DEVELOPMENT OF A DIGITAL DATA ACQUISITION SYSTEM
FOR MONOSTATIC LIDAR

by

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Associate Professor of Electrical Engineering

Date

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ABSTRACT

Lidar is a system for remote atmospheric measurements utilizing the scattered return from a transmitted laser pulse. The return signal for a monostatic or backscatter lidar is a high speed, wide dynamic range transient signal that presents special problems for data acquisition. Described herein is the development of a relatively simple and inexpensive system for automatic digital acquisition of monostatic lidar return signals.

A high speed gain switching amplifier was designed for compression of the wide dynamic range lidar signal. The signal is A/D converted and captured by a commercial transient recorder. A paper tape digital system was built for recording captured return signals along with necessary auxiliary information, the laser pulse energy and system zenith angle most importantly. Processing return data and the errors associated with the acquired signal are discussed.

CHAPTER 1

INTRODUCTION

The atmosphere is an extensive, continually changing physical system. A basic problem of atmospheric studies is the collection of data from the remote atmospheric system with sufficient speed and in adequate quantity to give a realistic picture of processes involved. One attractive means of atmospheric investigation which has been under study in recent years is remote sensing of atmospheric structure from the interaction of radiation with atmospheric constituents. Meteorological radar is a familiar example. Transmitted electromagnetic waves scatter off of hydrometers producing a signal dependent on the nature and number density of scatters.

The advent of pulsed lasers gave rise to the possibility of a new form of remote atmospheric sensing at visible and near visible wavelengths. Sensing at visual wavelengths is of interest because primary atmospheric constituents, gaseous molecules and aerosols, interact effectively with electromagnetic radiation of the visual range. Light radar or "Lidar" is a system for ranging and detection using light pulses from a laser transmitter. A lidar for atmospheric sensing consists basically of a pulsed laser transmitter and a telescope-photomultiplier tube receiver. For a monostatic system, as shown in

Figures 1.1 and 1.2, the backscatter signal produced by the laser pulse travelling outward through the atmosphere is picked up by a receiving telescope whose optical axis is parallel to the transmitted beam, producing a signal vs. range output from the receiving photomultiplier tube.

Many techniques have been proposed for processing lidar backscatter signals to obtain remote measurements of atmospheric parameters [Kent and Wright, 1970]. The elastic backscatter signal from air molecules and aerosols is related to air pressure and temperature, and the concentration and size distribution of aerosols. Analyzing the Raman scattered component or the dopper broading and shift of the backscattered signals has been proposed as a means of measuring such parameters as temperature, pressure or wind velocity remotely.

For whatever use lidar return signals are to be applied, there must be some means of recording the lidar return signal. Manual means of data recording and reduction, such as photographing and measuring oscilloscope traces, can be used, but since a primary feature of lidar remote sensing is that large amounts of data can be rapidly acquired, manual data analysis severely limits the application and usefulness of lidar systems. Manual processing of an hour's data can involve weeks of time. To realize the potential of light radar for rapid collection of atmospheric data, a system of automatic data acquisition and reduction is necessary. Specifically, a data acquisition system is needed that records the lidar return signals in a form that can be rapidly processed by a digital computer. The goal of the project described

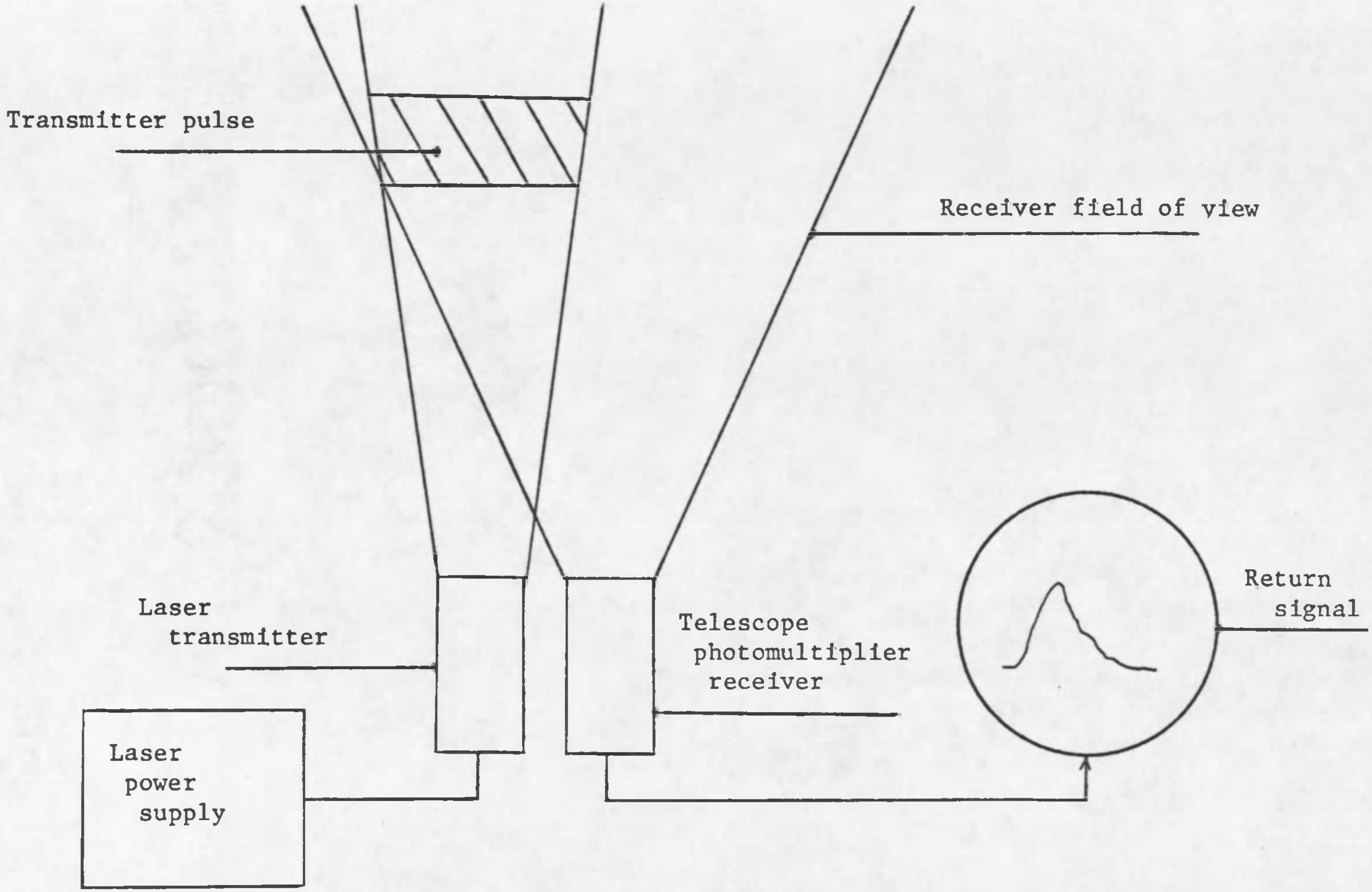


Fig. 1.1 Monostatic Lidar System

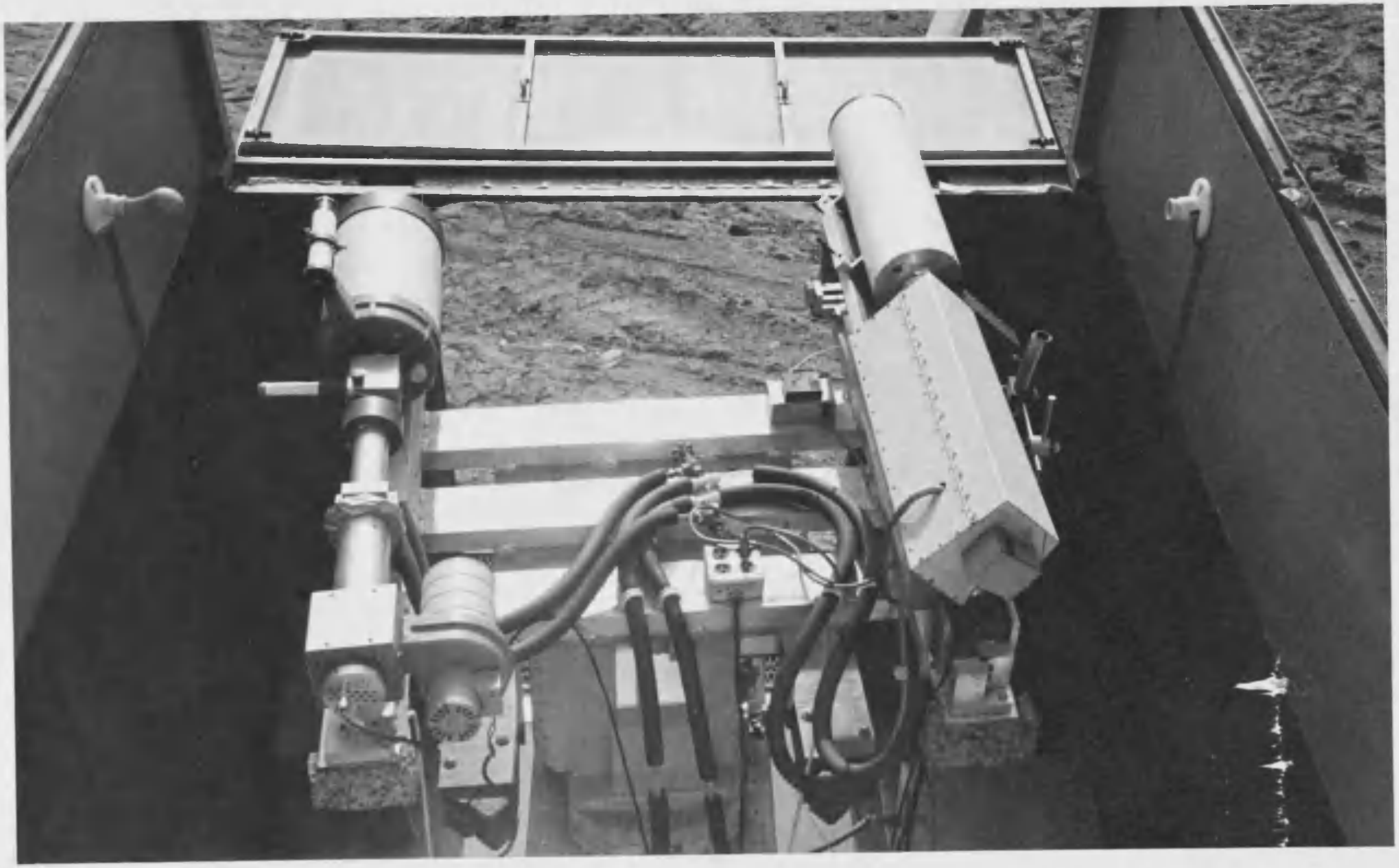


Fig. 1.2 The University of Arizona Monostatic Lidar System

herewith was to produce such an acquisition system for The University of Arizona monostatic lidar system.

1.1 Monostatic Lidar Equation

The theory of optical scattering and transfer and the theory of operation of backscatter lidar are available from many sources [Webster, 1971]. The following discussion is intended to only set down relations important to understanding the characteristics of backscatter lidar return signals. For a monostatic lidar designed to measure only the intensity of the backscatter return signal, such as The University of Arizona lidar, the return signal is due almost entirely to elastic scattering from air molecules and aerosols. The non-elastically scattered component of the backscattered signal, such as Raman scatter, is comparatively negligible. The instantaneous intensity of the backscatter return is proportional to volume backscatter cross-section, β, of the atmosphere at the return height times the two-way atmospheric transmittance to the height. The backscatter cross-section, which is the power backscattered by a unit volume per unit solid angle per unit incident flux, is the sum of the molecular, Rayleigh, backscatter cross-section and the aerosol, Mie, backscatter cross-section, $\beta = \beta_R + \beta_M$.

The monostatic lidar range equation giving the instantaneous received power for a return can be expressed in several different forms. The expression given below is the most useful for actual application [Fernald, 1973].

$$P(r) = ECY(r)\ r^{-2}\ \beta(r)\ T(r)^{2\ \sec\theta} \qquad (1.1)$$

where

$P(r)$ = instantaneous received power

r = range

E = total energy of transmitted laser pulse

C = calibration constant dependent on receiver optics

$Y(r)$ = geometry factor

θ = transmitter-receiver zenith angle

$\beta(r)$ = volume backscatter cross section

$T(r)$ = one way vertical atmospheric transmission

The backscatter cross section and transmission terms contain all dependence on atmospheric parameters. The transmission is often expressed in terms of volume extinction cross section $\sigma(r)$ or the partial optical depth $\alpha(r)$.

$$T(r) = e^{-\alpha(r)} = e^{-\int_{o}^{r} \sigma(r)dr} \qquad (1.2)$$

The geometry factor $Y(r)$ arises from the separation of the transmitter and receiver of a non-coaxial lidar system. Depending on the transmitter beam width, the receiver field of view and the transmitter-receiver separation distance, the transmitted laser pulse will not be totally in the field of view of the receiver until an overlap range, r_o, after which $Y(r) = 1$. $Y(r)$ is important in that the maximum dynamic range of the lidar signal is determined by $Y(r)$. An expression for $Y(r)$, which is a function of the energy distribution shape of the transmitted laser pulse, is given by Reagan [1968].

1.2 Monostatic Lidar Return Signal

Figure 1.3 is a representation of a backscatter lidar return showing the general characteristics found. There is initially no signal until the laser pulse enters the receiver field of view. The signal then increases to a maximum where the increase due to the transmitted pulse entering the field of view is offset by the $1/r^2$ decrease in the signal. At the overlap range the pulse is entirely in the field of view of the receiver and the signal is dominated by the $1/r^2$ decrease of signal intensity. Fluctuation of atmospheric scattering parameters with height appears as a fine structure superimposed on the return. The decay of signal with height is due, in addition to the $1/r^2$ fall off, to the increase of atmospheric and to the decrease of atmospheric backscattering cross section with height from density decrease of atmospheric aerosols and molecules.

Since the factor $Y(r)$ is dependent on the laser pulse shape, which is not well known, the lidar return signal is not usable until full transmitter receiver overlap is obtained. In practice $Y(r)$ is observed to be such that the maximum of the return signal is approximately twice the return strength at the overlap distance. The overlap distance is given by:

$$d = \frac{a}{\theta_r - \theta_T} \qquad (1.3)$$

where

d = overlap distance

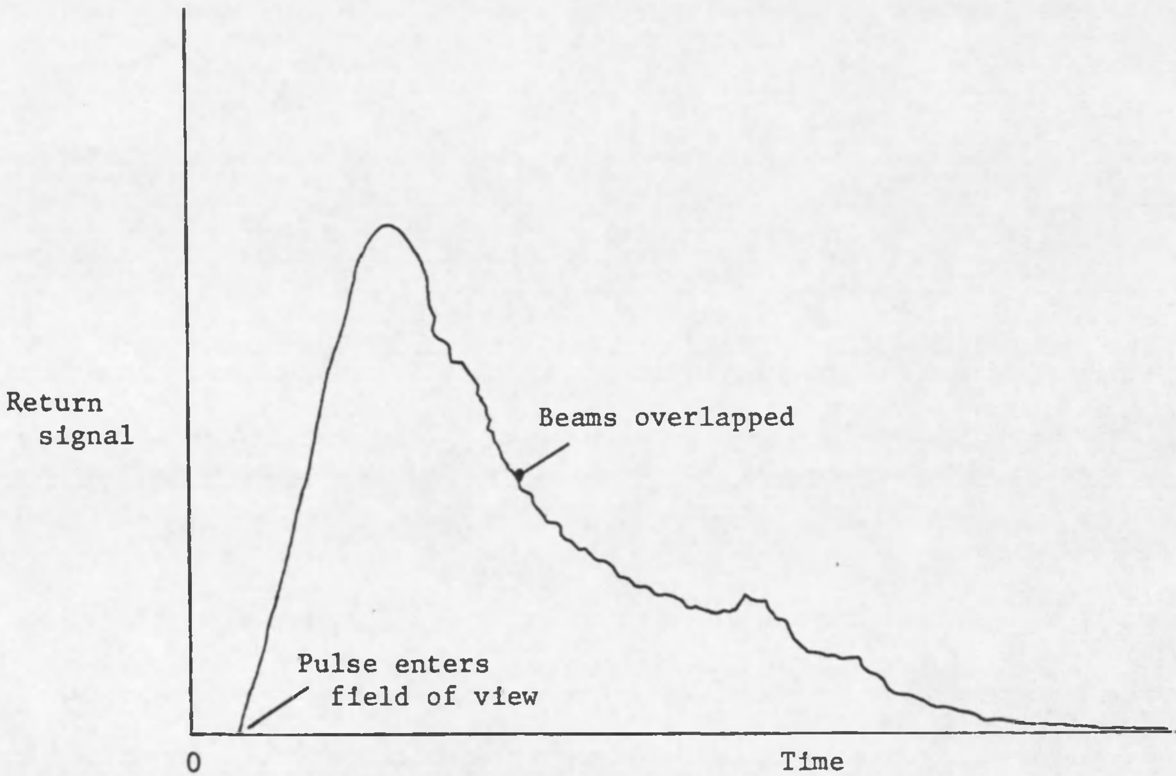


Fig. 1.3 Simulated Lidar Return

a = distance from the inner edge of the receiver aperture to the outer edge of the transmitter aperture

θ_r = receiver half angle field of view

θ_T = transmitter half angle, twice half power, beam width

For The University of Arizona lidar system, a = 1m., θ_T = .75 milliradians, and θ_r is normally 2 milliradians which gives an overlap distance of 800 m. Taking the practical range of the monostatic system as 10 Km. and using standard values of atmospheric cross section and transmission [Elterman, 1968], the decrease of the lidar return from its value at overlap can be estimated as a factor of 2500.

The time to range conversion factor for the backscatter return is 150 m/μs. For a return to 10 km the signal may be considered as a single polarity 67 μs pulse with an approximate rise time of 1 μs. The lowest frequency component of the return signal is DC since the signal is single polarity. Fluctuations of the backscatter cross section with range will superimpose on the return signal a high frequency component with the upper frequency limit being determined by the range integration caused by the physical length of the transmitted laser pulse. For a 20 ns laser pulse, the pulse length is 6 m., and the instantaneous scattering volume will be 3m. in length giving an upper limit of around 50 MHz. to the bandwidth of a return signal. In practice, when less range resolution is required, the bandwidth of the signal receiving apparatus can be the limiting factor for the return signal bandwidth.

The optical lidar return signal is converted to an electronic signal by means of a photomultiplier tube (PMT). The PMT acts as a current source with an output given by:

$$I_A = \mu\delta_K P_r \tag{1.4}$$

where

I_A = anode current

μ = current amplification factor

δ_K = photocathode sensitivity (amp/watt)

P_r = received optical power

The current signal is converted to a voltage by a load resistor chosen typically to match the impedance of a transmission cable. A photomultiplier tube is used as the detector since it combines high gain, μ is typically 10^6 - 10^7, with high bandwidth, typically DC to 50 MHz. A PMT is not, however, a perfect detector in that it adds a noise component to a received signal. Noise generated by a PMT has several sources but, except for very weak signals, is primarily due to signal shot noise. The signal related shot noise is given by

$$i_{RMS} = \mu[2e\ \delta_K\ P_r\ \Delta f]^{1/2} \tag{1.5}$$

where

i_{RMS} = rms anode shot noise

e = charge of an electron

Δf = bandwidth of the detecting system

The noise generated by the receiving PMT will be a significant component of a lidar return signal. Although the signal-to-noise ratio may be better than 50:1 for the return from 1 km, at only 5 km it would decrease to 2.5:1.

1.3 Acquisition of the Lidar Signal

Electronic acquisition of a monostatic lidar signal will consist basically of analog-to-digital conversion of the return signal and storing of the digital information. The first problem that presents itself is the speed of the return signal. To obtain even moderate range resolution, high A/D sampling rates are required. High A/D conversion rates can be expected to mean a low bit resolution of A/D conversion. With low A/D resolution it will not be possible to accurately acquire the wide dynamic range lidar signal directly. Some means of compressing the dynamic range of the return signal must be used. Relatively slow A/D sampling and low A/D resolution also means the distortion of the signal from A/D conversion will be significant. Such distortion will be considered later.

A complete acquisition system for monostatic lidar must record more than just the signal return. As seen from the range equation, the total energy of the transmitted laser pulses and the beam zenith angle should be monitored and recorded. Instrument settings such as gains and sampling rates need to be recorded, and recording of additional data, time and date of experiments for example, is also desirable.

CHAPTER 2

ACQUITISION SYSTEM

A data acquisition system for backscatter lidar signals will consist of the following parts: analog electronics to amplify and compress the signal, an analog-to-digital converter, and digital electronics for recording the signal. The primary consideration in building such an acquisition system is the accuracy with which the signal is recorded. For The University of Arizona lidar, it was desired to build a system that could record a single lidar signal to within 3% accuracy. Also, the system was to record all necessary data automatically to allow rapid data analysis and avoid human error. An additional goal was to make the construction of the acquisition system as simple as possible by making maximum use of available commercial instrumentation. Simplicity was desired not only to minimize construction costs and effort, but also to increase reliability.

2.1 Basic Design

Figure 2.1 shows a block diagram of the data acquisition system. In keeping with the goal of system simplicity, a Biomation 610B transient recorder was chosen to serve as the major component around which the rest of the data acquisition system was designed. Transient recorders have been used by other lidar research groups [Fox and Eloranta, 1972]. The transient recorder functions as a digital recording and

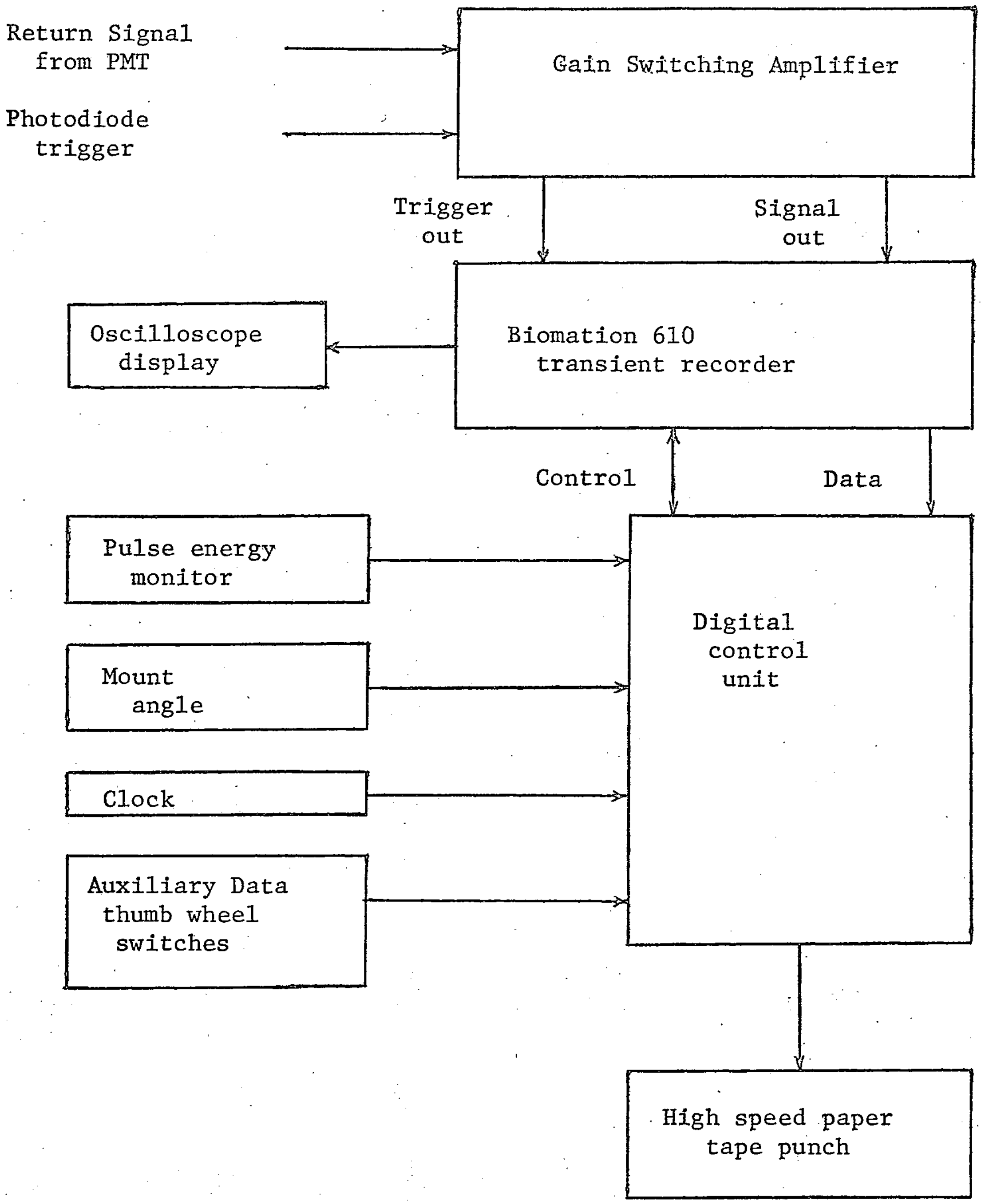


Fig. 2.1 Acquisition System

storage device for analog signals. The operation of the Biomation recorder is highly versatile in that it is self triggering, has a variable voltage sampling range and a variable sampling rate, and can store internally and then display on an oscilloscope a recorded waveform for as long as necessary. A recorded signal can be read out of the recorder in digital form and stored on some permanent medium, paper tape in the case of the acquisition system.

As the high speed Biomation recorder has only 6 bit A/D conversion capability, an accurate means of compressing the wide dynamic range of the lidar signal is especially necessary. A gain switching amplifier was chosen as the most straightforward and accurate means of signal compression. The signal from the photomultiplier tube is fed directly into the gain switching amplifier. The switching amplifier increases the gain on the signal in discrete steps as the level of the lidar signal falls off. The gain increases maintain the signal level in a range that can be accurately handled by the A/D converter. The gains of each of the amplifier stages are fixed values that are accurately known when the signal is processed.

The Biomation recorder contains timing and control logic for the A/D conversion and high speed digital recording of the lidar signal. The additional digital electronics needed for the acquisition system serve to load the acquired signal, plus other necessary data, onto the paper tape storage medium. The acquisition system includes digital readouts of the laser pulse energy, beam zenith angle and time. In addition, there are thumb wheel switches for entering the sampling rate and gain of the Biomation recorder. Schematics of all circuits designed for the acquisition system will be found in Appendix A at the end of the paper.

2.2 A/D Conversion

The Biomation transient recorder (shown in Fig. 2.2) used for A/D conversion of the lidar signal has 6 bit accuracy which allows a signal to be quantitized into 64 levels. The A/D converter in the transient recorder is preceded by a variable, fixed gain amplifier allowing the signal range of the recorder for A/D conversion to be varied from .05 to 50 volts. The threshold voltage of the A/D conversion window can be offset from zero to $\pm$ the voltage range set for the input amplifier. In addition, the recorder is equipped with a differential signal input, and the signal can be inverted or AC coupled.

When triggered, the transient recorder samples and stores 256 points from the input signal waveform. The sampling interval can be varied from .1 μs to 5 ms. Triggering, to initiate sampling and recording of a waveform, is similar to that of an oscilloscope. The unit can be triggered either internally on the signal to be recorded or on an external signal. The triggering mode can be adjusted for single triggering, in which case the unit must be manually rearmed to capture another signal, or normal triggering for which the unit rearms itself.

Dynamic shift registers are used in the Biomation recorder to store a recorded signal. As the signal is circulated in the memory, it is D/A converted and available for continuous display on an

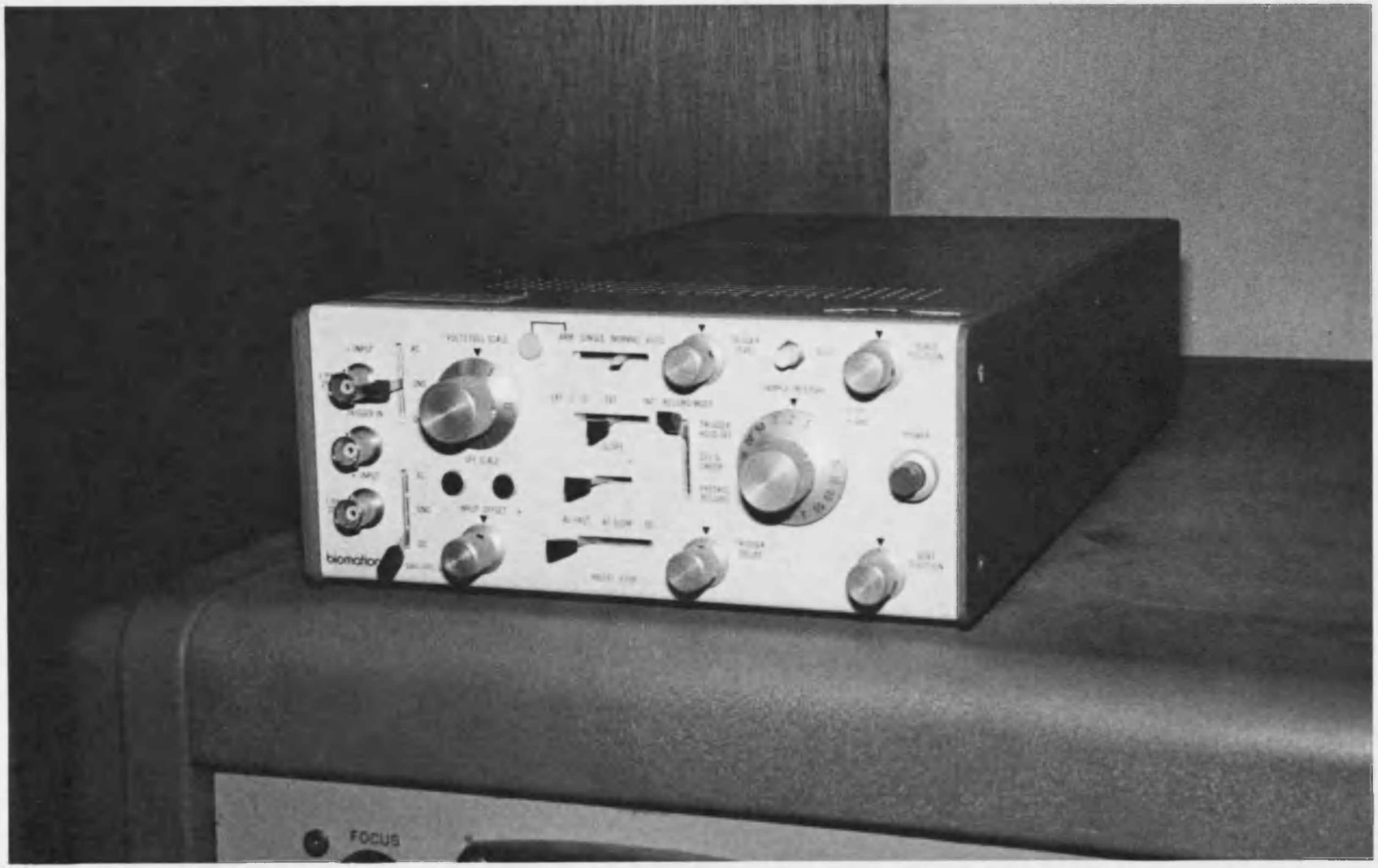


Fig. 2.2 Biomation 610B Transient Recorder

oscilloscope. The recorder provides the signal to drive the horizontal sweep of the scope, but only the first 200 points of the recorded signal are available for display on the oscilloscope.

For recording a lidar signal, it is necessary to trigger the recorder at the time the Q-switched laser pulse is initiated. In order to do so, the negative going pulse from a photodiode mounted behind the rear reflector of the laser is used to externally trigger the transient recorder. Due to the speed and length of the lidar signal, only two signal sampling rates are of practical use for recording most lidar signals, namely, .2 and .5 μs. The range resolution and total range for recording a lidar signal at these sampling rates are 30 m and 7.65 Km, and 75 m and 19.125 Km, respectively.

The speed of the lidar signal also limits the usable input voltage ranges for the transient recorder. Below the 2 V input range, the bandwidth of the input amplifier of the Biomation recorder decreases from its maximum of 2.5 MHz. By the sampling theorem, the least distortion is caused in digitizing a wave form if the signal is band limited at one half the sampling frequency. When sampling at 5 MHz, the bandwidth of the input amplifier to the A/D converter thus needs to be maintained at its maximum by keeping the input voltage range equal or above 2 V. Of course, limiting the voltage sampling range is useful only if the bandwidth of other signal processing electronics is maintained above 2.5 MHz.

2.3 Digitization Error and Signal Compression

In recording a single lidar return with 6 bit accuracy, the major source of error will be that due to digitization of the continuous signal. The maximum digitization error possible for a signal $V(t)$ at a given time, t, is $\Delta V/V(t)$ when ΔV is the digitization voltage increment. The digitization error acts in theory, assuming perfect A/D conversion, as additive random noise on the digitized signal and can be reduced by averaging. However, with the inherent slow pulse repetition rate of a ruby laser lidar system, only a relatively small number of return signals can be averaged together, and it is important that $V(t)$ does not become small with respect to ΔV if accuracy of signal acquisition is to be maintained. Since the lidar return signal strength varies by over three orders of magnitude and only 6 bit digitization is available, a means of signal compression is a necessity for accurate acquisition of a lidar signal.

One means that is widely used for compressing range decreasing signals is a logarithmic amplifier. The logarithmic amplifier, however, is not usable with low accuracy A/D conversion. The gain of the logarithmic amplifier is known only by its output voltage level which, when the logarithmically compressed signal is digitized, results in severely expanding the digitization error of the signal. It can be shown that the maximum digitization error resulting from using a logarithmic amplifier with A/D conversion is $|1-10^{D/n}|$ where n is the number of digitization levels and D is the number of decades of signal compression.

For our case of 64 levels and 3-1/2 decades, the maximum error would be 14%.

An alternate method of signal compression that has been used by other lidar researchers [Frush and Schuster, 1972] is gain switching. By using a gain switching amplifier for signal compression, the gain is a fixed value known by knowing which gain stage is activated, and the maximum digitization error is $\Delta V/V_s(t)$ where $V_s(t)$ is the output of the gain switching amplifier. The gain switching amplifier considered here was designed so that the gain is increased when the signal falls below a given level, V_o, thus maintaining $\Delta V/V_s(t)$ at a satisfactory level. As the signal does not fall below V_o, the 64 level A/D conversion window can be offset to V_o, effectively reducing $\Delta V/V(t)$. Figure 2.3 is a representation of the technique used. If the gain is multiplied by a factor A for each gain switch, the upper level for the digitization window needs to be greater than A x V_o. The amount greater than depends on the magnitude of fluctuations on the signal. In practice, a value of 3.01 was used for A. With a two volt A/D sampling window, .8 volts is a satisfactory value for the offset voltage. These values give a maximum single shot digitization error of about 3%. Changing the gain by a factor of three requires eight gain stages to cover the dynamic range of the lidar signal. The gain from the first to last stage thus changes from 1 to 2239.

2.4 Gain Switching Amplifier

Accurate operation of the signal compression amplifier is highly important to the performance of the data acquisition system.

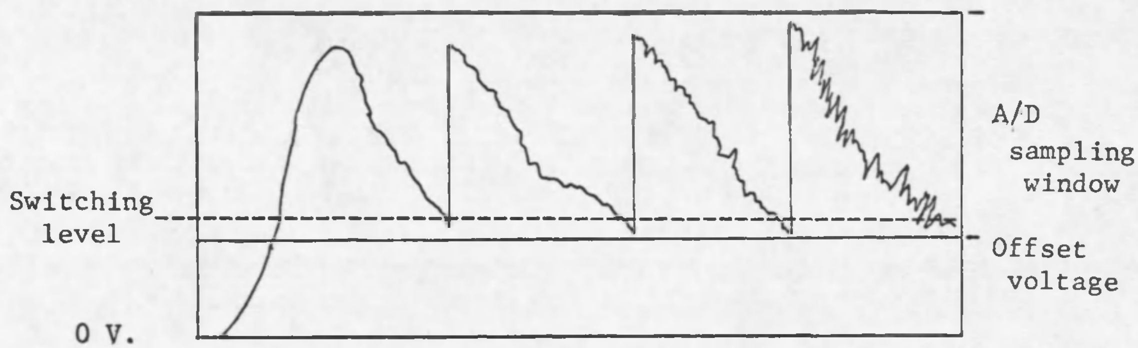


Fig. 2.3 Signal Level Switching Mode

Errors in signal compression will not average out when data is processed and will have a significant effect on final results. There are several important considerations for the proper functioning of the gain switching amplifier. The amplifier should have sufficient band width at all gains to avoid distortion of the signal. The gain of each stage must be accurately known. The gain stages must switch and settle rapidly so that only a small part of signal is lost due to switching. All stages must also be well balanced so that the DC offset of the amplifier doesn't change as the gain changes. The last consideration is especially important because as the gain changes from 1 to 2239, an offset due to say a ground loop or temperature drift which may initially be unnoticeable, can completely swamp the signal in the final stage.

A gain switching amplifier is basically an op amp or op amps with several feed back and/or input resistors which can be electronically switched. The standard method of designing gain switching amplifiers is to use FET switches to change resistance networks. However, due to the resistance and capacitance of FET switches, designing an accurate, high-speed, gain switching amplifier with small switching transients using FET switches is a difficult matter. Instead, to simplify design and improve performance, a gain switching amplifier was constructed using a unique, monolithic programable operational amplifier made by Harris Semiconductors (Model 2405). The Harris 2405 amplifier is an operational amplifier that has four sets of differential inputs and one output. By a two bit logic signal, any one of the four inputs can be selected with the other three inputs being isolated. With proper compensation, the amplifier can switch and settle in less than 1 μs, without appreciable transients. The 8 MHz unity gain bandwidth and moderate temperature stability of the HA 2405 are adequate for the purpose of amplifying a lidar return.

The configuration used to construct the gain switching amplifier is shown in Figures 2.4 and 2.5. Two HA 2405's are used to obtain eight stages of gain. The first stage switches the gain by a factor of 3.01 while the second stage switches gain by factors of 3.01^2 so that the gain can thus be changed from 1 to 3.01^7 in multiples of 3.01.

The programmable operational amplifiers are connected as voltage followers to switch in and out other amplifiers which provide the needed gain. There are two reasons for doing so. First, the unity gain bandwidth of the programmable amplifiers is 8 MHz, and to maintain an overall needed bandwidth of 3-4 MHz, gain must be provided by higher speed auxiliary amplifiers. The other reason is that by having a separate input amplifier to each input of the programmable amps, the DC offset can be separately adjusted. The symmetrical configuration also allows the relative effect of offset drift between stages to be minimized. An amplifier follows the second switching stage so that the overall gain and offset of the amplifier can be adjusted. A line driver for the output is necessary since the integrated circuit operational amplifiers are unstable under the capacitive load of a signal cable.

The HA-2625 monolithic operational amplifiers used for the gain stages were chosen for their 100 MHz gain bandwidth product and

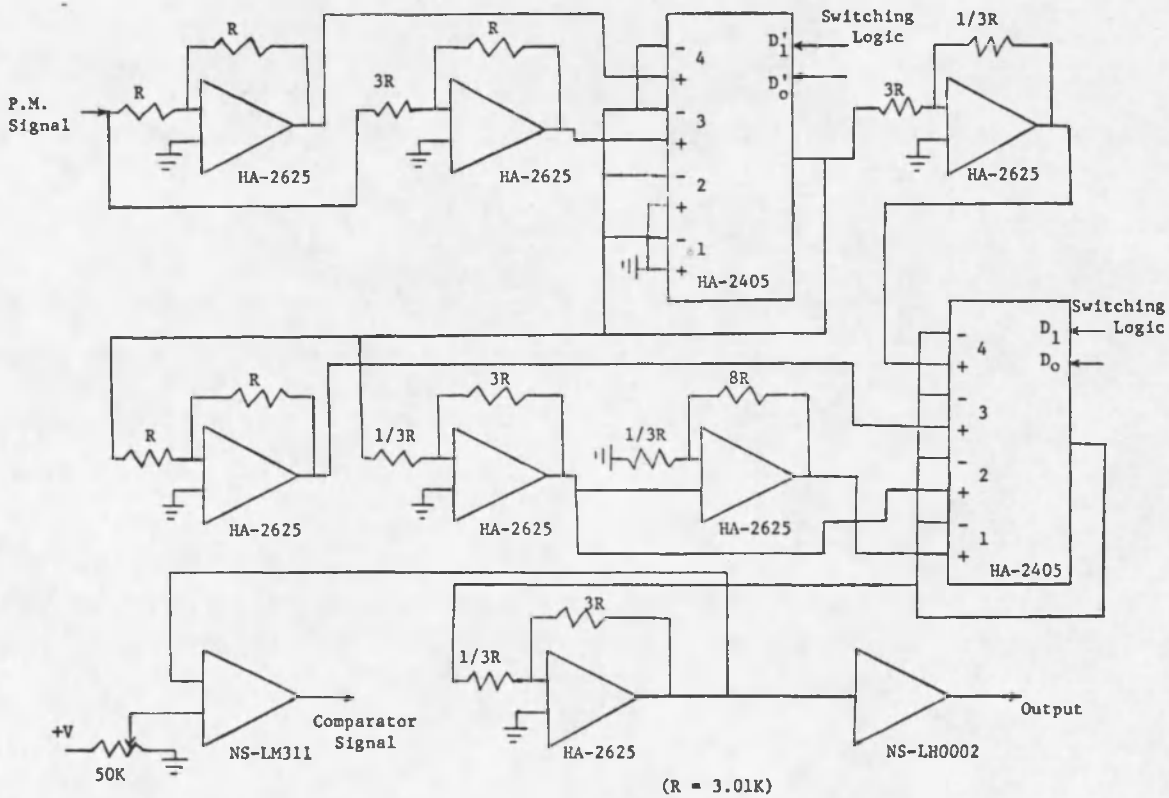


Fig. 2.4 Gain Switching Amp

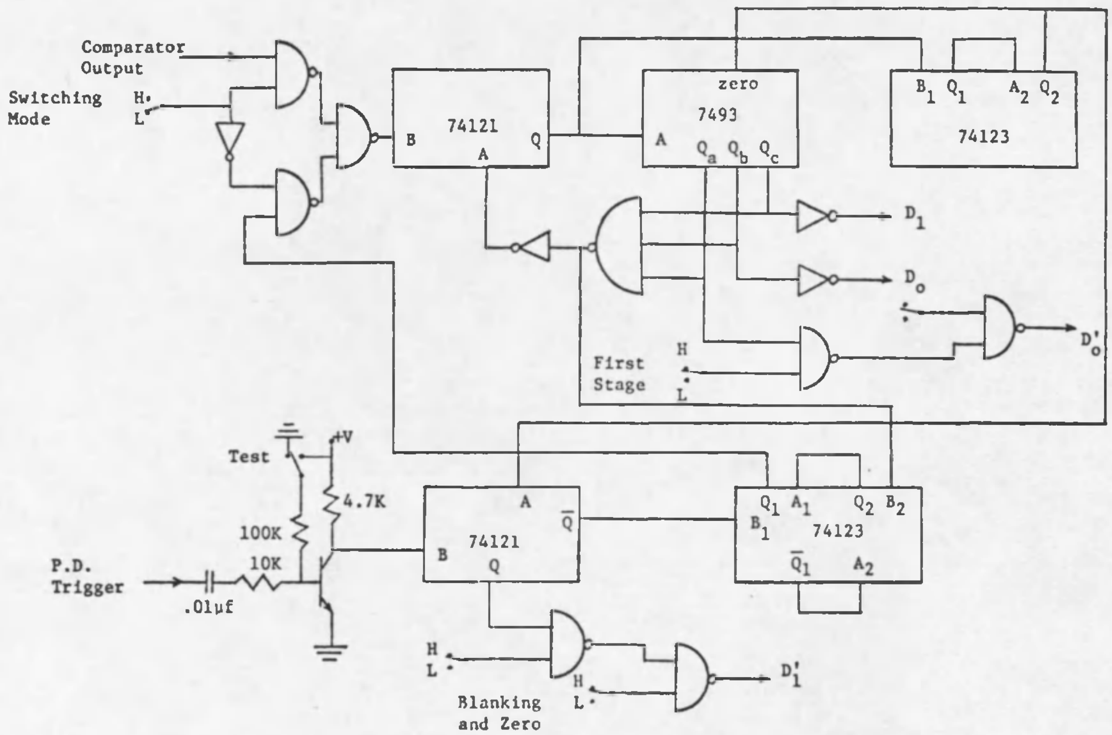


Fig. 2.5 Switching Logic

relative low cost. At a gain of nine, the HA-2625's were measured to have a bandwidth of 9 MHz. For a cascade of five amplifiers of equal bandwidth, the overall 3 db bandwidth is reduced by a factor 2.5 from that of the individual stages. The resultant bandwidth of the gain switching amplifier is therefore 3-4 MHz on all stages. To give sufficient accuracy of gain, the feedback resistance ratios for the operational amplifiers were chosen within .01%.

For amplifying a lidar signal, the gain switch must be controlled to sequentially increase the gain with time. The circuit which drives the logic inputs of the programmable operational amplifiers to sequence the gain is shown in Fig. 2.5. Standard TTL logic was used to implement the circuit. A 7493 counter provides the sequential signal to drive the programmable operational amplifiers. The counter is driven from a 74121 monostable multivibrator which may be activated in either of two manners. A comparator sensing the output of the gain switching amplifier allows the gain to be increased whenever the output signal falls to the set level. This is the normal mode of operation for data acquisition purposes. The stages can also be switched sequentially by a fixed time delay generated by a 74123 dual monostable multivibrator. In the time delay mode, the sequencing must be initiated by a trigger signal. The trigger circuit is set up to operate off the rear photodiode of the laser. An output trigger signal is generated for triggering other equipments. When the counting sequence has reached the highest gain of the amplifier, further incrementing of the counter is inhibited, and after a sufficiently long time delay, a pulse is generated, by a 74123, to reset the amplifier to initial conditions. An additional feature is that the first stage of the switching amplifier can be controlled by a pulse generated after receiving a trigger signal to allow the input to the gain switching amplifier to be initially zeroed, or blanked. The initial portion of a lidar signal, before the beams are overlapped, can thus be removed to decrease the dynamic range of the signal.

Since it is important that all stages of the switching amplifier have no DC offset, the switching logic was designed to automatically cycle through the gain stages when a level of the time delay circuit is switched. Another switch allows the input to be grounded for testing purposes. If it is desired to use four gain stages instead of eight, an additional control is provided to prevent switching of the first stage of the amplifier.

Due to the close proximity of an operating Q-pulsed ruby laser, the environment in which the gain switching amplifier must operate is, electronically, extremely noisy, and necessary precautions must be taken to prevent this noise from entering the analog circuits. Noise from the laser has two sources, a 1000 amp peak current pulse driving the flashlamp and a 5 KV, 10 ns risetime pulse driving the Pockel's cell Q-switch. The Pockel's cell pulse is a source of high frequency electromagnetic radiation which can be eliminated only by double shielding all signal cables and enclosing circuits in a grounded metal chassis. The ground circuit for the laser and signal electronics must be isolated, except at earth ground, to prevent flash tube ground currents from flowing in the signal grounds. Ground loops through the signal cables must be eliminated, and grounds must be returned to earth ground at a single point. No signal cable shield can be allowed to carry ground currents.

2.5 Digital System

Digital electronics are required to interface between the data sources and the paper tape punch. The design of such a digital system is straightforward. The major problem associated with building the paper tape digital system was the actual physical construction of the circuits so that operation was reliable and immune to external noise sources. All digital circuits with the exception of the digital clock were constructed using standard TTL logic.

In addition to storing the digitized lidar return in the transient recorder, information on the laser pulse energy, transmitter elevation angle, signal sampling rate, signal gain and time of observation need to be loaded onto the tape for each shot. The laser pulse energy is obtained by integrating the output of a photodiode which samples the laser pulse. The peak of the integrated laser pulse, which is proportional to pulse energy is detected and A/D converted to provide a three digit BCD readout of the pulse energy. The source for the time is a digital clock constructed from a MOS LSI integrated circuit. The mount angle is obtained from IC up-down counters operated through reed switches driven by a magnet attached to the mounted drive mechanism. All additional data are loaded through thumb wheel switches.

A block diagram for the basic layout of the digital circuitry is shown in Fig. 2.6. There are two central circuit boards, one which provides timing and control signals and one which gates data from various sources onto the paper tape punch. Additional boards consist of various information sources and are parallel to serial shift registers for loading and transferring data to the data flow board.

The recorded waveform stored in the transient recorder is punched onto the tape ahead of the auxiliary data. Data recording is initiated by switching the transient recorder into the data output mode. Data words are transferred out of the transient recorder in 6 bit parallel form. Transmission of data out of the transient recorder involves three signal lines. When data transmission is initiated, the "write" signal goes high and remains high until transmission is completed. "Write" is used to gate the output registers of the transient recorder into the input register of the paper tape punch. When a data word is available in the output register of the recorder, the "flag" signal line goes high and the control board will issue a pulse on the punch request line of the paper tape punch. After the data word has been punched, as indicated by the busy-done line of the tape punch, the "stroke" line of the transient recorder is pulsed which causes the next data word to be placed in the recorder output register.

After all the data from the transient recorder have been punched, the auxiliary data are loaded into shift registers by a "set" pulse issued by the control board. The data are shifted 4 bits at a

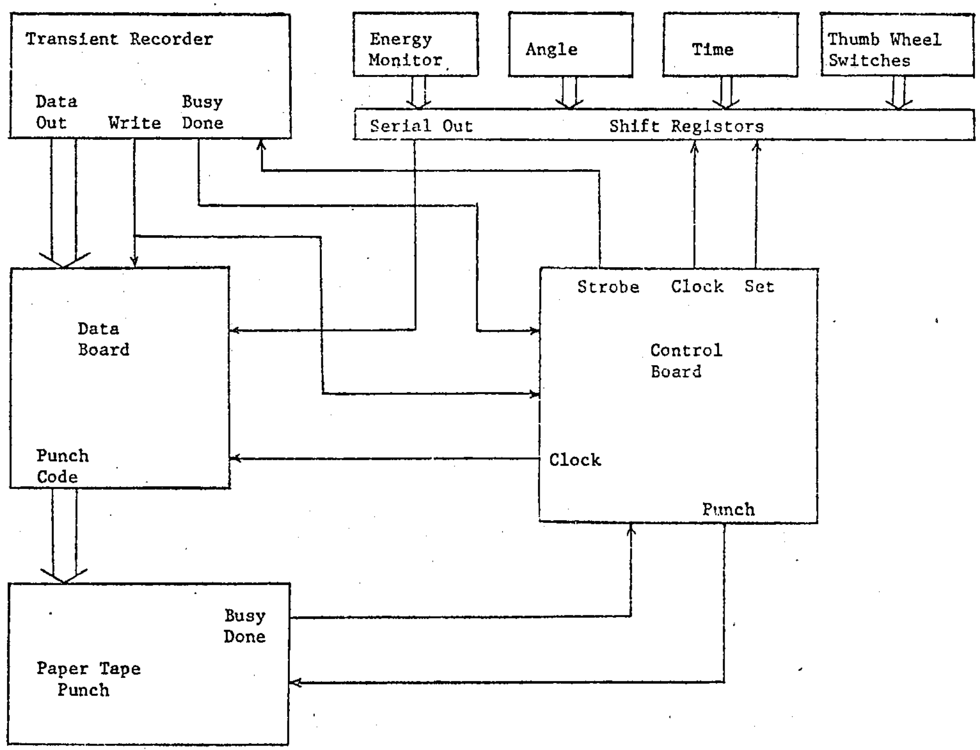


Fig. 2.6 Digital System

time into a serial to parallel register which is gated into the input register of the tape punch. The control board issues the proper number of shift and punch sequences to complete loading of the auxiliary data onto the tape. As an additional means of loading data onto the tape, a switch is provided for punching the BCD number encoded on a thumb wheel switch onto a single frame of the tape. This allows such things as date or the surface level temperature and pressure to be punched onto the tape after a run is completed.

Data is punched onto the tape in 6 bit with seventh odd parity bit format. The parity bit is provided by a parity generator in the data flow board. The parity generator is set up so that an even parity frame will be punched whenever there is a mispunch. The data words of the transient recorder are in 6 bit binary form, but the auxiliary data is punched out as 4 bit BCD numbers, one to each frame. Of the 256 data words recorded by the transient recorder, only 255 are punched on the tape, the first word not being available. The computer used for data reduction reads paper tape 150 frames at a time, and to simplify programming, the digital electronics were set up to punch 300 frames for each shot, thus leaving some frames on each record which are not used. One of the blank frames is used for punching a code indicating that a record is the last one of a given data run.

The operation of the digital electronics is controlled from a panel containing the necessary readouts and switches. LED readouts are used to display the energy monitor reading, angle, time, and a direct two digit octal readout of the output register of the transient recorder for use in setting the baseline of the A/D converter. A count is made of the number of shots taken during a data run, and this is also displayed. Associated with each readout is a switch or switches for setting the particular function to initial conditions. The angle readout can be switched to display either the horizontal or zenith angle.

At the end of a data run, it is necessary to punch a 7 hole leader on the end of the tape to pad out the data so that a parity error won't be returned when the last record is read. A switch on the control panel allows the punch to be operated in either the normal run, punch leader, or single punch mode. In the single punch mode, toggling the single punch switch on the control panel causes the number loaded on the fourth thumb wheel switch to be punched on the tape. For the last record of a data run, the last punch switch is thrown to give the computer a means of recognizing the end of the tape.

Punching a record is initiated manually by pushing the data output button on the transient recorder. The transient recorder was modified so that the data output switch could be actuated by an external signal to allow data recording to take place automatically after the laser fires. The "auto-manual" switch on the control panel allows data recording to be initiated either manually or automatically. In the auto mode, a record is run several seconds after the laser fires. Throwing the switch to manual before a record is punched will block the automatic initiation of a record even if the laser has just fired.

The major problem associated with building the paper tape digital system was preventing improper operation caused by external electronic noise. Noise affecting the digital electronics is of two types, ground noise and power line noise. Both types of noise were a problem since the lidar data acquisition system operates in a remote location with many noisy devices (relays, motors, laser, etc.) tied into a marginal power distribution and ground system. Line noise was handled by installing a commercial line filter on the AC line of the logic power supply. Ground noise is especially a problem with TTL logic. Eliminating ground noise problems required installing a separate earth ground for the data acquisition system that was isolated from the AC power ground of the lidar trailer. In addition, all logic ground lines were made with heavy wire and were returned to the logic power supply at a single point.

2.6 Data Reduction

The purpose of the automatic data acquisition system is to greatly simplify and speed up the production of processed data, but to do so, the raw data on paper tape must be transformed into usable form. For each signal return the gain switching must be corrected for and the signal normalized relative to the pulse energy. When data are collected, more than one shot is generally taken at a given angle and time, and one is interested in the average value of the returns, which must be computed.

The paper tapes are processed on The University of Arizona CDC 6400 computer. The program written to process the tapes reads the tapes into the computer, checks for errors and edits any which occur, normalizes and averages the returns and outputs the processed data. The format of the data as it appears on the tape is shown in Fig. 2.7. The tape is read into the computer with a "Buffer in" operation. The frames (one data word or one row of holes across the tape) are read in with several frames packed into a central memory word and must be separated with shift and mask operations.

In processing, the data words from the transient recorder are first changed to signal voltages by multiplying by the digitization voltage step and adding the offset voltage. Gain switches are found by comparing the ratio of successive data points of the signal return. The increase in the signal from a gain switch is greater than any natural increase of the signal. When a gain switch is detected, the signal is divided by the increased gain, and it is also necessary to throw out data points that were taken while the gain was switching. Each shot is normalized by dividing by its energy monitor reading. After the returns are reduced, the average and variance of shots taken at the same angle are computed. The processed data are printed out and stored on a magnetic tape for future use.

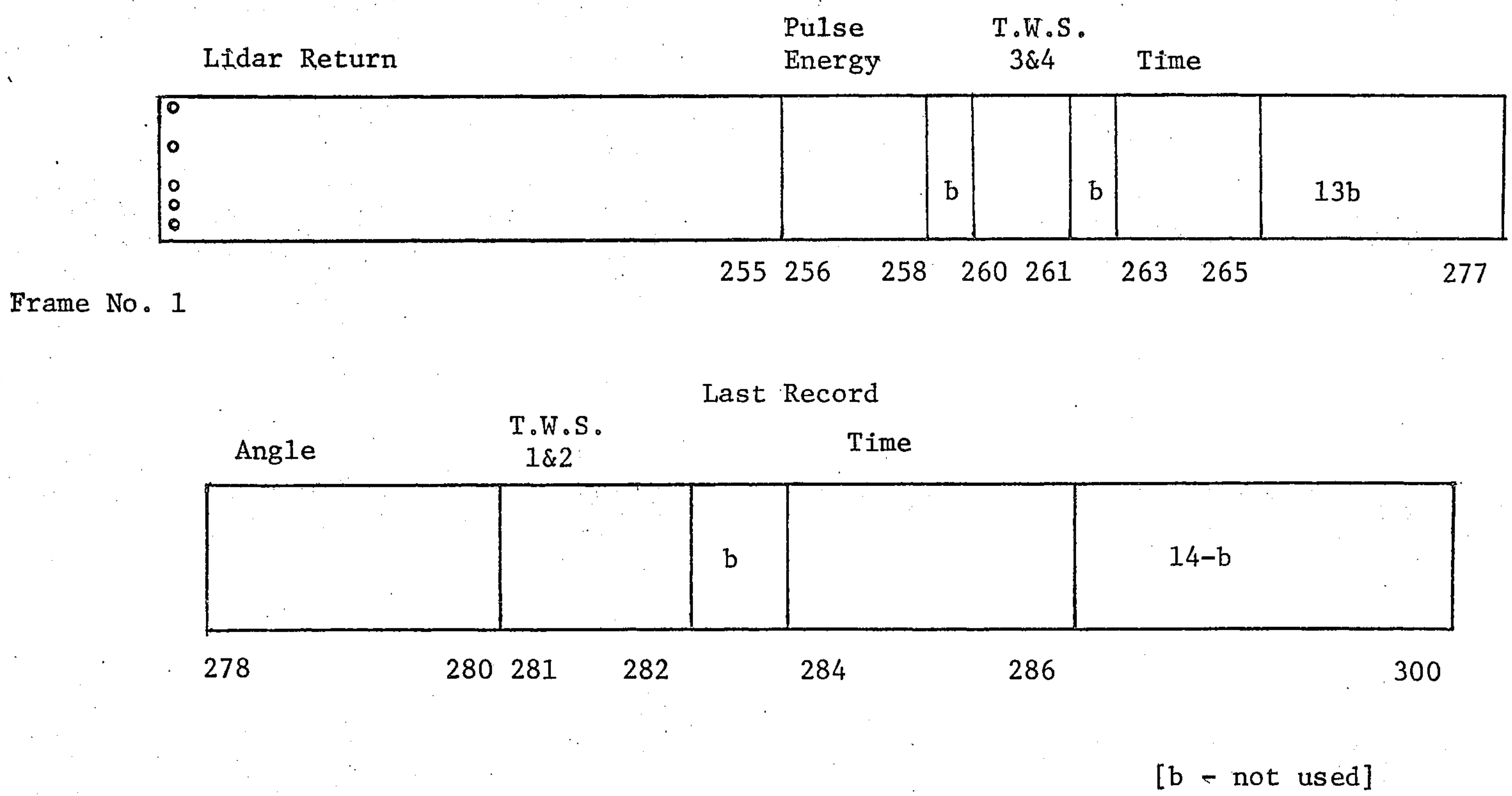


Fig. 2.7 Tape Format

CHAPTER 3

CONCLUSIONS AND ERROR DISCUSSION

The lidar data acquisition system is installed at The University of Arizona monostatic lidar trailer (Fig. 3.1), located at The University of Arizona Campbell Avenue Farms. The acquisition equipment is mounted in a standard 19" rack chassis as shown in Fig. 3.2. The oscilloscope below the transient recorder is used to display the recorded returns. The paper punch used is a Roytron model #500. Above the punch is the chassis containing the necessary power supplies and above that a standard card rack holding the digital circuit boards. On the central control panel are mounted all switches for operating the acquisition system plus the necessary readouts and the input for the energy monitor electronics.

The gain switching amplifier shown is the second model to be built and is mounted in a slide-out rack for ease of adjustment and servicing. Figure 3.3 is an oscilloscope trace of the output of the gain switching amplifier for a typical return using the level switching mode and a per stage gain change of three. A portion of the non-gain switched return is also shown in Fig. 3.3. Figure 3.4 gives a range compensated (multiplied by the range squared) graph of the average of sixteen vertical returns which were recorded by the acquisition system on January 29, 1974 at 9:00 p.m. The error bars in Fig. 3.4 denote the rms deviation of the returns.

Fig. 3.1 Monostatic Lidar Trailer

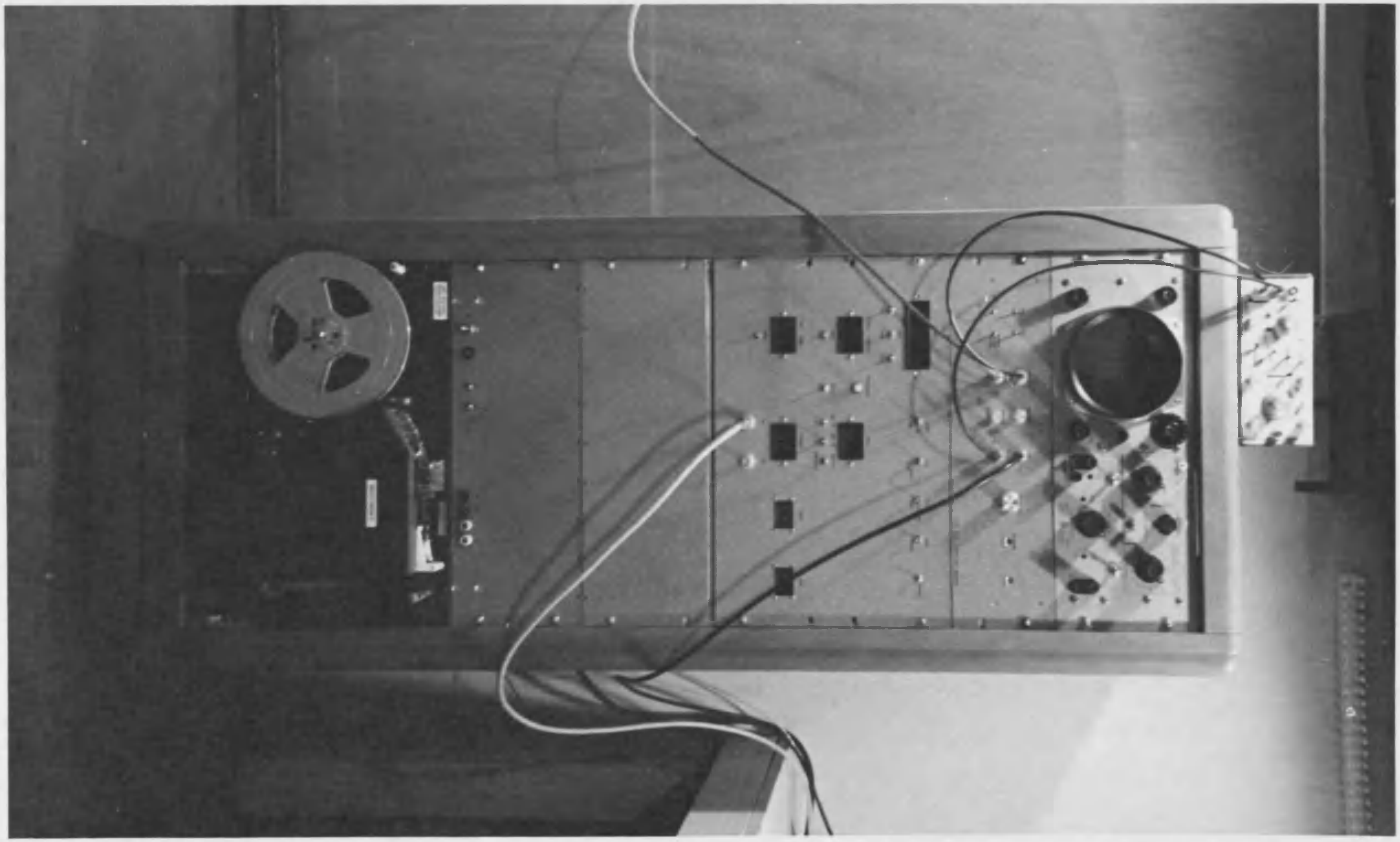


Fig. 3.2 Data Acquisition System

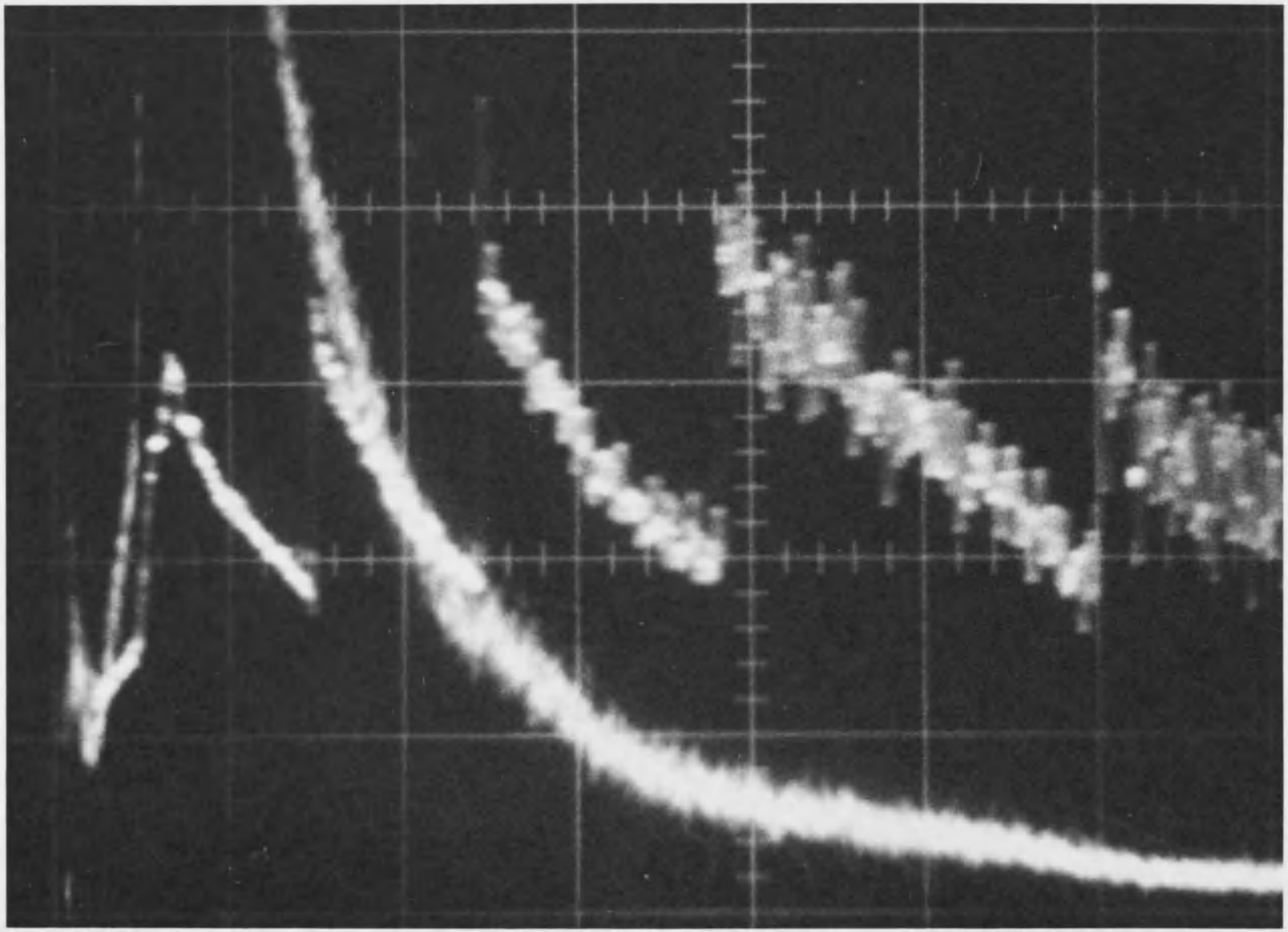


Fig. 3.3 Lidar Return

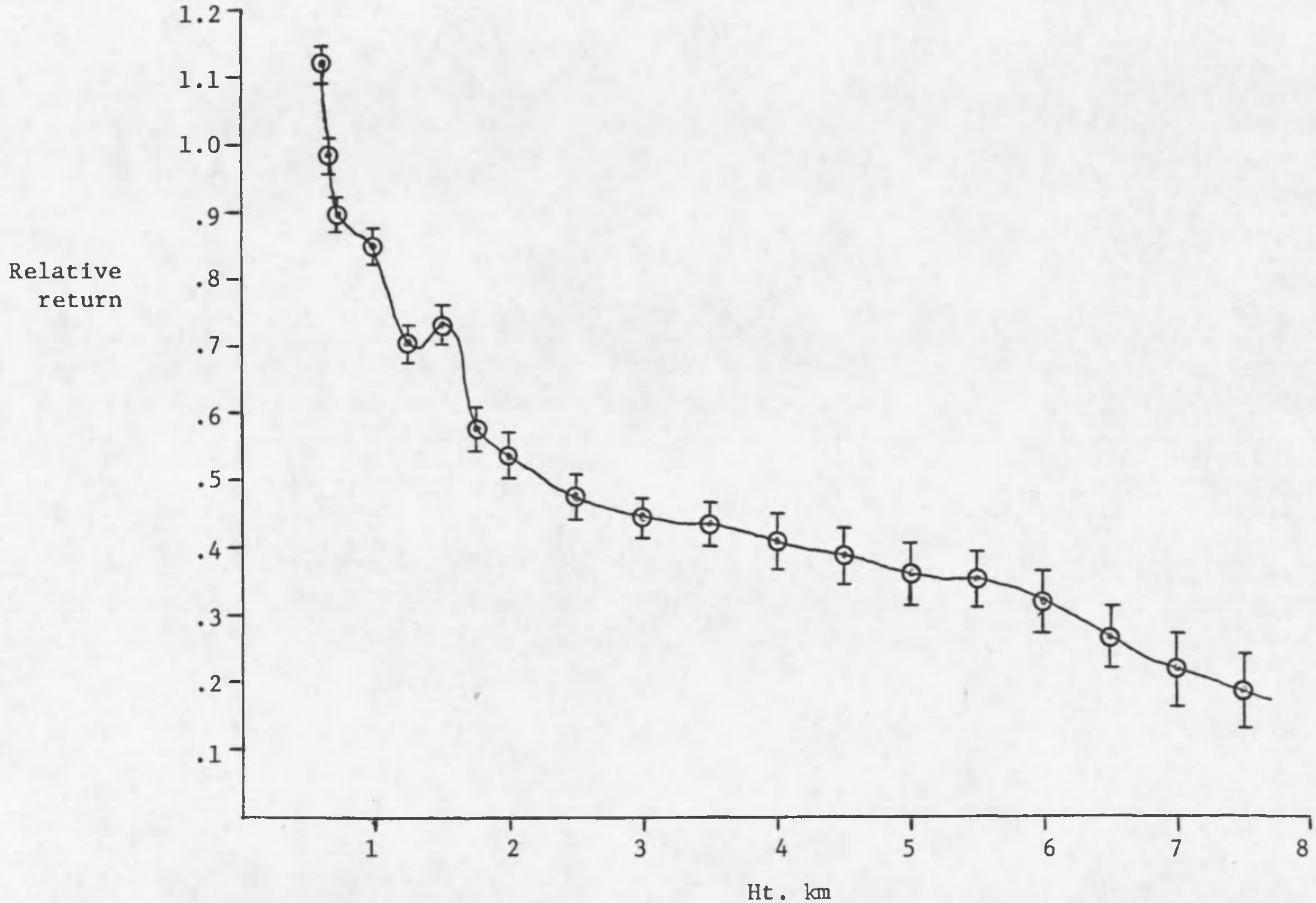


Fig. 3.4 Vertical, Range Compensated Lidar Backscatter Return, January 29, 9 p.m.

In its present form the acquisition system has proved to be capable of recording large numbers of lidar returns reliably. A single return can be recorded and punched in six seconds which is compatible with a realistic pulse repetition rate for the ruby laser.

3.1 Error Discussion

For most applications of lidar return data, one would be interested in the error associated with the measured signal return. Both random and systematic error may be associated with a return signal. Random errors are any type of noise on the signal that is reduced statistically by averaging multiple returns. Photomultiplier noise is an example. Systematic errors are errors such as improper calibration of instruments and are not reduced by averaging returns.

Due to scattering fluctuations caused by the motions of the molecular and particulate scatterers, there will be a noise component associated with the optical lidar return. However, as shown by Mackinnon [n.d.], the variance due to scattering fluctuation is insignificant. As given before, the variance due to shot noise of the PMT is proportional to the received power and to the bandwidth of the detecting system. Figure 3.5 displays a plot of the expected signal-to-noise ratio of a standard return which is assumed to be noise limited by signal shot noise (i.e., typical of nighttime operation).

For daylight operation of the lidar system, the effect of background radiation must be considered. Background radiation will cause both a DC offset of the PMT output and an added noise component on the signal from the shot noise associated with background light. The laser

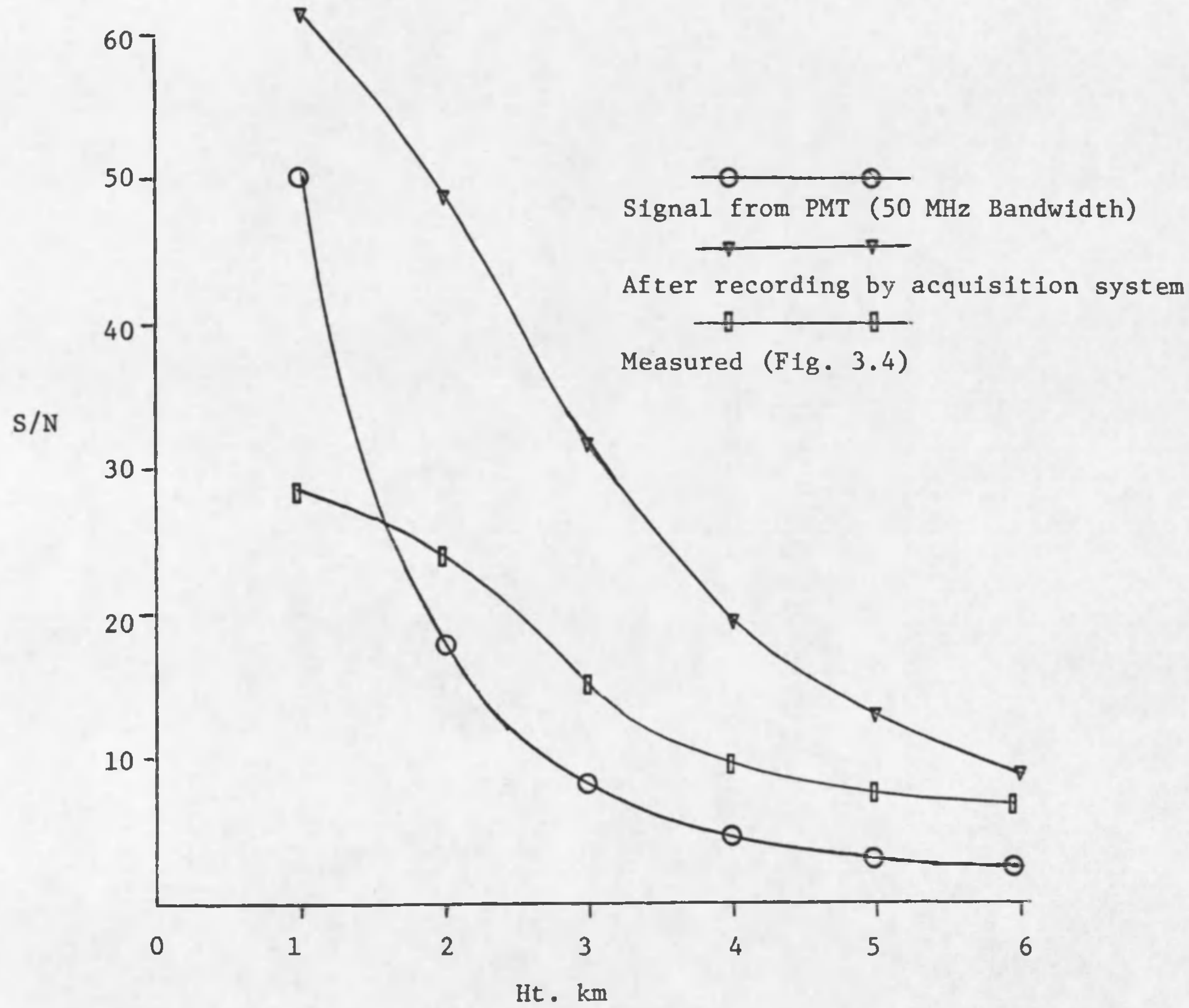


Fig. 3.5 Lidar Return S/N Ratio (Night operation)

receiver is equipped with a narrow band interference filter to minimize background light, but for daylight operation, the background signal is still comparable to the lidar return signal from 6 or 7 km for standard operating conditions.

The approximately 2.5 MHz bandwidth of the data acquisition system will reduce the signal variance due to shot noise. Signal variance will be increased, however, by the 6 bit digitization of the signal. As stated before, if the signal digitization is perfect, the digitization noise will be reduced by averaging as if it were a random noise. The variance of the quantized signal will be given closely as:

$$v_q^2 = v^2 + 1/12\ (\Delta v)^2 \qquad (3.1)$$

where

v_q^2 = variance of the quantized signal

v^2 = variance of signal before quantization

Δv = quantization voltage step

Assuming uniform amplitude distribution for the signal, the signal-to-noise ratio generated by digitization may be taken to be n, the number of digitization levels [Maley, 1972]. The expected signal-to-noise ratio for a standard return which has been recorded by the data acquisition system is shown in Fig. 3.4.

Digitization of the signal, however, is not ideal. There will be a variance and mean associated with the quantization voltage steps, Δv. The effect of the variance of Δv on the recorded signal will depend on the nature of the signal and the magnitude of the mean and variance of Δv. In general, it may be expected that the fluctuation in Δv will lead to a fixed error that cannot be reduced by further integration [Clark, 1973].

Of the possible fixed errors which the data acquisition system may allow, the most serious is the uncertainty in the threshold voltage of the A/D converter. By not knowing exactly the baseline voltage for A/D conversion, a fixed error is added to the signal at every level. That the uncertainty of the threshold level is significant is due to a design limitation of the transient recorder. As the instrument is designed, it is probably not possible to set the threshold voltage to closer than 1/4 Δv giving an error of approximately .5%. Other possible fixed errors, such as those related to the gains of the stages of the gain switching amplifier or the measurement of the laser pulse energy, should be small by comparison.

3.2 Conclusions

The goal of this thesis was to develop a relatively simple and inexpensive system for automatic data acquisition of monostatic lidar return signals. The performance of the system that has been constructed is thought to be adequate in view of the finite amount of money and time that were available to the project. If more resources were available, some limitations of the present system could be improved upon. The limited sampling rate and accuracy of the present A/D conversion system could be significantly improved, but the increase in expense would be major. The present system of recording each return on punch paper tape is time consuming and subject to many difficulties. A real time signal averaging system and magnetic tape recording would be an improvement, and a necessity if a higher pulse repetition rate was desired. An on-line minicomputer would offer the most powerful and productive means for handling and processing acquired lidar return data.

The acquisition system in its present form has proved to be of use in collecting meaningful atmospheric data and has facilitated the performance of atmospheric remote sensing experiments [Spinhirne and Reagan, 1973; Spinhirne, Herman and Reagan, 1973].

APPENDIX A

CIRCUIT DIAGRAMS

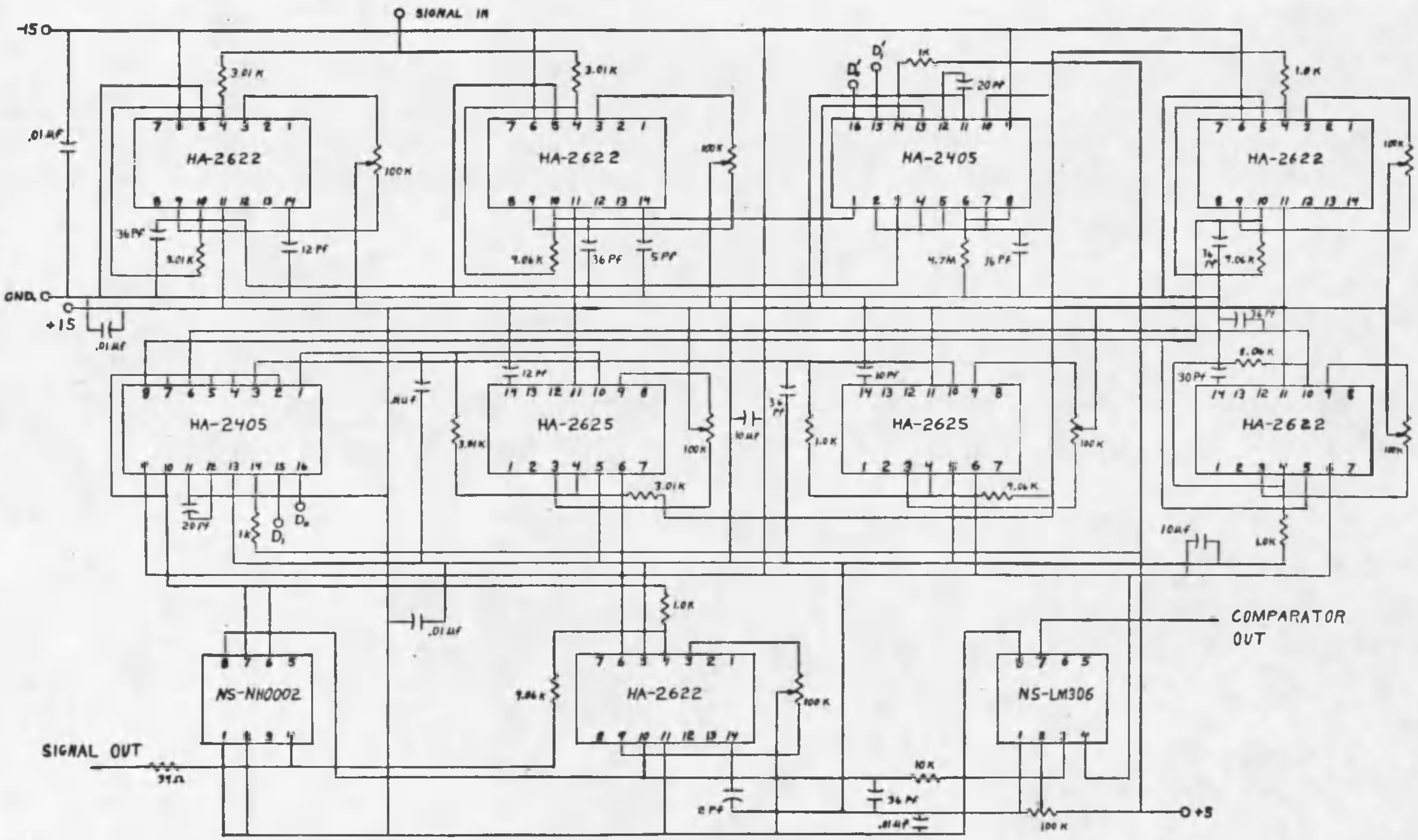


Fig. A.1 Gain Switching Amplifier

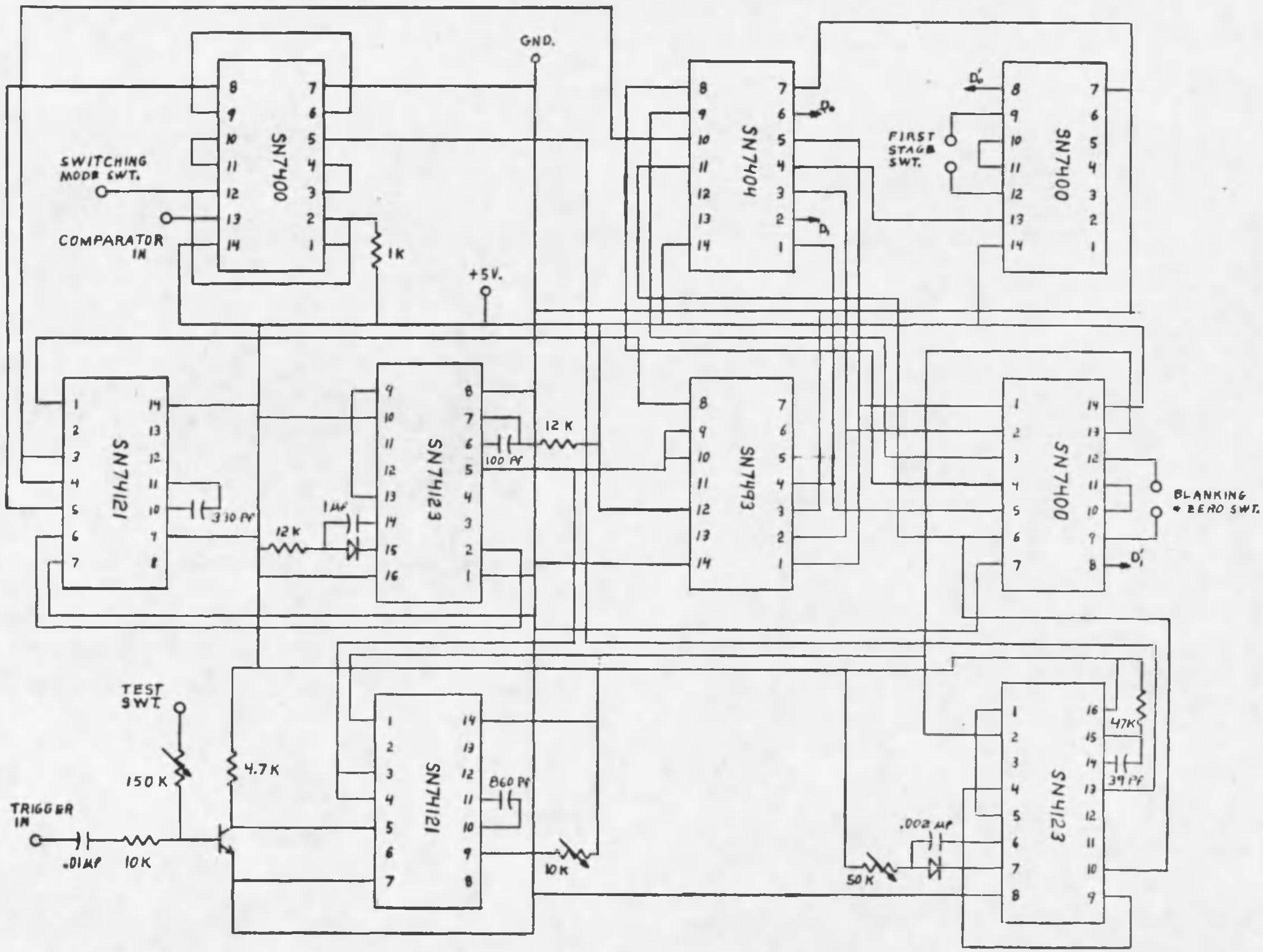
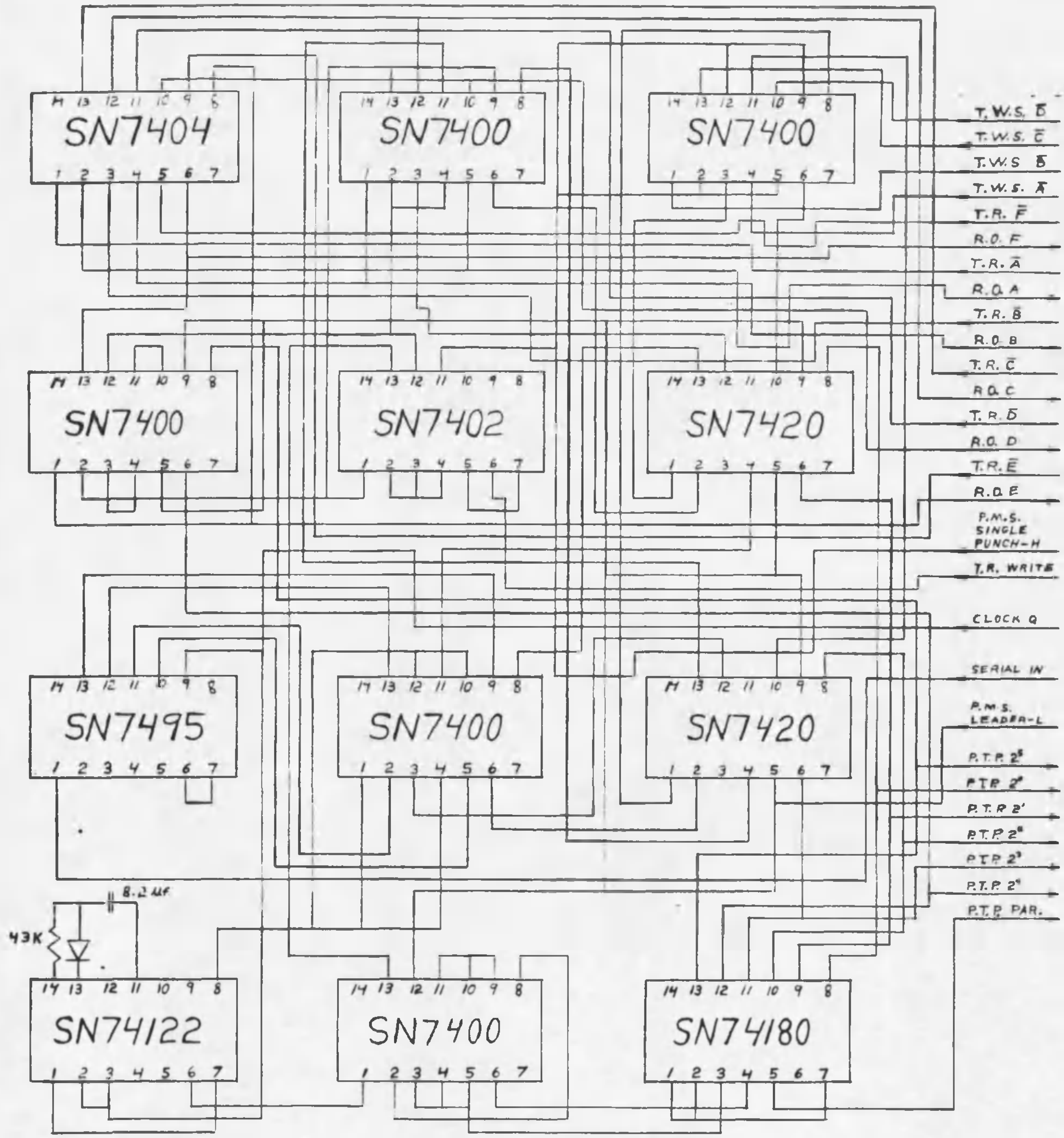


Fig. A.2 Gain Switching Amplifier Driving Logic



P.M.S. – PUNCH MODE SWITCH
P.T.P. – PAPER TAPE PUNCH
R.O. – READ OUT
T.R. – TRANSIENT RECORDER
T.W.S. – THUMB WHEEL SWITCH
(PINS 7-GND, PINS 14- +5V.)

Fig. A.3 Digital Data Flow Circuit

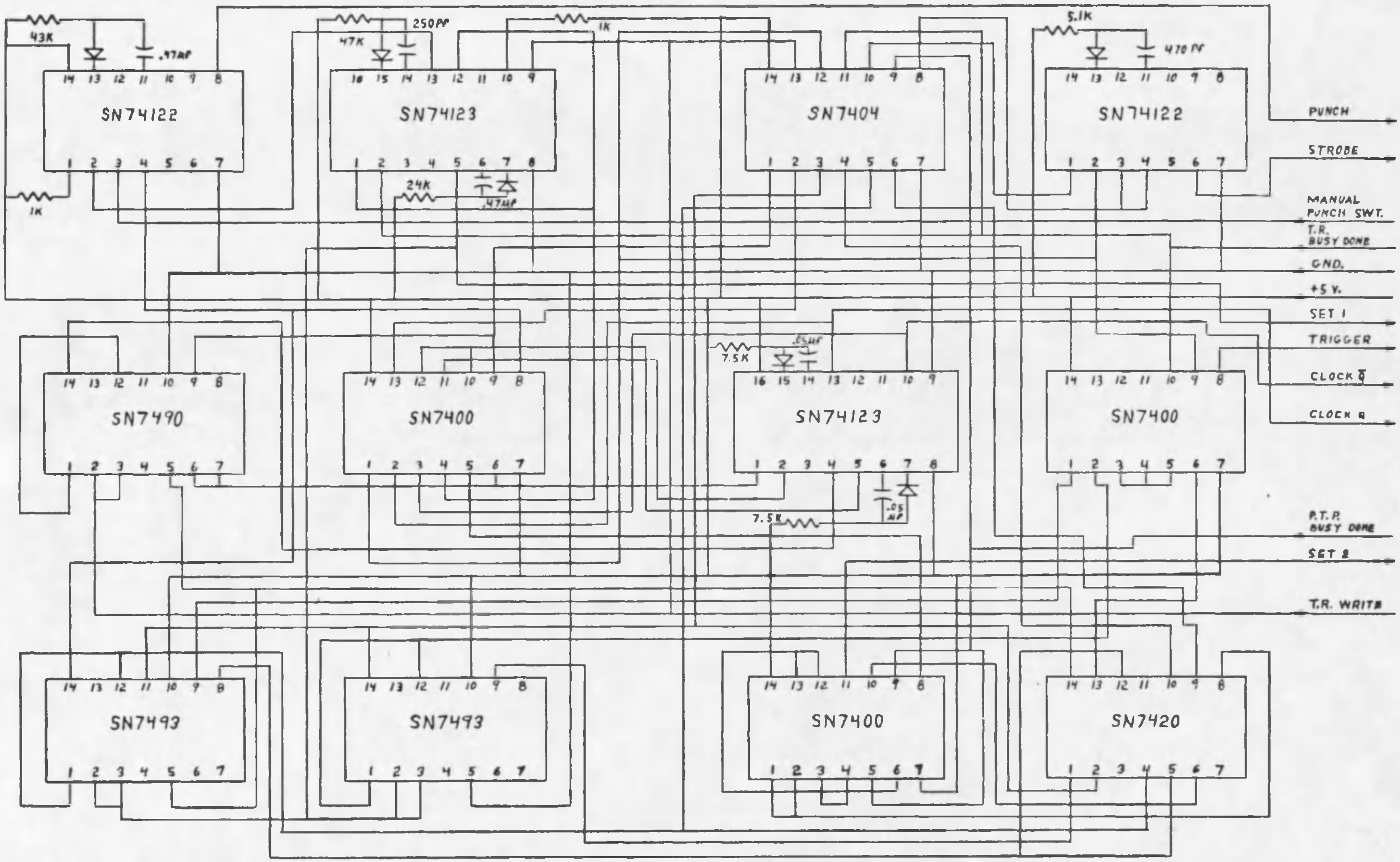


Fig. A.4 Digital Control Circuit

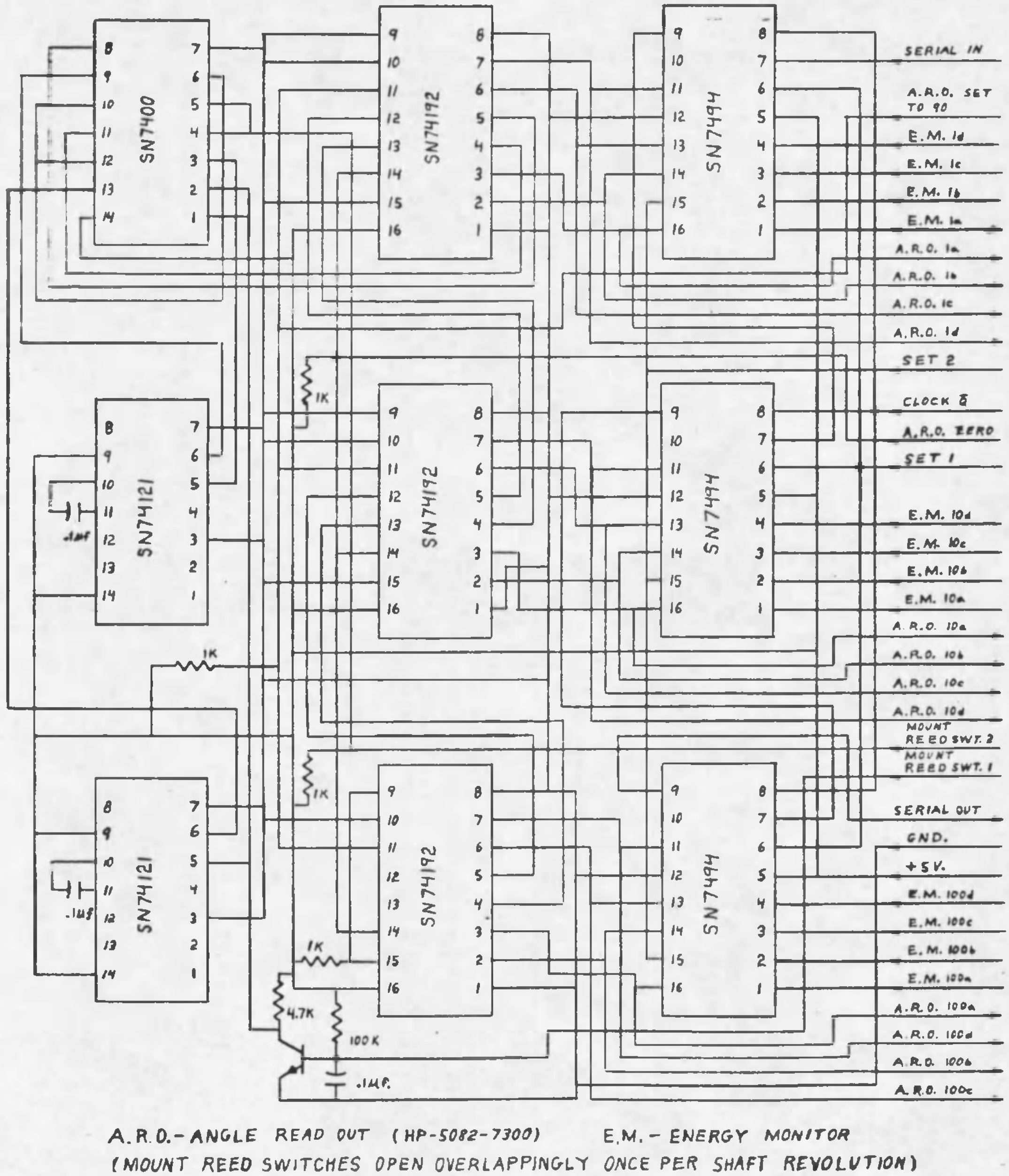
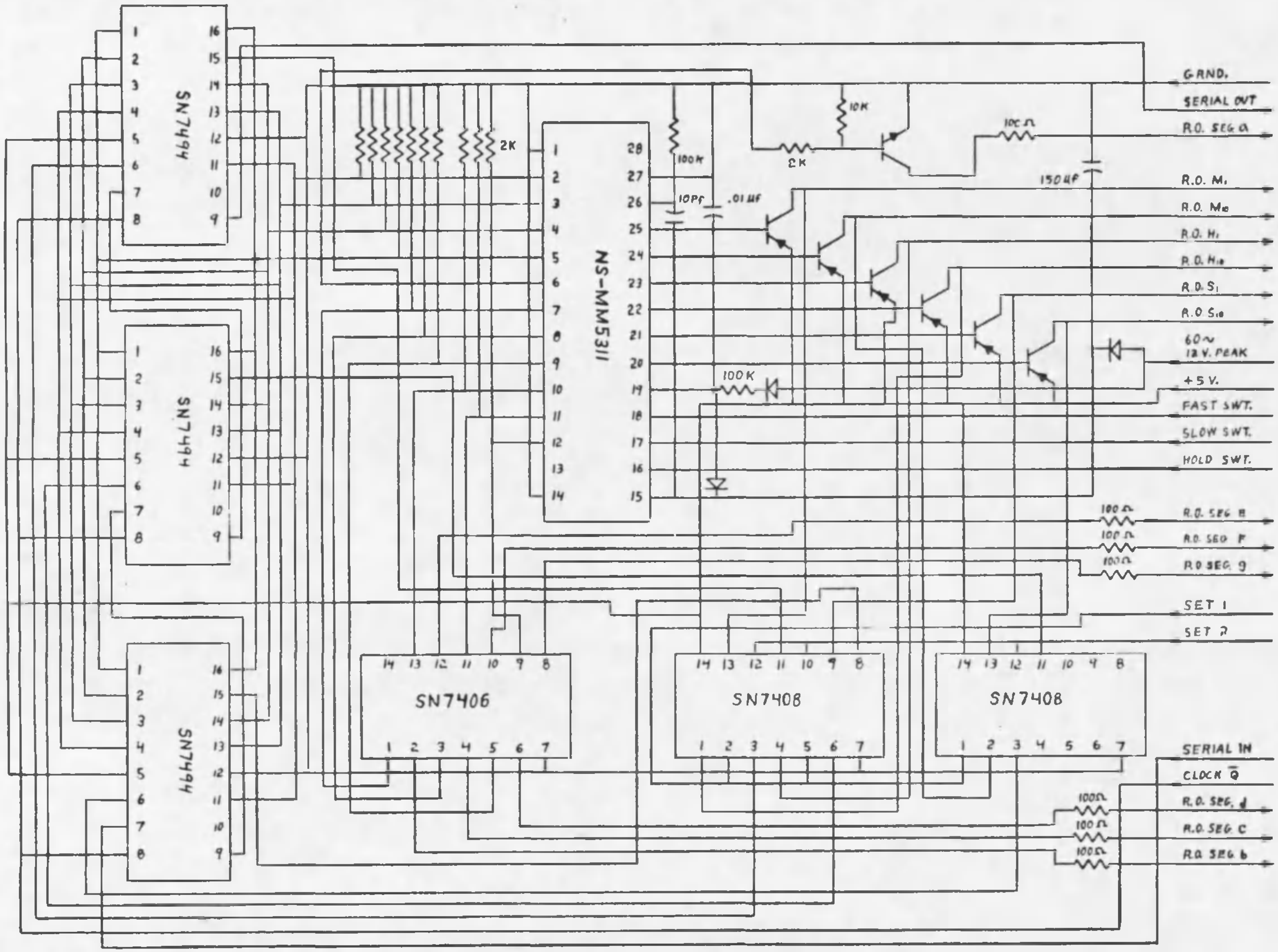


Fig. A.5 Mount Angle and Shift Register Circuit



R.O. - READ OUT (MAN-1 LED)

Fig. A.6 Clock

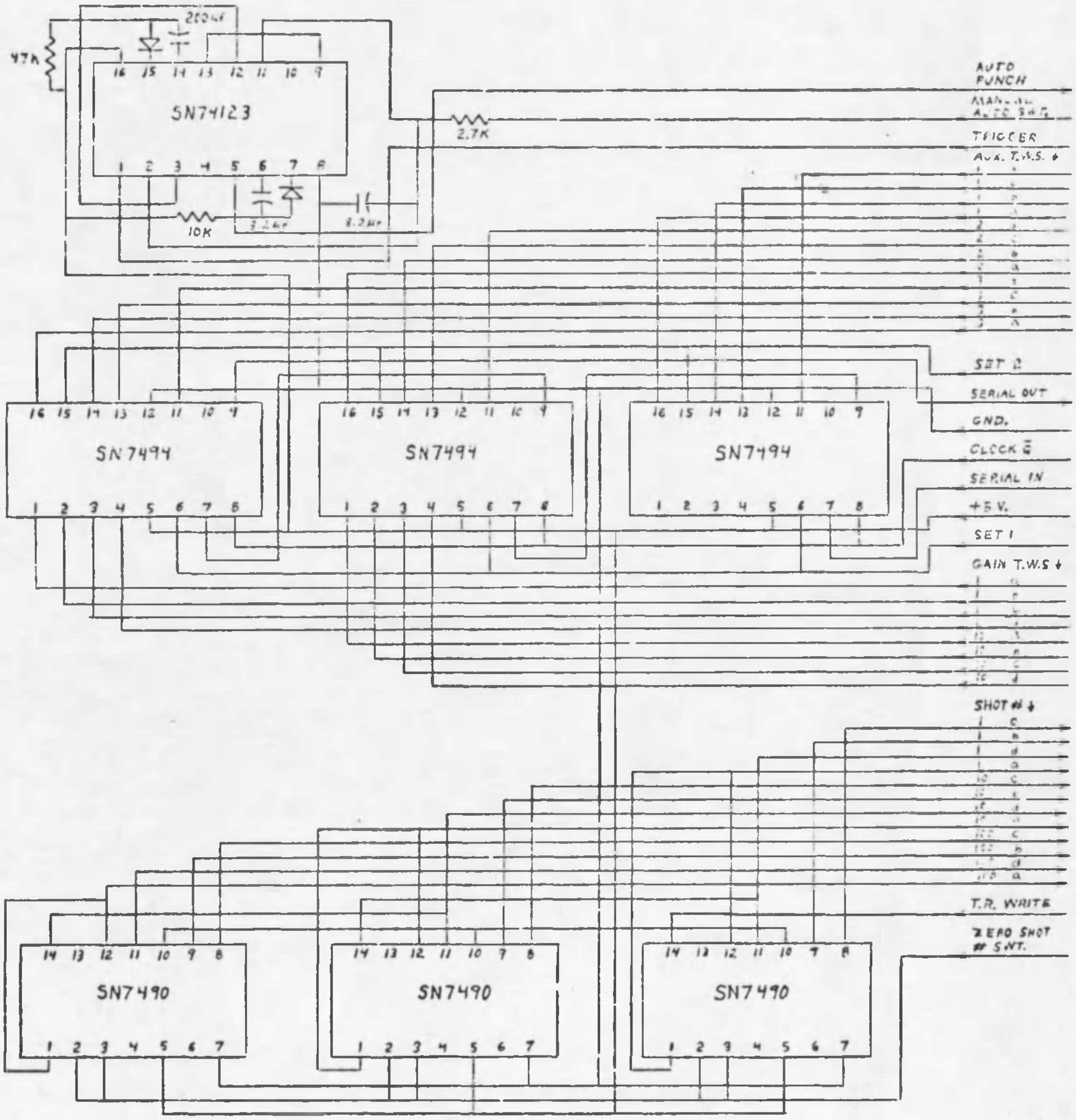


Fig. A.7 Shot Count, Shift Register and Auto-Punch Circuit

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