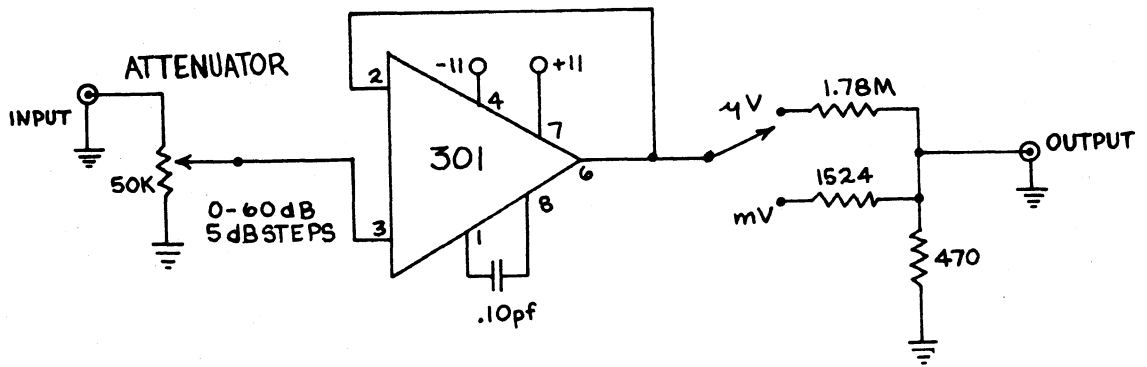


Fig. A3.2.3 Attenuator-follower.

Power supply uses TR289 mercury batteries.

A3.3 PORTABLE DC RECEIVER

A compact, battery-powered, portable receiver and chart recorder were used for most of the DC mapping sites during the 1975 field season. The system is also suitable for recording EM transient waveforms. Many of the components in this receiver are the same as the computer receiver described in Section A3.1. We made some improvements in the receiver based on our experience with the first system. A block diagram is shown in Figure A3.3.1.

The receiver consists of two identical channels. Electric field measurements were normally made simultaneously in NS and EW directions. For the DC mapping measurements, the dipole length was typically 30.5 m.

The calibration signal was injected across a 10-ohm series resistor. Calibrating the system in this way was more convenient than disconnecting the electrodes and readjusting the DC balance every time we injected a calibration signal. The DC calibrator consisted of a battery, voltage divider, and push button (Figure A3.3.2).

The input circuit and preamplifier are shown in Figure A3.3.3. A simple RC low-pass filter with a 3-db point at about 2 Hz provided protection against power line interference, yet passed the 0.1 Hz ("DC") signal without alteration. The precise cutoff point of this

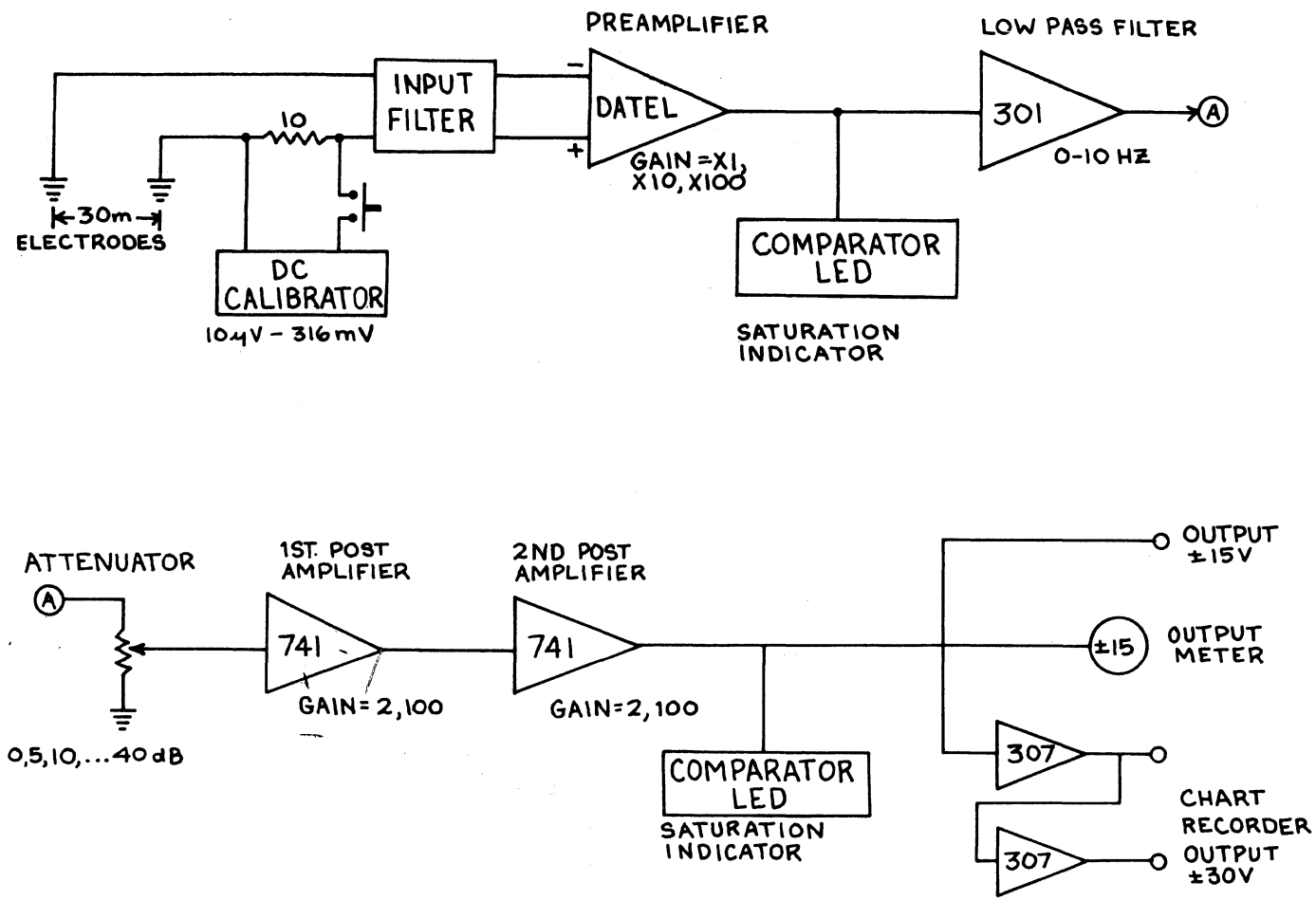


Fig. A3.3.1 Portable DC receiver block diagram.

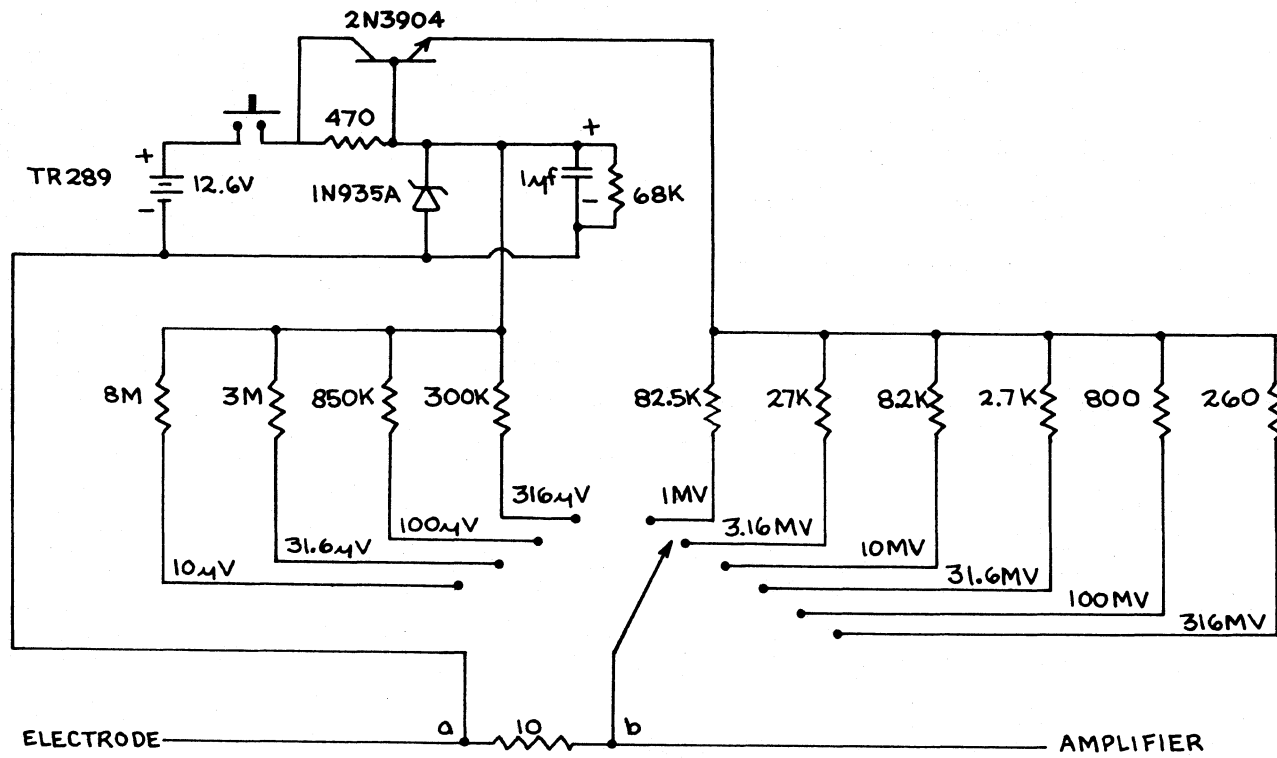


Fig. A3.3.2 DC calibrator

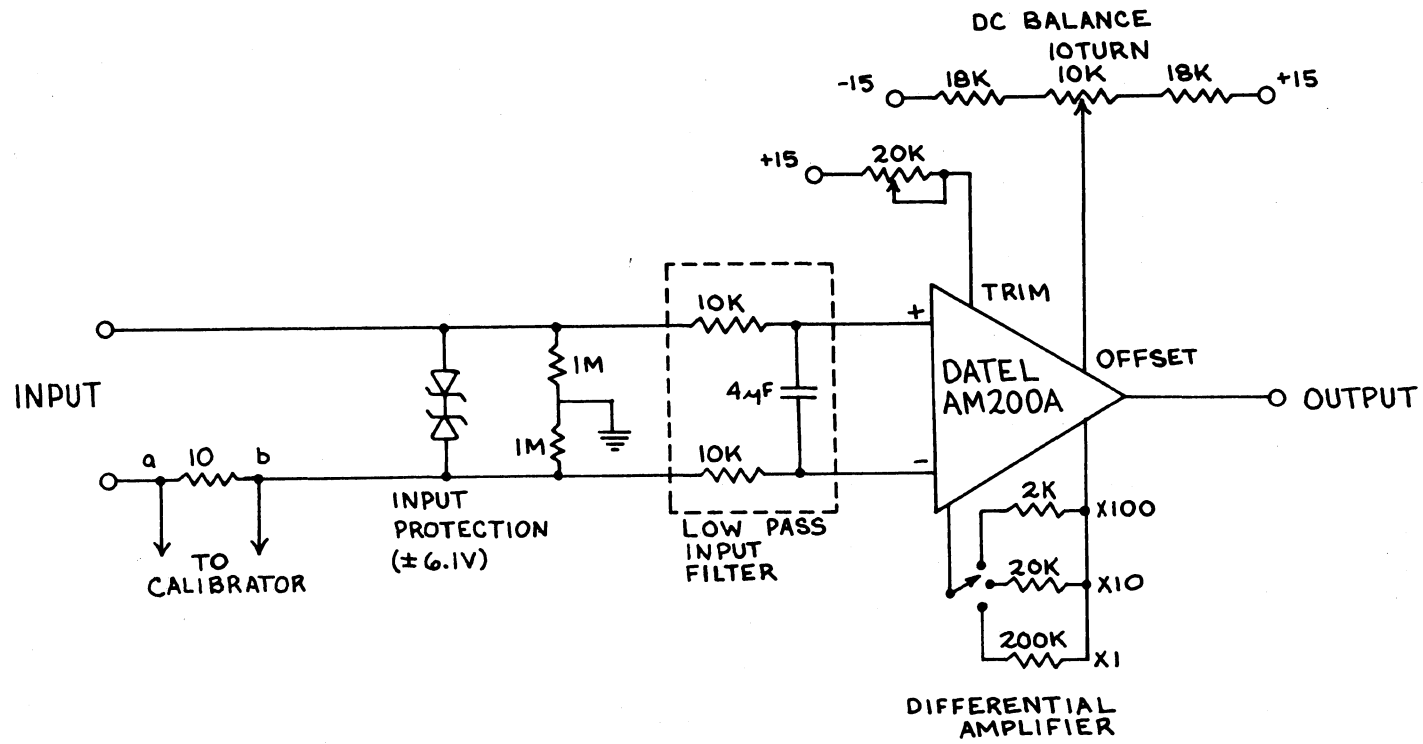


Fig. A3.3.3 Input stage

filter depends somewhat on the electrode contact resistance. An improved filter, which is also suitable for wideband transient measurements, is discussed in Section A6.1.

A comparator circuit (Figure A3.3.4) was placed after each gain stage. If the output of a gain stage equals a reference voltage (the reference voltage is slightly less than the amplifier saturation voltage) then an LED is lit. Noise levels can fluctuate an order of magnitude or more during a recording and the LEDs provide a convenient method of monitoring the condition of the receiver. Because of the strong low-pass filtering in later stages of the receiver, saturation due to high frequency noise in one of the early stages may not be obvious in the output. It often appears only as a gain change or a slight nonlinearity of the waveform.

The low-pass filter (0 to 10 Hz) is shown in Figure A3.3.5. The capacitors C1 and C2 may be easily changed for other bandwidths. The appropriate capacitors are determined by:

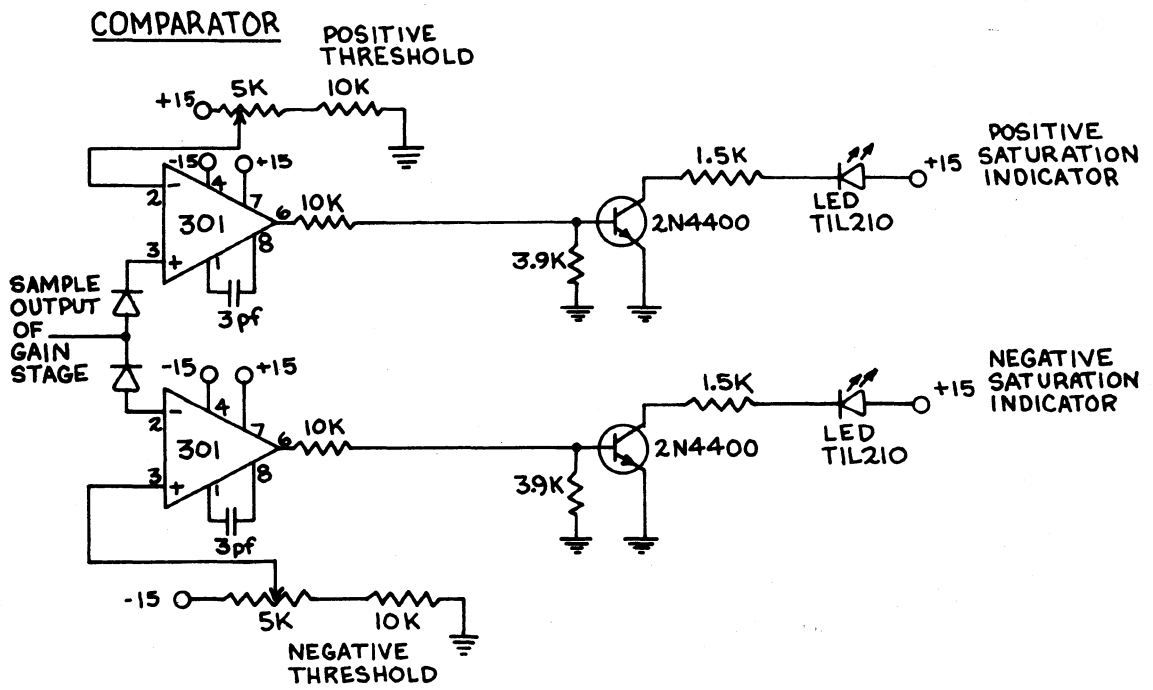


Fig. A3.3.4 Saturation indicator.

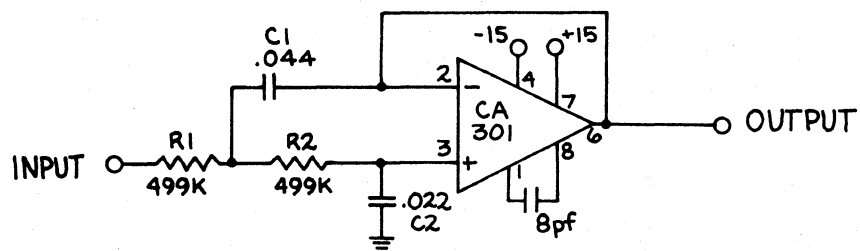


Fig. A3.3.5 Active 10 Hz low pass filter

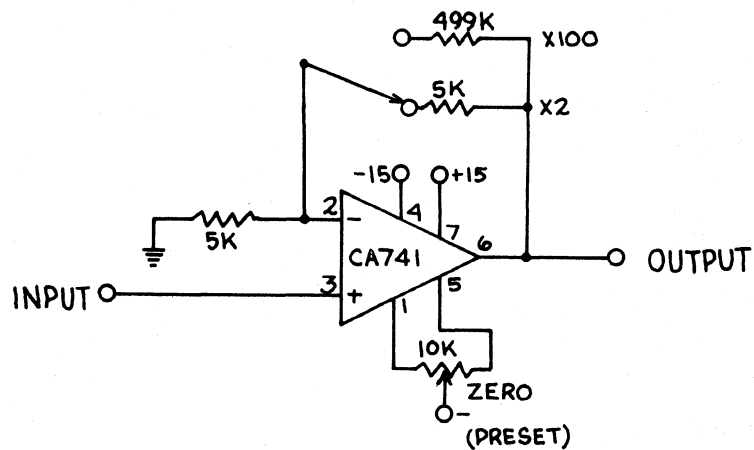


Fig. A3.3.6 741 Post amp.

$$C1 = \frac{R1 + R2}{\sqrt{2} R1 R2 \omega_c}$$

$$C2 = \frac{\sqrt{2}}{(R1 + R2) \omega_c}$$

where $\omega_c = 2\pi f_c$ is the desired cutoff frequency. Provision was made for addition of a high-pass active filter preceding the low-pass filter for high frequency (100 Hz to 10 KHz) transient measurements.

The post-amplifier gain stages are shown in Figure A3.3.6. The output from these stages goes to: (1) a direct output, (2) a chart recorder driver-amplifier (Figure A3.3.7), and (3) a meter (Figure A3.3.8). The chart recorder driver uses two 307 operational amplifiers to provide ± 30 volts output. The recorder was a 2-channel Brush strip chart recorder.

The output meter is used primarily as a quick indication of the signal level and for DC balance. The chart record provides an accurate determination of the DC level (and of the transient waveform). The chart record gives a permanent record of signal quality and can be used to select pulses with the lowest noise level. Several pulses may be averaged (stacked) to improve the S/N ratio.

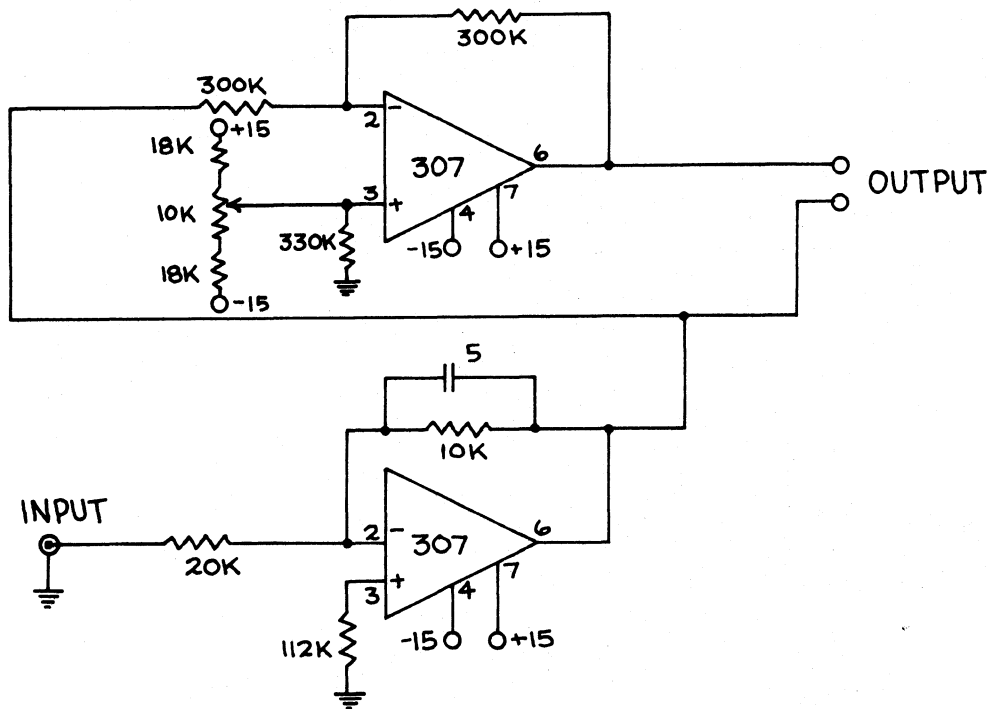


Fig. A3.3.7 Chart recorder driver

1) Drives a BRUSH strip chart recorder, pen driver has 100 ohms input impedance.

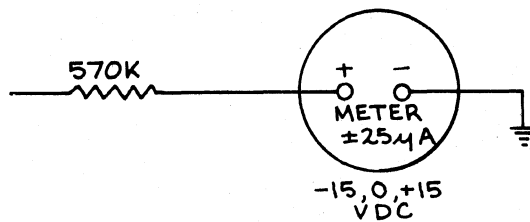


Fig. A3.3.8 Meter.

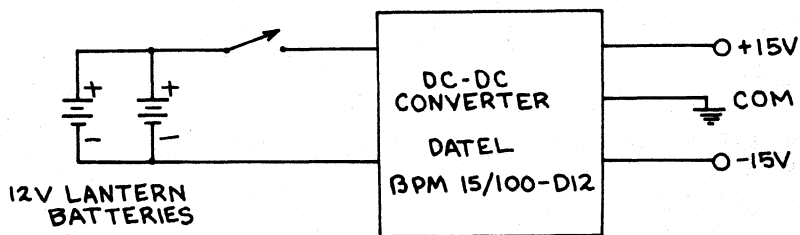


Fig. A3.3.9 Power supply.

A pair of 12-V lantern batteries and a DC - DC converter (Figure A3.3.9) were used for the power supply. The power drain from the lantern batteries is approximately 250 ma.

A4. DATA ACQUISITION AND SYNCHRONIZATION

A4.1 COMPUTER BASED DATA ACQUISITION SYSTEM

The signal level is typically well below the level of natural micropulsation noise at large distances from the transmitter. Since the period of each transmitted pulse is known, the signal-to-noise (S/N) ratio may be enhanced by averaging or stacking many received pulses. With this method, the S/N ratio improves as the square root of the number of stacks for perfectly random noise.

The equipment we chose for stacking was the Digital Equipment Corporation's LAB 8/E system. This system uses a PDP 8/E computer which can be programmed for control of the digitizer and display, and for arithmetic operations such as computing the stack. The LAB 8/E software includes programs for multichannel digitizing, stacking, display, and editing of data. A block diagram of the system is shown in Figure A4.1.1.

A complete description of the LAB 8/E hardware is given in the following Digital Equipment Corporation manuals: 1) Lab 8/E Users Handbook. DEC-LB-HRZA-D, 1973; 2) PDP 8/E Small Computer Handbook,

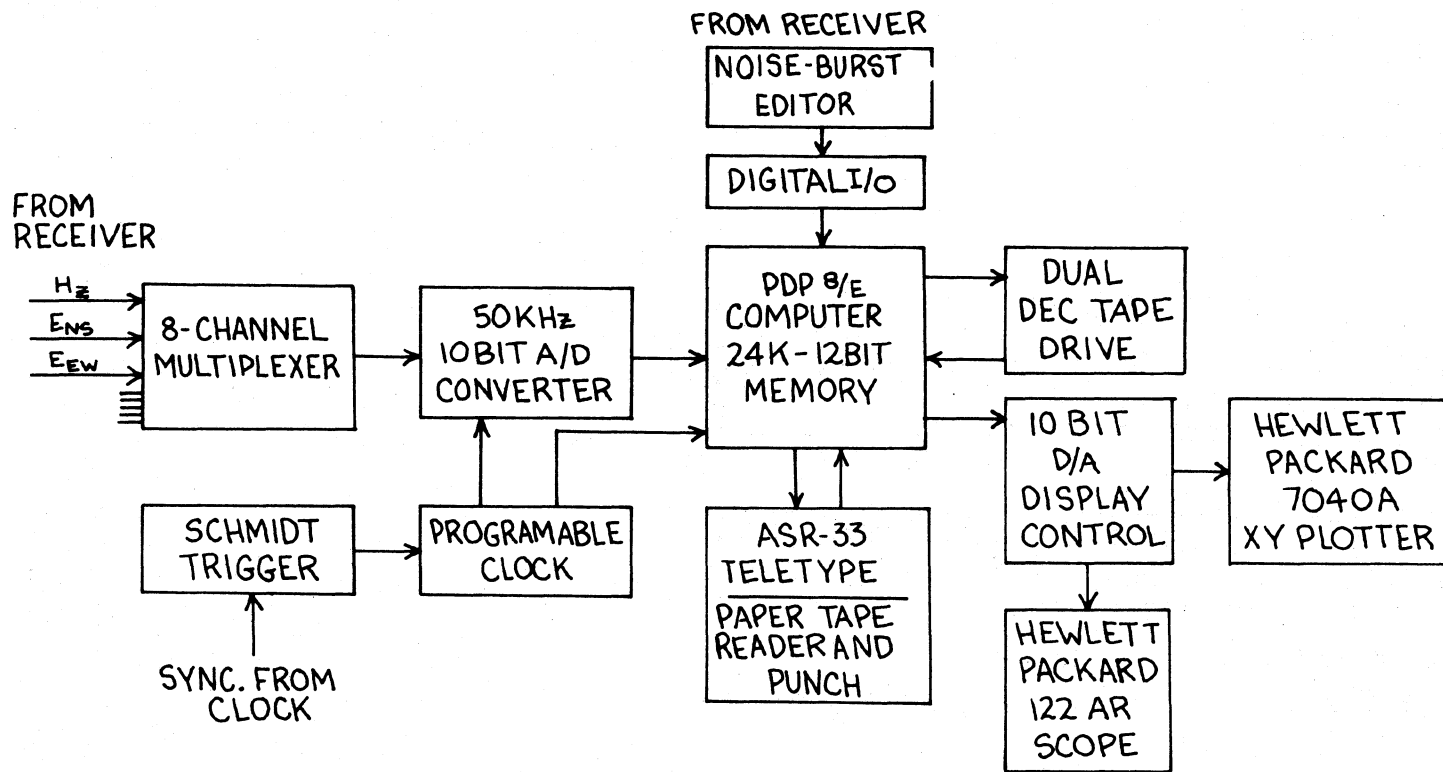


Fig. A4.1.1 Digital data acquisition system block diagram.

1972. The data acquisition software is described in: LAB 8/E Software System Users Manual, DEC-8E-ALUMA-A-D, 1972.

The computer rests on a shock mounted platform in the truck. The entire system is in a rack enclosure and mounted on castors so that it can be conveniently brought into the laboratory for other uses. The PDP 8/E functioned reliably in the field environment. On warm days, however, an air conditioner was required. All of the equipment was run off the generator without problems, except the teletype which was sensitive to the power line frequency.

The PDP 8/E was also used for Fourier transformations, filter corrections, apparent resistivity calculations, and some of the one-dimensional model inversions. See Appendix B for descriptions and listings of these BASIC programs.

A4.2 IMPROVEMENT OF S/N - - EDITING

Simple additive stacking of the pulses was generally effective in increasing the signal-to-noise (S/N) ratio, but large bursts of noise on just a few sweeps would sometimes completely eliminate any trace of the signal. These bursts of noise were usually most intense when a thunderstorm was in the vicinity. The motion of passing cars was also responsible for bursts of noise on the H channel. We found that by editing out the noisiest pulses, the

final S/N ratio could be improved considerably.

We constructed a threshold detector to determine when a large noise burst occurs within a sweep interval. A block diagram of this equipment is shown in Figure A4.2.1 and a circuit diagram in Figure A4.2.2. Two 301 operational amplifiers were used as a comparator to test whether a high-pass-filtered output of the receiver is above a certain threshold. If the signal exceeds the threshold, an LED is lit and a signal is sent to the digital input board in the PDP 8/E.

The LAB 8/E multichannel averager software was designed to accept a pulse if the digital input register receives a signal during a sweep interval. A slight change in the assembly language code is needed for the program to reject the pulse if the digital input register receives a signal during a sweep interval. This change could not be completed before the 1975 field season so the edit pulse was entered manually by the operator if no noise bursts were detected during a sweep interval.

A4.3 CLOCKS

Signal averaging (stacking) requires precise synchronization of the transmitter and receiver. If the synchronization (sync) pulse does not have exactly the same period at both the transmitter and receiver, then the same part of the transient will not be added to

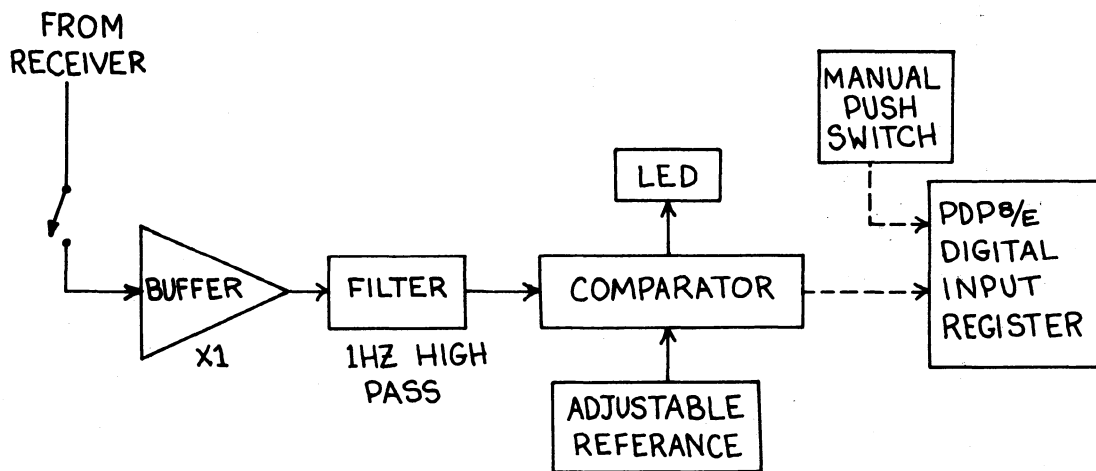


Fig. A4.2.1 Noise burst editor, block diagram.

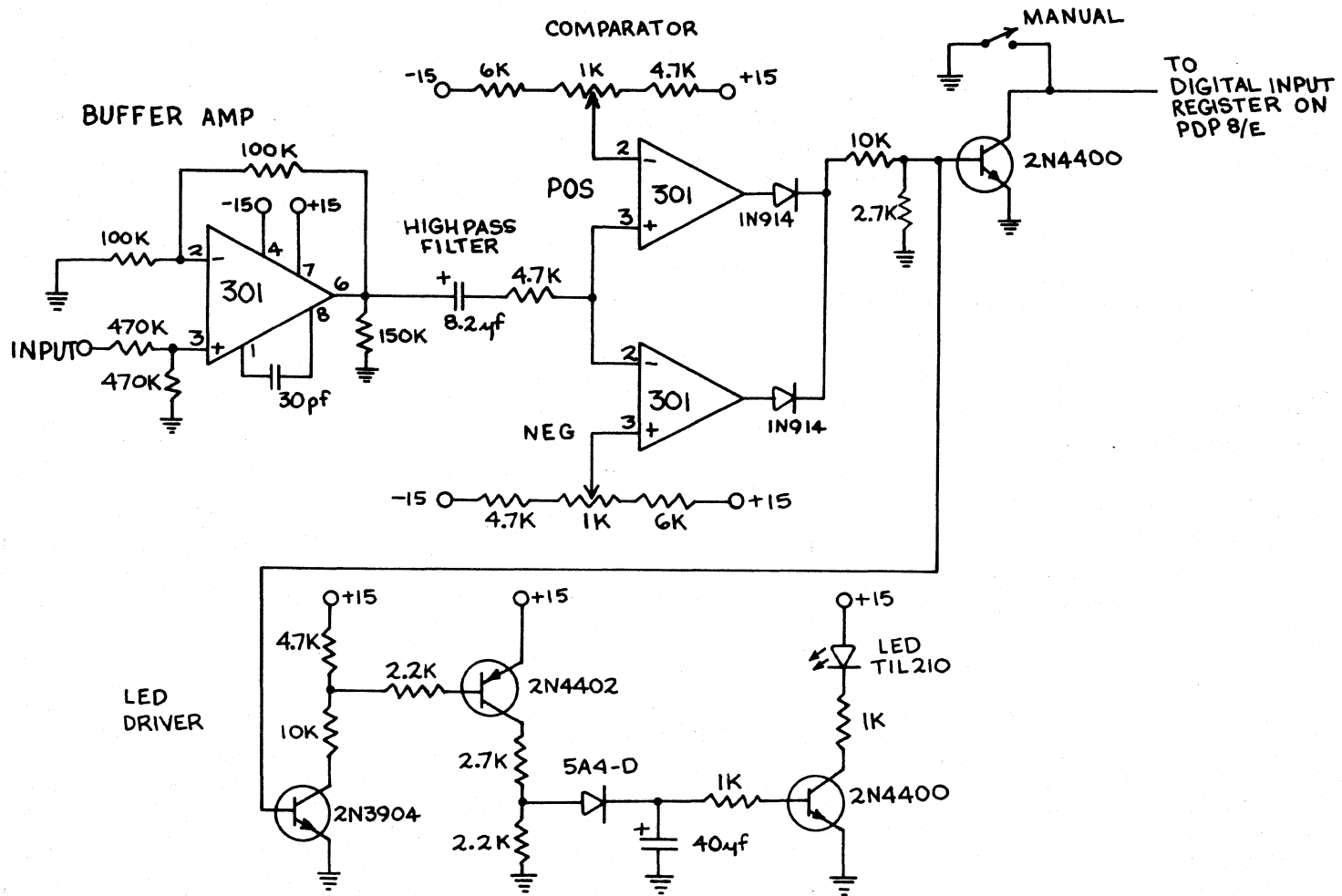


Fig. A4.2.2 Noise burst editor, circuit diagram.

the stack at each sweep and the stacked waveform will be distorted. Quartz crystal oscillators were used as time standards in the transmitter and receiver clocks because they have frequency drifts of less than 1×10^{-9} ($\Delta f/f$)/day. The oscillator's 10 MHz frequency was counted down to the periods used in the experiment. The high quality of the clocks permits both clocks to run freely and to hold a constant phase difference within the requirements of the experiment.

The beginning times of the transmitter and receiver clocks can be synchronized electronically by connecting them together. A tone synchronization could be used over radio and telephone links to start the transmitter and receiver clocks at the same instant (see next section). Telephones or 100 W SSB radios were used for communications.

A block diagram of the clock circuit is shown in Figure A4.3.1. Two 12-volt car storage batteries were used to supply uninterrupted power for several days without charging. A power-fail indicator circuit (Figure A4.3.2) was used to determine if power had been lost for even a fraction of a second. If the power fail light goes out, then the counters in the clock will be behind those in the other clocks and synchronization will have been lost.

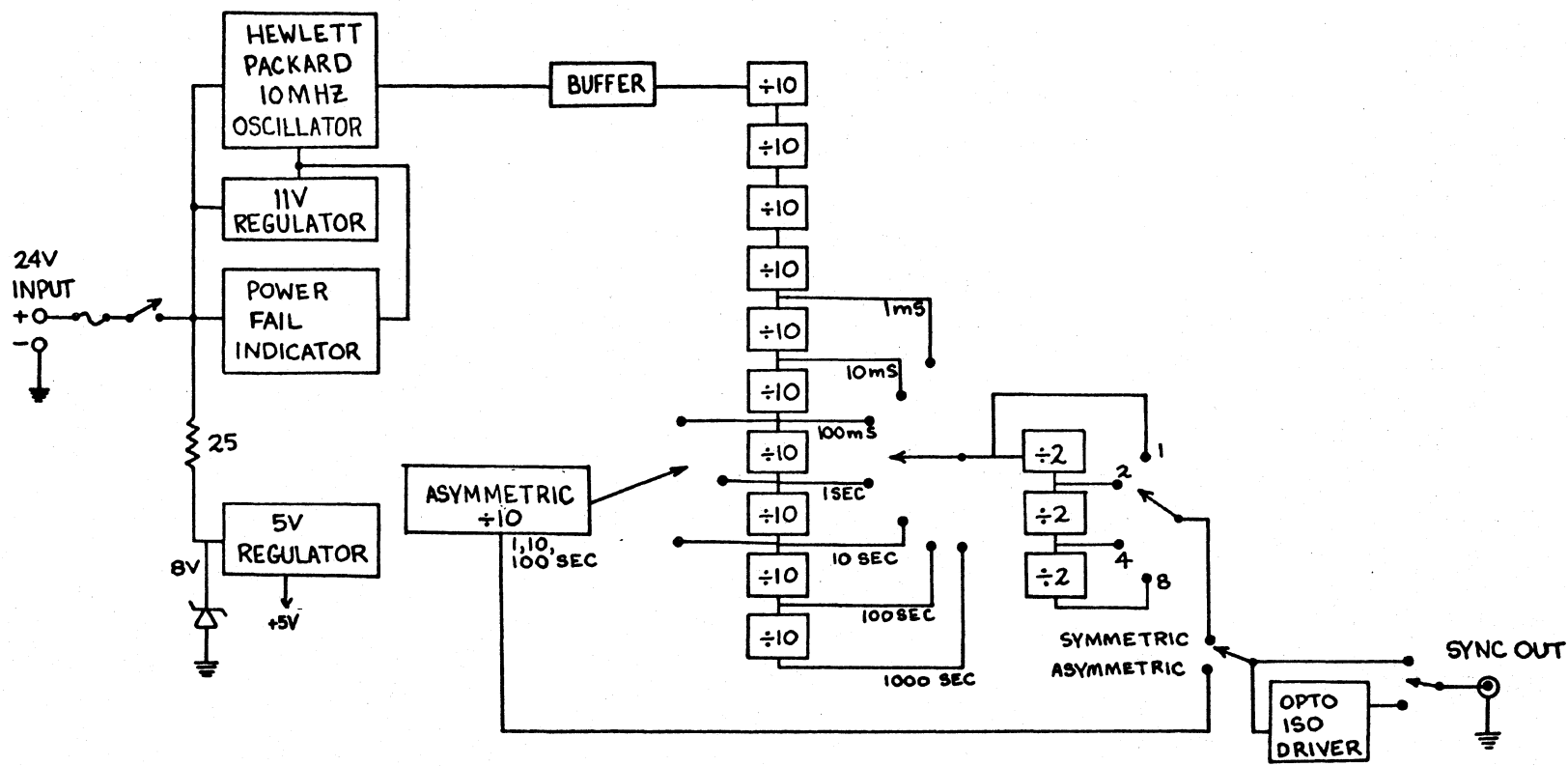


Fig. A4.3.1 Clock block diagram.

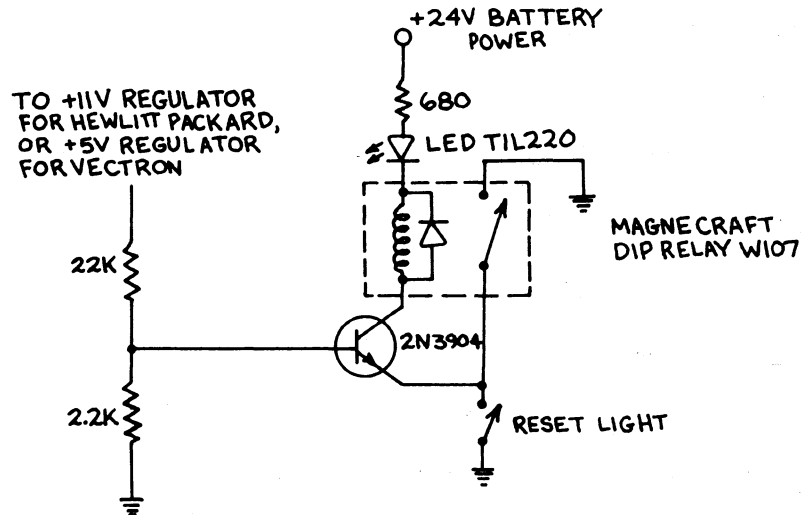


Fig. A4.3.2 Power fail indicator
Change the 22 K and 2.2 K resistors to 6.8 K
for the Vectron oscillator.

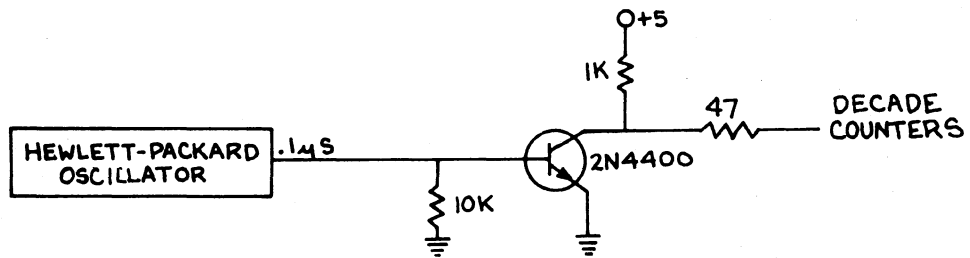


Fig. A4.3.3 Buffer amplifier.

The 24-volt supply is for the crystal oven. A standard commercial regulator was used for the 5-V supply and a circuit described in the H.P. clock documentation was used for the 11 V supply.

Quartz crystal oscillators are temperature sensitive so they are enclosed in a small constant-temperature oven. Hewlett Packard (H.P.) 10544A quartz crystal oscillators (drift = 5×10^{-10} /day) were used in two of the clocks. A Vectron CO-217 oscillator (drift = 1×10^{-9} /day) was used in a backup clock. The Vectron oscillator did not require the 11 volt regulator nor the buffer amplifier between the oscillator and the decade counters.

The buffer amplifier which was used between the H.P. oscillator and the divide logic is shown in Fig. A4.3.3. Decade counter integrated circuits were used to divide the 10MHZ frequency down to the periods used in the experiment. TTL 7490 decade counters were used in two of the clocks (Fig. A4.3.4). COSMOS CD4026AE decade counters were used in a third clock (Fig. A4.3.5). The COSMOS logic requires much less power. Divide-by-two counters were used to give periods which were integer multiples of 1, 2, 4, and 8 (Fig. A4.3.6 and A4.3.7). One of the decade counters was wired to give an asymmetrical waveform (Fig. A4.3.8). The asymmetrical waveform could be used for identifying the polarity of the transmitted waveform at the mobile DC recording sites where clock synchronization was not available.

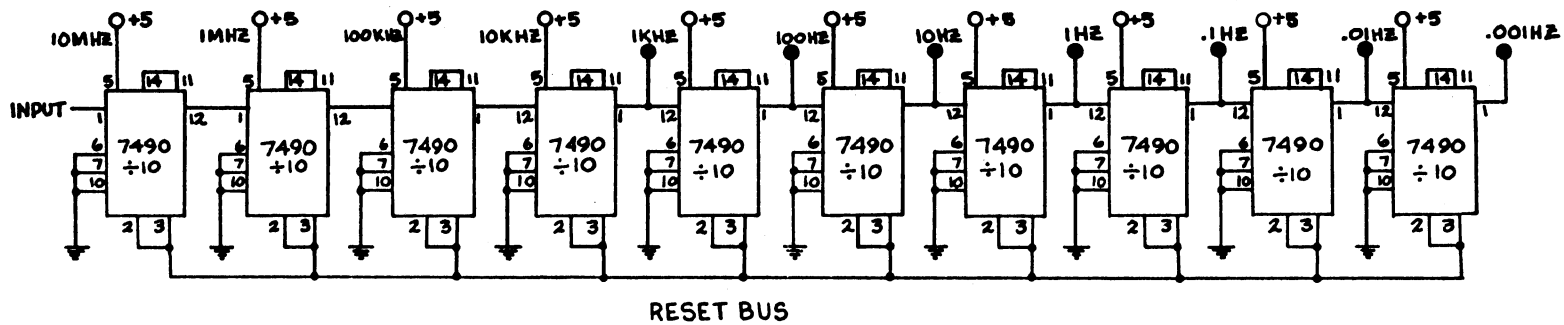


Fig. A4.3.4 TTL decade counters.

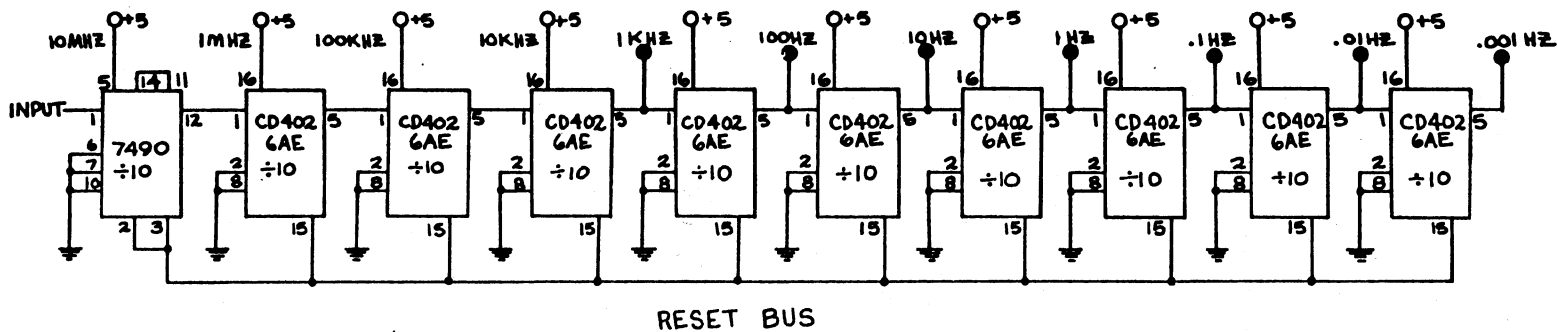


Fig. A4.3.5 COSMOS decade counters.

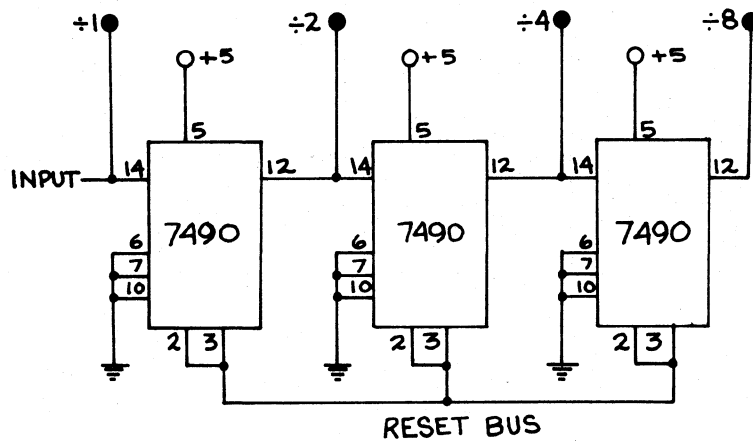


Fig. A4.3.6 TTL divide by 2 counters.

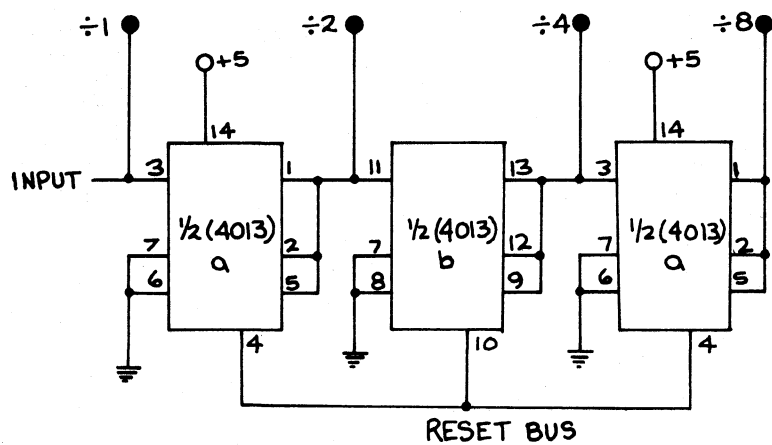


Fig. A4.3.7 COSMOS divide by 2 counters.

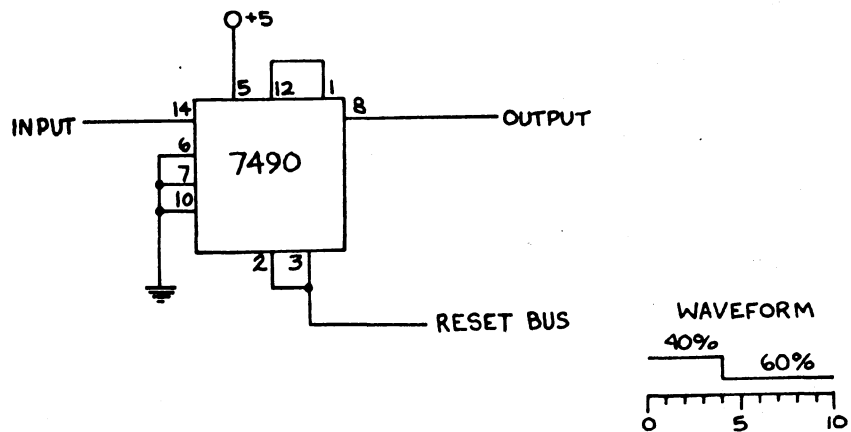


Fig. A4.3.8 Asymmetrical decade counter.

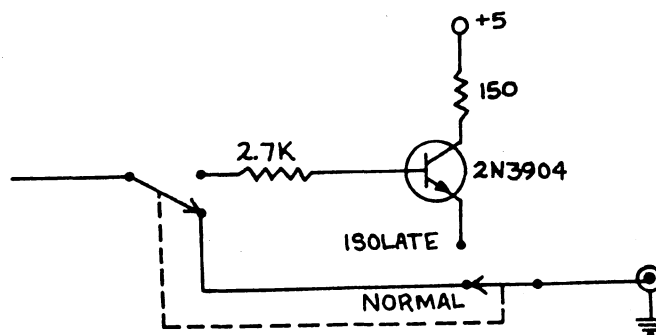


Fig. A4.3.9 Optical isolator driver.

A reset circuit is described in the next section which simultaneously resets the count of all the decade counters in the clocks to zero. A transistor driver (Fig. A4.3.9) could be switched into the sync output circuit in order to provide a sufficiently large signal to drive the optical isolator in the mobil transmitter.

The average power drain for all the components in the clock (oscillator oven plus logic) was 0.52A for the TTL logic and H.P. oscillator and 0.20A for the COSMOS logic and Vectron oscillator.

A4.4 REMOTE SYNCHRONIZATION OF THE BEGINNING TIME OF THE CLOCK PULSE

Signal averaging (stacking) requires, first of all, precisely the same pulse period at both the transmitter and receiver clocks. We also need to know the beginning time of each pulse in order to analyze the transient. We can determine this by two procedures:

- 1) Remotely synchronize the transmitter and receiver clocks in order to remove any constant phase difference between them.
- 2) Estimate zero time by searching for the first arrival of the air wave.

When a pulse is applied to pins 2 and 3 of the TTL logic or to pin 15 of the COSMOS logic, the count is reset to zero. If a reset pulse is applied simultaneously to both the transmitter and receiver

clocks, there will be negligible phase difference between the clocks until 1) eventually the frequency drift causes a measurable phase difference, 2) power is lost to one of the clocks, or 3) the divide-by-two or asymmetrical period switch is changed.

The clock reset circuit is shown in Fig. A4.4.1. A pulse can be initiated from a manual reset pushbutton or from a tone detector circuit. The negative going edge of this pulse triggers a monostable which produces a pulse of 1 ms duration. The pulse is amplified and applied to the reset bus. The output of the monostable may be connected by a cable to another clock so that both can be reset simultaneously. This same connection is used for reception of a sync pulse. A reset receive indicator light shows that a synchronizing pulse has been received.

When it is not practical to connect the two clocks together, and when we need a more precise synchronization than can be obtained by simply pushing the manual push buttons on both clocks on command, we may use a tone generator-detector circuit to transmit a synchronizing pulse to two widely separated clocks. The tone generator circuit is shown in Figure A4.4.2. It consists of a 566 function generator integrated circuit tuned to 1400 Hz. The output goes to the local clock and to a remote clock via a telephone line or SSB radio. The tone detector circuit is shown in Fig. A4.4.3. After amplification, a 565 tone decoder is used to detect the 1400 Hz tone. The bandwidth of the decoder is 200 Hertz. An LED indicates

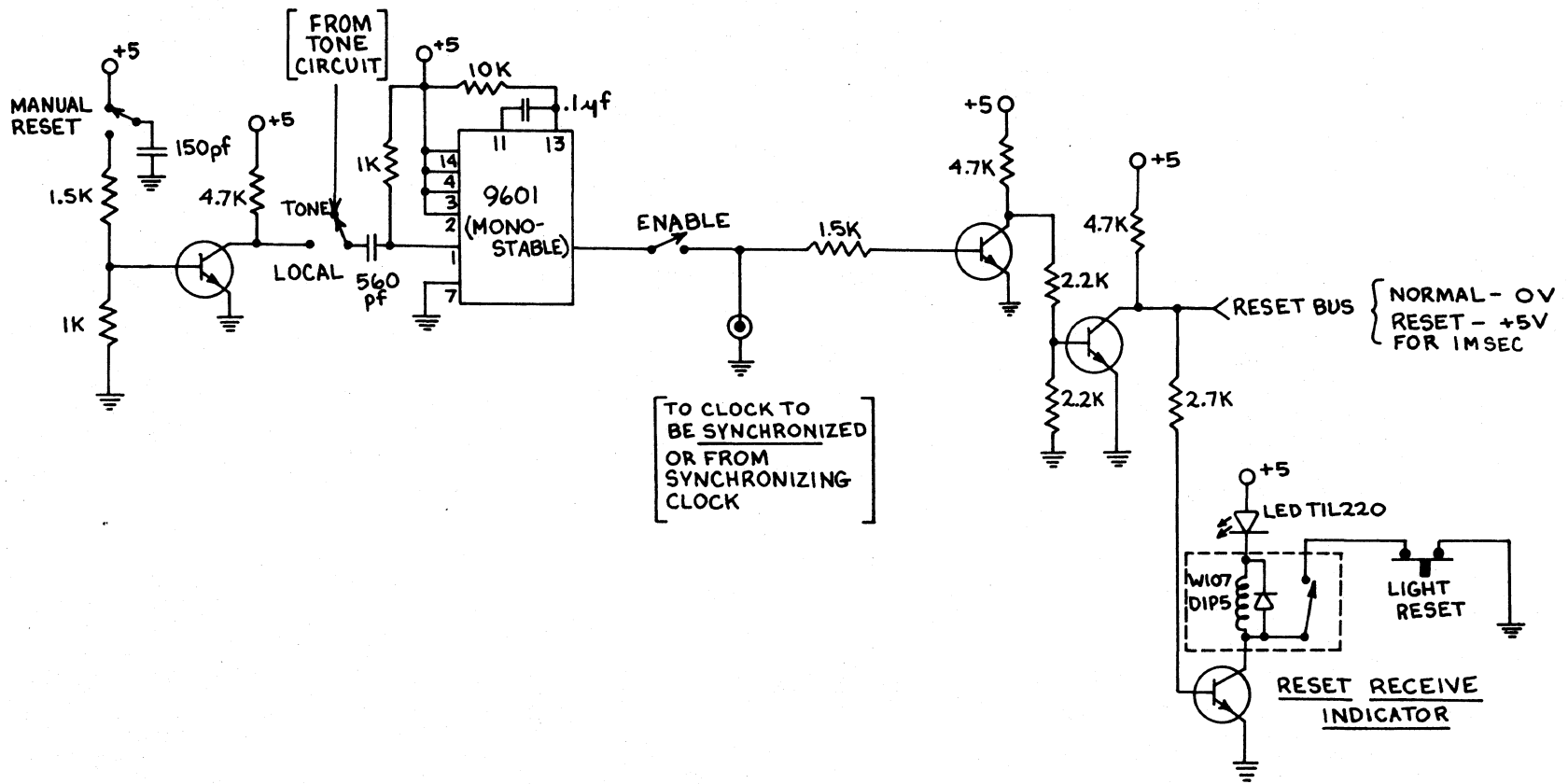


Fig. A4.4.1 Clock reset circuit. All transistors are 2N4400.

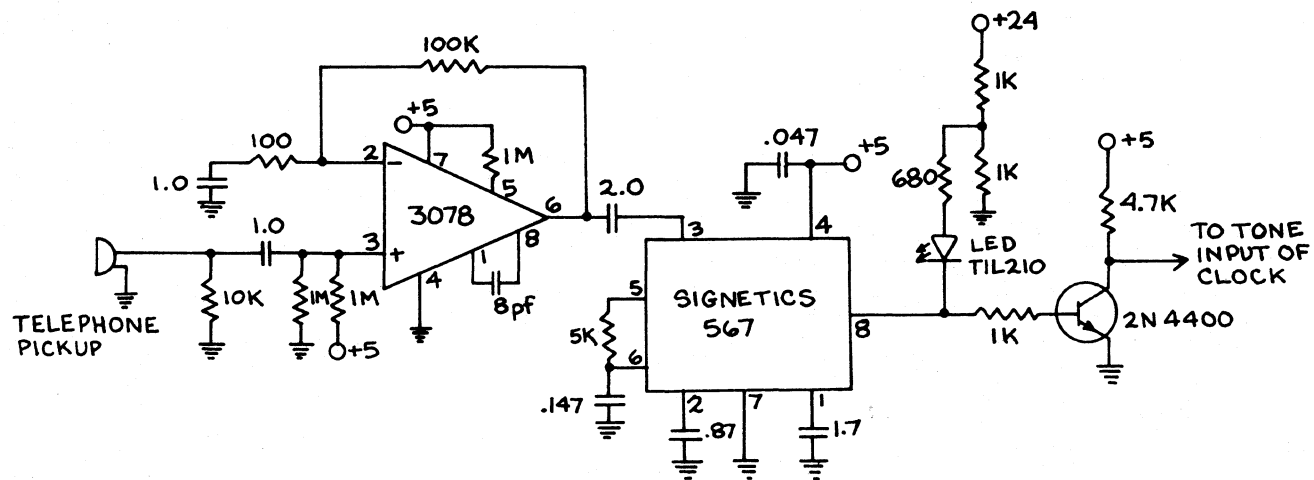
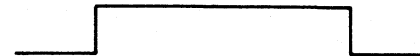


Fig. A4.4.3 Tone receiver Circuit.

1) Output of 3078 amplifier :



2) Output of tone detector :



Synchronization Point

reception of the tone. Turn-off of the tone initiates synchronization.

The tone synchronization system worked well over telephone lines. We found that the SSB radio had to be very carefully tuned and have good reception in order to work properly.

We may approximately determine zero time of the transient waveform from the data itself. An airwave travels almost instantaneously from the transmitter to the receiver. By searching the received signal for the first arrival of energy, we may determine zero time.

The limitations of determining zero time from the data are: 1) We must have good S/N ratio during the initial transient. The air wave has a large amplitude, but the need to strongly filter the 60 Hz power line noise limits the information in the received transient to about 0 to 40 Hz. 2) The uncertainty of zero time can be no less than the digitizer sampling interval. Available memory limits the total number of samples of the transient to about a thousand. The estimate of zero time can be improved during the least squares inversion process (see Appendix B).

At most of our long-range transmission sites we did not have access to telephone lines and SSB radio reception was not sufficiently good to receive the tone clearly. Therefore, at most of the long range sites zero time was determined from the arrival of the air wave.

A5. AUDIOMAGNETOTELLURIC EQUIPMENT

During the 1975 field season, a number of audiomagnetotelluric (AMT) soundings were made with equipment loaned to us by Kennecott Copper Corp. This equipment is briefly described in Strangway, Swift, and Holmer, 1973. We review here the essential features of this equipment based on this article. The details of the equipment are considered confidential by Kennecott.

Fig. A5.1 is a block diagram of the equipment. The electric (E) field sensors consist of two copper rod electrodes spaced about 30 m apart. The magnetic (H) field sensor is an induction coil with about 10,000 turns of copper wire wrapped around a ferrite core. Both the electric and magnetic channels had a set of 10 narrow-band filters which cover the frequency range from 14 Hz to 10,000 Hz. The filtered and amplified E and H signals are rectified and then integrated for a period of about one minute. The scalar apparent resistivities were calculated from the E/H ratios and the system parameters.

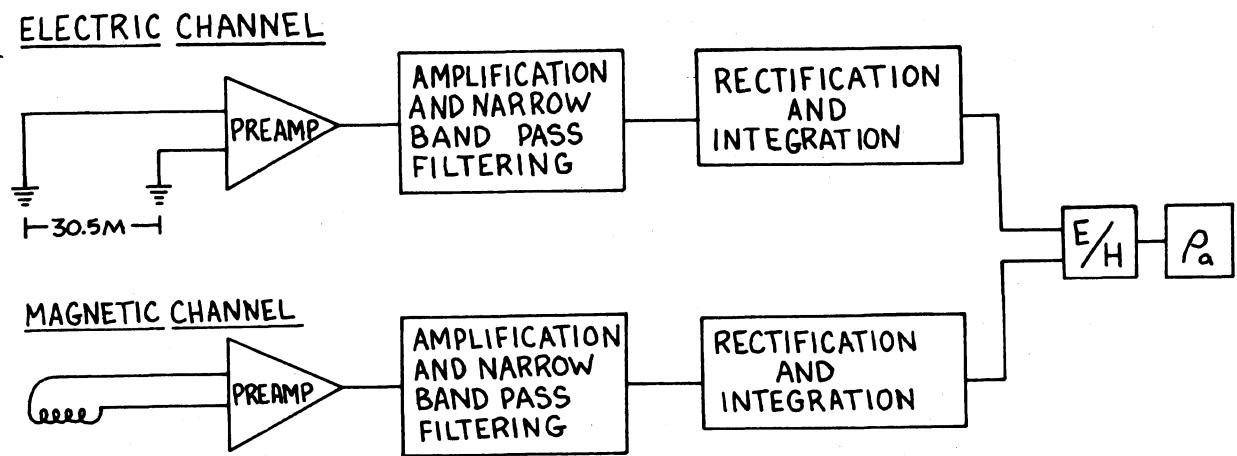


Fig. A5.1 AMT equipment block diagram.

A6. RECOMMENDED IMPROVEMENTS TO EQUIPMENT

A6.1 RECEIVER

We found that the first odd harmonic of the power line noise (180 Hz) is often troublesome and should be passively notch filtered along with 60 Hz before any active amplification is done. Low-frequency radio stations (around 10 KHz and higher) can be large enough to cause nonlinear behavior in the first stage and should also be passively low-pass filtered.

Low-noise, low-drift amplifiers are being improved rapidly. For future systems, the latest DATEL or Burr-Brown amplifier modules should be considered as replacements for the DATEL differential preamplifier in the electric channel or the chopper stabilized preamplifier in the magnetic channel. The remainder of the receiver is adequate for earth sounding experiments in the usual frequency range of 0.01 Hz to 10,000 Hz.

A6.2 MOBIL TRANSMITTER

The primary limitation of the present transmitter is the 400-volt rating of the switching transistor. We found that it was very difficult (and often impossible) to get the electrode contact resistance down to 40 ohm in order to get 10 A into the ground with a voltage of 400 V. TRW Semiconductors has recently announced

development of a switching transistor with an 800 V collector-to-emitter sustaining-voltage rating. It is likely that even higher-voltage transistors will soon be available. A DC power supply with an 800-volt or higher rating will also be required.

A6.3 DATA ACQUISITION SYSTEM

The primary limitation of the present digital data acquisition system is the 10-bit digitizer (resolution of 1 part in 1024). This limits the dynamic range or our ability to resolve details of the transient waveform. To obtain the maximum information from the transient it would be desirable to have at least a 12- or 14-bit digitizer. The more dynamic range the better.

A6.4 CLOCKS

The clocks worked well for their primary purpose of providing a pulse at both the transmitter and receiver with precisely the same period. Synchronizing the clocks to remove any constant phase difference proved to be difficult under field conditions. It was usually necessary to approximately determine zero time from the data.

A useful addition to the clock is shown in block diagram form in Fig. A6.4.1. The circuitry allows addition of a few extra counts to the decade divider chain. By pressing the #1 push button the phase can be shifted by 10 ms. By pushing the #3 push button the phase can be shifted by 0.1 ms. The synchronization procedure would consist of applying the clock pulse to the external sweep trigger of an oscilloscope. The signal to be synchronized with (e.g., another clock, WWV, or a tone burst) is applied to the vertical input. The phase of the clock is adjusted until the edge of the displayed pulse is at zero time. This procedure has the advantages that the reference signal may be quite noisy and that we do not have to change the phase of the reference signal.

A6.5 EDITING WHILE STACKING

Our limited experience with editing has shown that dramatic improvements in the S/N ratio can be obtained by rejecting from the stack those sweeps which contain large bursts of noise. Top priority should be given to changing the assembly language stacking program so it automatically rejects these sweeps as described in Section A4.4.

A possible improved editing procedure would consist of writing a new stacking program which would test each digitized point to see

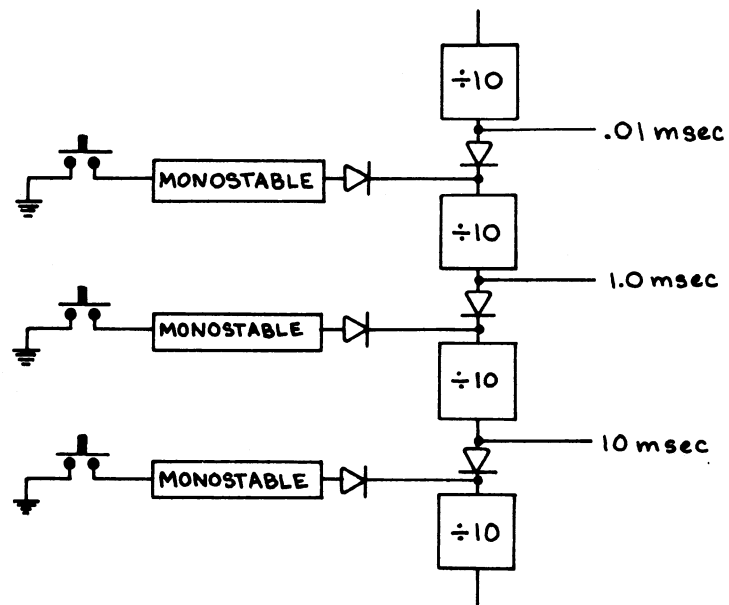


Fig. A6.4.1 Clock modifications.

- 1) Output of the monostable is a 10 μ sec long pulse.
- 2) Blocking diodes must be high speed.

if it was within some prescribed percentage of the current stack value. If not, the single point would be rejected. Such a program would have to be written in assembly language and carefully optimized in order to function in real time at reasonable digitizing rates.

A7. ACKNOWLEDGEMENTS

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