DESIGN OF AN ON-LINE INPUT-OUTPUT SYSTEM FOR THE M3 COMPUTER

A Thesis

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by

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UNIVERSITY OF SASKATCHEWAN

Electrical Engineering Abstract 67A95

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Student: Y.F.Cheu Supervisor: Dr. A.D. Booth

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ABSTRACT

A proposed design of an on-line input-output system for the M3 computer is described. Although this system is primarily designed for correlation analysis of two channels of physiological data, it is capable of digitizing two channels of analog signals with frequency components in a spectrum from 0.5 cps to 100 cps for other analysis.

The accuracy of the analog to digital conversion technique employed is analyzed. The minimum number of samples required for an accuracy of 10% is limited to 1000 samples for crosscorrelation and 5000 samples for autocorrelation.

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ABBREVIATIONS

S	sampling gate
H	holding circuit
M	multiplex switch
FF	flip-flop
OS	one-shot multivibrator
I	inverter
G	and gate
OR	or gate
A	amplifier
A-D	analog to digital converter
D-A	digital to analog converter
IH	inhibit gate

1. INTRODUCTION

1.1 General

Autocorrelation and crosscorrelation analyses, which have been used in statistical communication theory for the study of random functions, can be applied to the study of physiological data, particularly to the study of electroencephalographs (EEG's).

Autocorrelation analysis yields information concerning the inherent rhymicity of an EEG. Crosscorrelation analysis of two EEG's from two different locations on the scalp makes possible a comparison of the activity at these two locations. In addition to the study of EEG's, correlation analysis can also help physicians to solve clinical problems in EEG[1] and ECG[15]. For example, a physician can easily determine the location of a cerebral tumor in a patient with reference to correlograms of the EEG. It is also possible to classify the heart diseases through the interpretation of the ECG crosscorrelograms.

In order to obtain correlograms, various correlators have been developed, and may be divided into two classes: continuous with analog computation, and sampled with digital computation. Although these units provide correlograms with good accuracy for analysis, they are expensive to construct.

Since calculation of correlation functions requires multiplications, additions and division (section 4.1), it is possible to employ a general purpose digital computer to obtain correlation functions.

There are two different ways to employ a digital computer for calculation of correlation functions from analog functions. One is to program the computer with digital data which are obtained by visually sampling the analog records. The other is to feed the analog records to the computer directly through the use of an analog to digital converter.

The first method does not require an A-D converter, but introduces the error due to visual sampling and consumes considerable time in manually scaling the record. The second method makes a direct connection of analog signals to the digital computer. This can very greatly speed up the process of obtaining correlation functions.

1.2 Scope of Thesis

The object of this work is to design an on-line input-output system coupled with the M3 computer for correlation analysis of physiological data.

Before starting design of the system, several works must be carried out. These include the study of characteristics of physiological data, the accuracy of analog to digital conversion techniques, the number of samples which is required for correlation analysis of physiological data and the requirements of the M3 computer.

After this, a logical and a components design are made for the incorporation of a commercially available A-D converter and X-Y recorder with the M3 computer.

2. CHARACTERISTICS OF PHYSIOLOGICAL WAVEFORMS

2.1 Electroencephalogram (EEG)

The EEG waveforms depend on the state of awareness and vary from one area of the brain to another. Fig. 2.1 shows an EEG taken from a human at different states of awareness.

The characteristic EEG waves of humans are classified by frequency. The most outstanding normal waveform is the so-called "α" wave. These waves are between 8 and 13 cycles per second (cps) and they are about 20 μV in amplitude measured on the surface of the scalp. The "α" wave is usually present in an individual who is relaxed, with eyes closed, and in a quiet room.

The "β" wave is in the frequency range of 14 to 40 cps and has a smaller amplitude than the "α" wave. This wave is usually predominant in the wakeful and alert individual.

The "δ" wave is between 0.5 and 5 cps and has larger amplitude (50 - 100 μV). This wave is usually present in deep sleep.

2.2 Electrocardiogram (ECG)

Shown in Fig. 2.2 is a normal ECG waveform. This waveform represents the electrical activity of the heart as measured between two electrodes placed at standardized positions on the body. To digitize this waveform in binary codes, information must be available about the amplitude versus frequency spectrum before the minimum sampling rate can be estimated.

It is noted from Fig. 2.2 that the maximum harmonic content of the ECG occurs at the QRS complex. The QRS complex can be approximately considered as a periodic isosceles-triangle wave with period T and

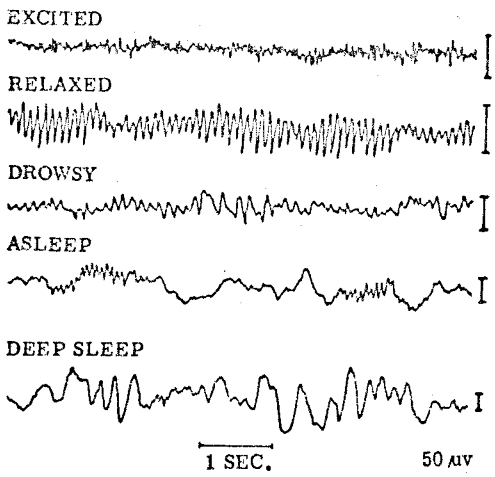


Figure 2.1 EEG during different states of sleep and wakefulness (From Penfield and Erickson)

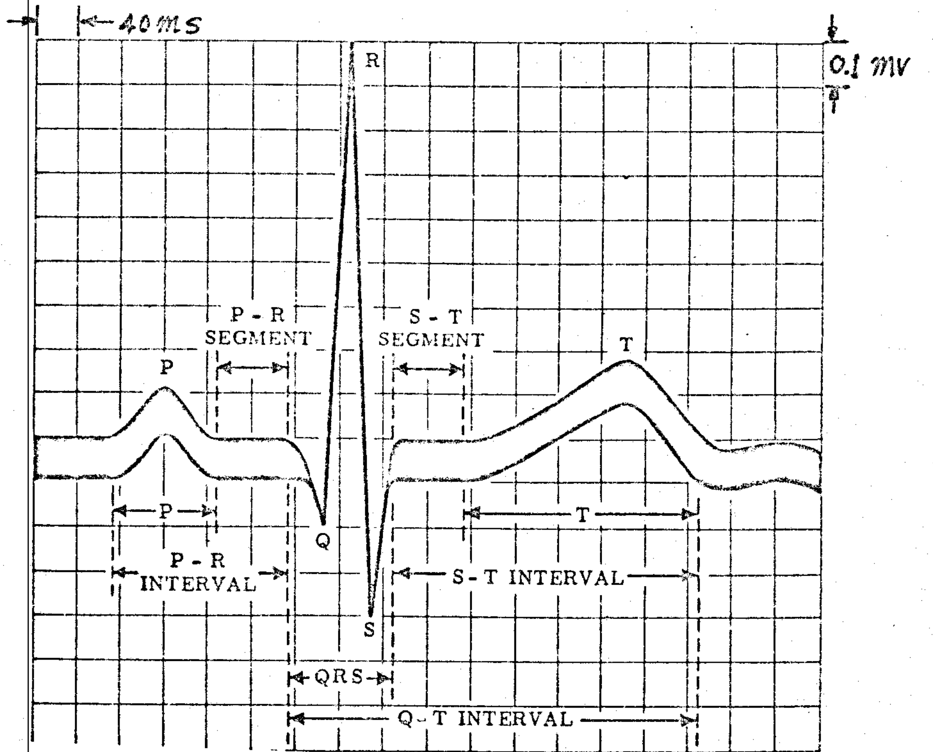


Figure 2.2 A normal ECG waveform (From Burch and Windsor)

duration $2t_1$ as shown in Fig. 2.3(a).

The coefficients of Fourier series of the isosceles-triangle wave are given by Eq. 2.1. For the QRS complex, $t_1 = 20$ ms, $T = 700$ ms and $A = 1.1$ mv, the amplitudes of the harmonics are calculated by Eq. 2.1 and plotted in Fig. 2.3(b).

$$C_n = \frac{2At_1}{T}\left(\frac{\sin\frac{n\pi t_1}{T}}{\frac{n\pi t_1}{T}}\right)^2 \qquad .....(2.1)$$

Since the period is 700 milliseconds, the fundamental frequency is 1.43 cycles per second. The frequency of the 35^{th} harmonic is thus 50 cps. It is observed from Fig. 2.3(b) that the amplitude of the 35^{th} harmonic is zero, and the harmonics higher than this are negligible.

For actual ECG's, both normal and abnormal, the results of analysis that have been published [12, 13, 14] indicate that the useful information appears at frequencies below 100 cps.

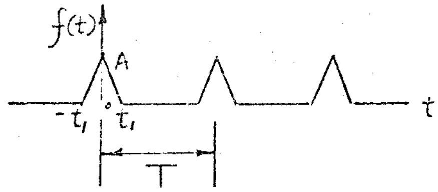


Figure 2.3(a) Isosceles Triangle Waveform Approximation

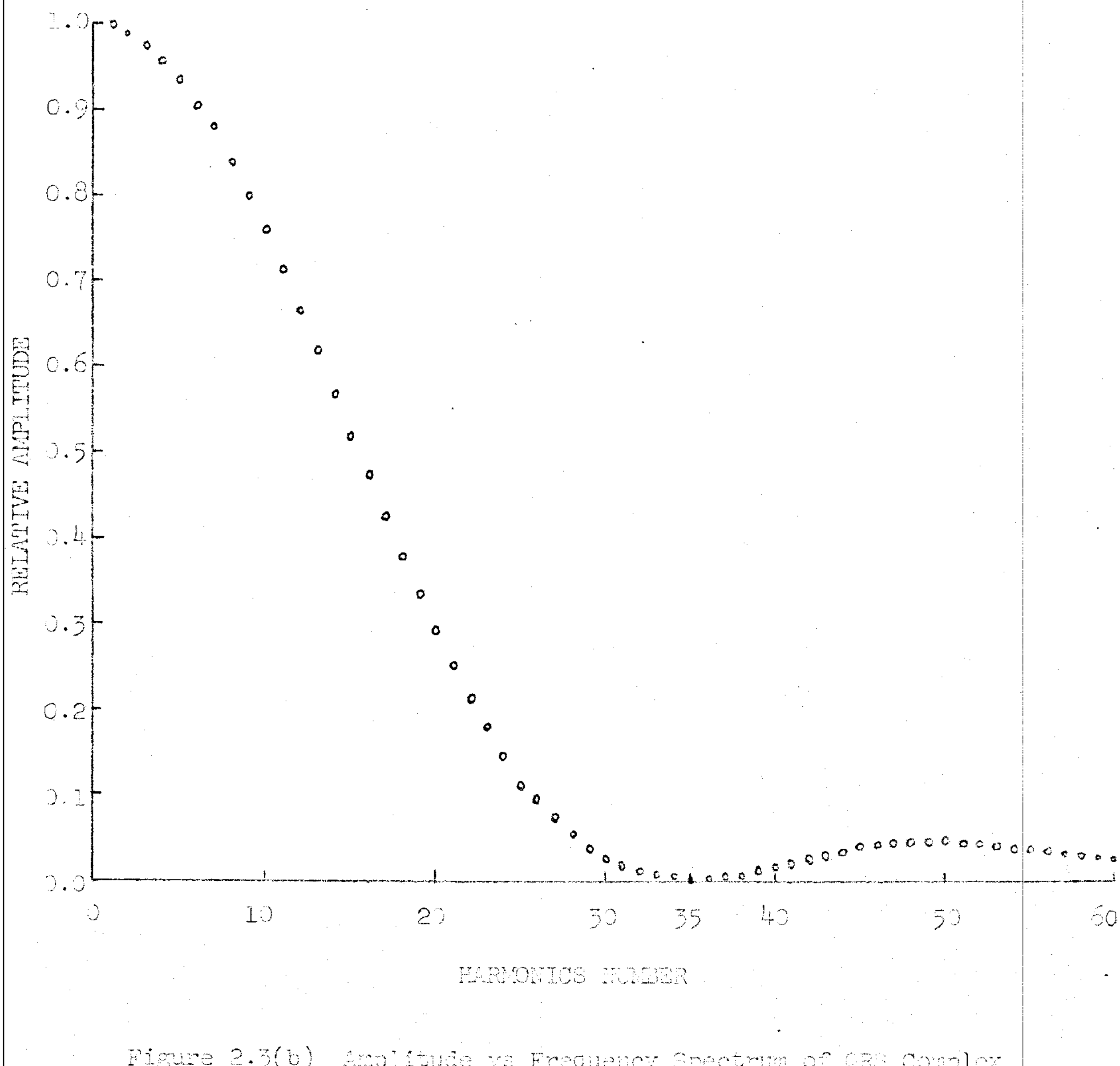


Figure 2.3(b) Amplitude vs Frequency Spectrum of QRS Complex

3. ERRORS OF ANALOG TO DIGITAL CONVERSION TECHNIQUE

3.1 Sampling

As a digital computer performs calculations in a discrete manner, the continuously time varying physiological waveforms which are used as inputs to the computer must be sampled at discrete time intervals and then converted into digital form. The problem is to choose an adequate sampling rate. The memory of a computer involved in looking at too many samples is undesirable, while looking at too few samples raises the possibility that some information may be lost. Minimum sampling rate is set by the sampling theorem [11]. This theorem states that a waveform can be completely described if it is sampled at a rate greater than twice the highest frequency component contained in that waveform. However, in practice, a sampling rate in the order of 5 to 10 samples per period of the highest frequency component is recommended[11].

3.2 Quantization error

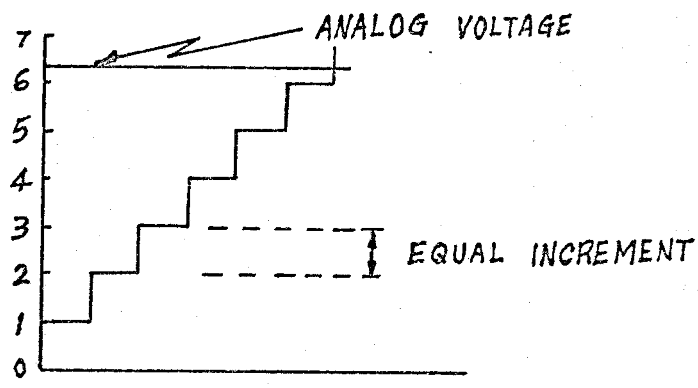


Figure 3.1 Quantizing process

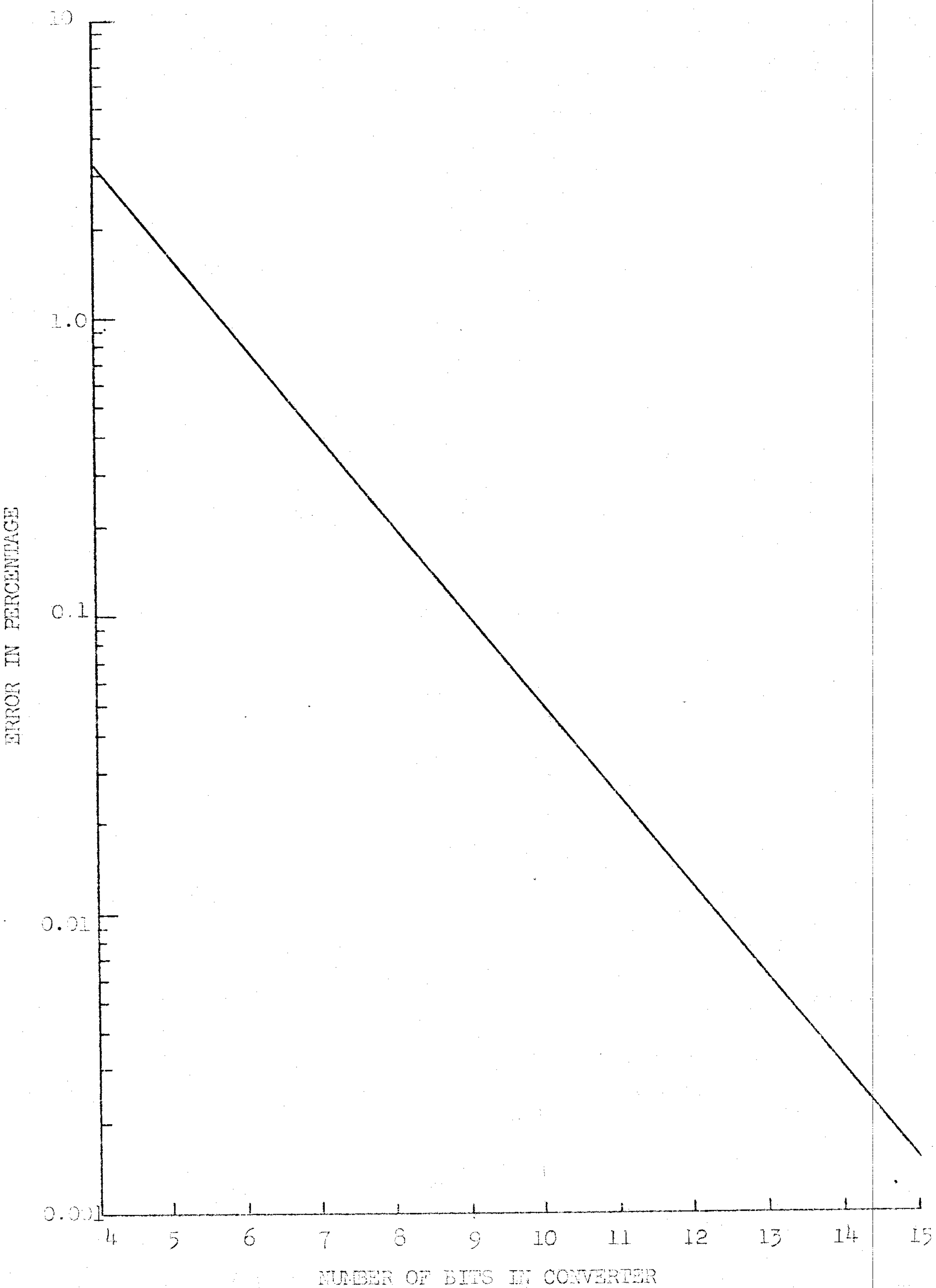


Figure 3.2 Quantization Error

Fig. 3.1 shows the quantizing process. Here the amplitude of the analog voltage is greater than 6 and less than 7. However, it is closer to 6 rather than 7 and is represented by 6. Thus, if no other errors are present, the digital output of a voltage to digital encoder does not vary from the actual analog input by more than one-half of the quantization level. This level is equal to the analog value of the least significant bit of the A-D converter. Therefore, the quantization error in an A-D converter is $\frac{1}{2}$ the least significant bit ($\frac{1}{2}$LSB).

The percent quantization error can be calculated by

$$\epsilon = \frac{1}{2(2^n - 1)} \times 100\%. \qquad \text{.....} \quad (3.1)$$

where n = number of bits of the A-D converter

Equation 3.1 is plotted (Fig. 3.2) and graphically shows the quantization error in percentage as a function of the number of bits of the converter. For example, the quantization error is 0.2% in an 8-bit analog to digital converter.

3.3 Aperture Error

As shown in Fig. 3.3, it requires a finite time (To) to take a data sample from the analog signal being digitized. This time interval is called aperture time or sampling time. The effect of aperture time is that the amplitude being sampled varies during this time interval. Thus the aperture time effect can be considered as an amplitude error for a given time at which the measurement is occurring.

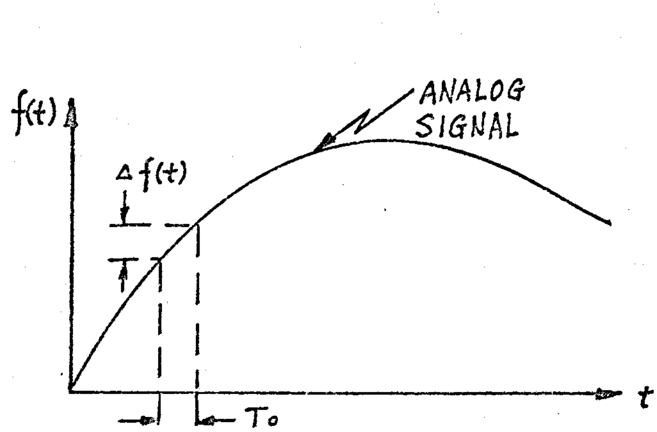


Figure 3.3 The aperture time effect

The aperture time error can be approximated by analyzing a sine wave. Because a sine wave is changing most rapidly as it passes through the points of zero amplitude, the maximum error will occur at these points.

Let the sine wave be

$$V = V_m \sin 2\pi ft .$$

The maximum rate of change of the sine wave is

$$\left.\frac{dV}{dt}\right|_{max} = 2\pi f V_m$$

Therefore, the maximum aperture error in percentage can be expressed by

$$\epsilon = \frac{\Delta V}{V_m} \times 100 = 2\pi f T_o \times 100\% \qquad \text{..... (3.2)}$$

where T_o = aperture time.

Equation 3.2 is plotted in Fig. 3.4 to show the maximum aperture

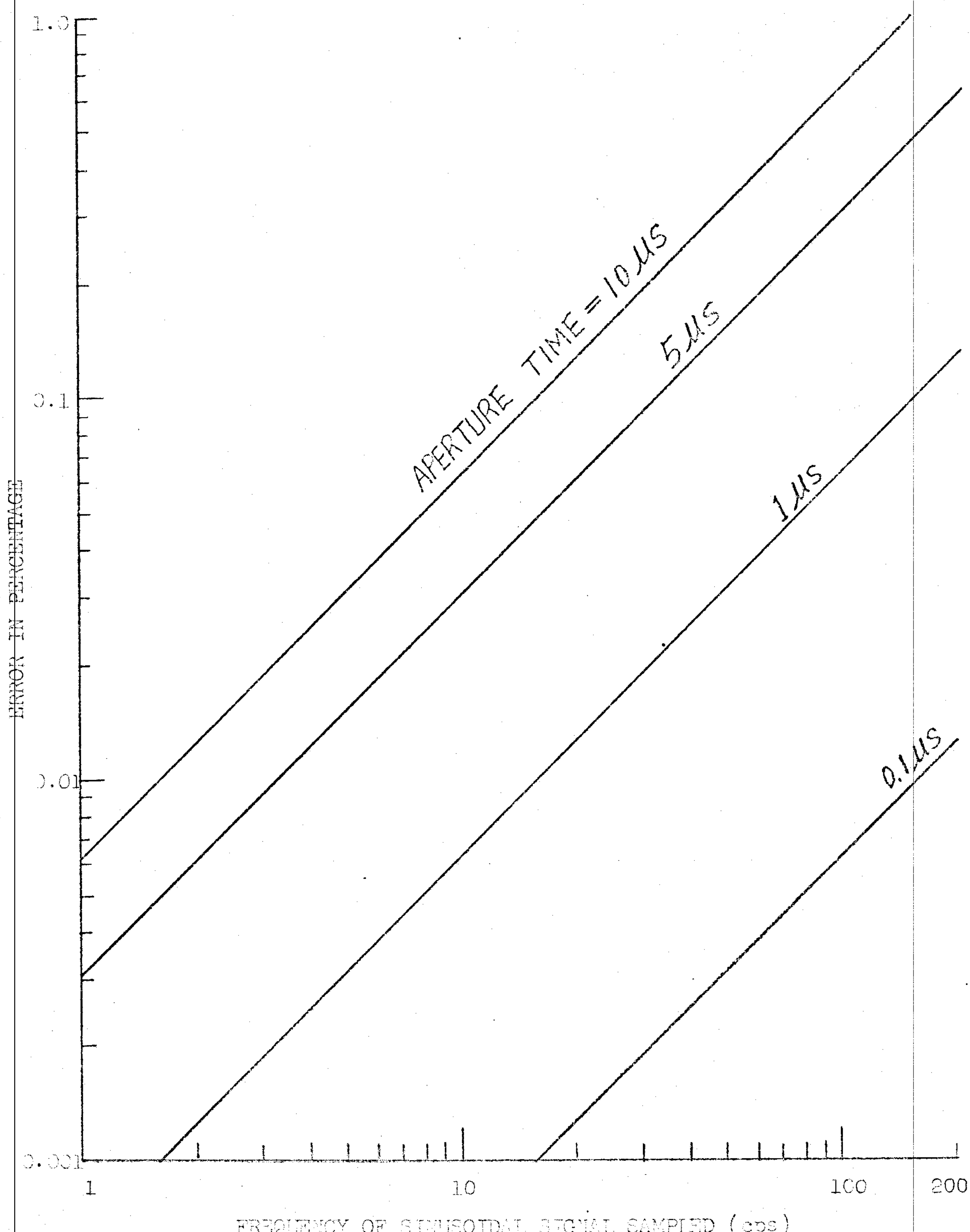


Figure 3.4 Maximum Aperture Error

error as a function of the frequency of the sampled signal with different aperture times. It is noted that a 100 cps sine wave, which is sampled for a time of 10 μs, results in a maximum aperture error of 0.62%.

3.4 Errors Due to Sample and Hold

The sample and hold circuit can be represented as shown in Fig. 3.5. While the switch is closed, the capacitor charges to the value of the input signal; then it follows the input. This is called the "sample" mode. When the switch is opened, the capacitor holds the same value that it had at the instant the switch was opened. This is called the "hold" mode.

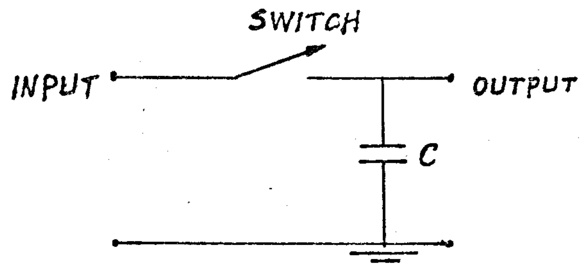


Figure 3.5 Sample and Hold circuit

The sample and hold circuit used ahead of a successive approximation A-D converter can reduce the aperture error, but other errors will be introduced by this circuit. These errors are due to:

(1) incomplete capacitor charging

(2) capacitor discharge between samples.

During the "sample" mode, the sample and hold circuit is equivalent to the RC charging network, here the R is the forward resistance of the sampling switch.

The charging equation for the RC circuit is

$$Vo = Vi\ (1 - e^{-To/\tau_c})$$

where Vi = input voltage

Vo = output voltage

τ_c = time constant

To = charging time

The incomplete capacitor charging error is thus

$$\epsilon = \frac{Vo - Vi}{Vi} \times 100\%$$

$$= - e^{-To/\tau_c} \times 100\% \qquad \text{..... (3.3)}$$

The absolute magnitude of Eq. 3.3 is plotted in Fig. 3.6. This shows graphically the incomplete capacitor charging error as a function of the ratio of the charging time to the charging time constant. For example, a ratio of the charging time to the charging time constant equal to 9.2 will give 0.01 percent error.

During the hold time, the holding capacitor will discharge through a high input impedance source-follower (Fig 6.5) which is connected to the output of the capacitor. This capacitor voltage decay causes the discharging error. Although this error is small, it is important enough to be considered here.

As the capacitor voltage decays exponentially, the error is thus:

$$\epsilon = (1 - e^{-Th/\tau_d}) \times 100\% \qquad \text{..... (3.4)}$$

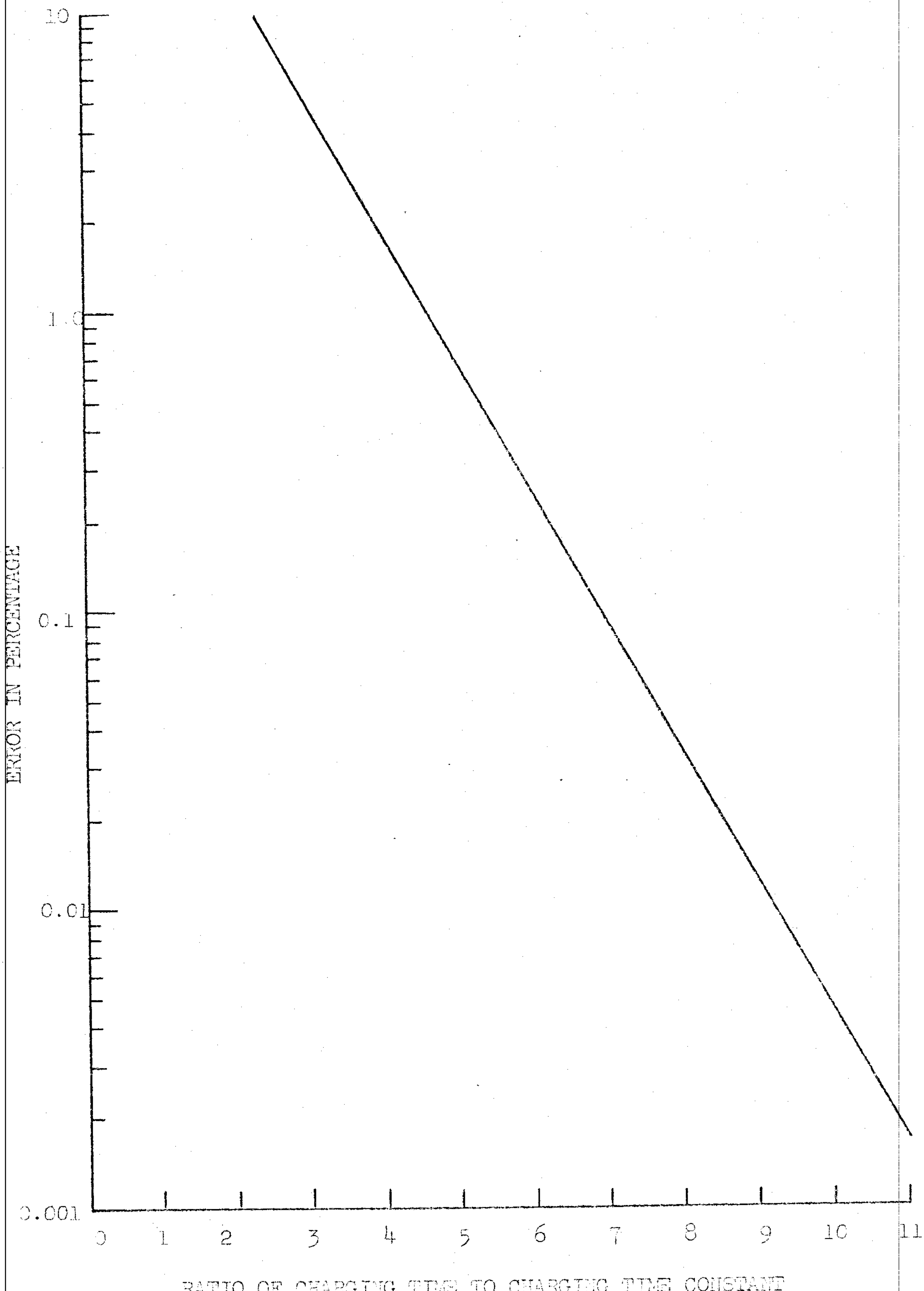


Figure 3.6 Incomplete Charging Error

where

T_h = holding time = discharging time

τ_d = discharge time constant

Equation 3.4 is plotted in Fig. 3.7 which graphically shows the discharging error as a function of the ratio of discharing time to discharge time constant (T_h/τ_d).

As shown in Fig. 6.5, the holding capacitance and the input impedance of the source follower are:

$C = 2200\ \mu\mu f$

$R = 1000\ M\Omega$,respectively,

then $\tau_d = 2.2$ seconds.

For $T_h = 2$ ms, T_h/τ_d will be equal to 0.999×10^{-3}.

Thus, the discharging error is 0.1% (Fig. 3.7).

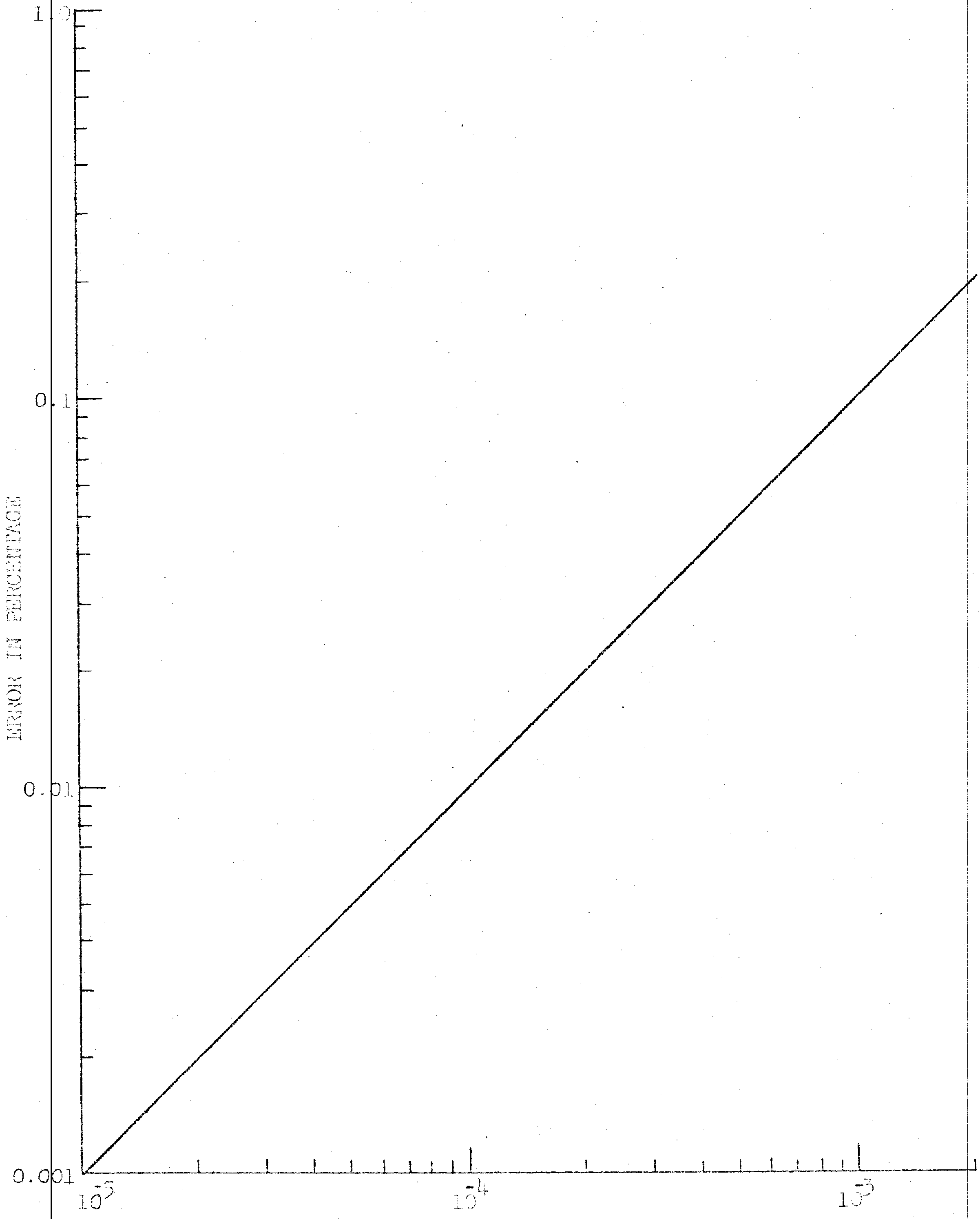


Figure 3.7 Discharging Error

4. CORRELATION ERRORS DUE TO FINITE RECORD LENGTH AND NUMBER OF SAMPLES

4.1 Autocorrelation and Crosscorrelation Function

The autocorrelation function is defined as

$$\varphi_{11}(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_{-T/2}^{T/2} f_1(t)\, f_1(t+\tau)\, dt \qquad \text{..... (4.1)}$$

$$\varphi_{11}(\tau) = \frac{1}{T}\int_{-T/2}^{T/2} f_1(t)\, f_1(t+\tau)\, dt \qquad \text{..... (4.2)}$$

Eq. (4.1) is used when $f_1(t)$ is a random function, and Eq. (4.2) is used if $f_1(t)$ is a periodic function with period T.

Similarly, the crosscorrelation function of two random functions and of two periodic functions with the same fundamental period T is defined by Eq. (4.3) and (4.4), respectively.

$$\varphi_{12}(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_{-T/2}^{T/2} f_1(t)\, f_2(t+\tau)\, dt \qquad \text{..... (4.3)}$$

$$\varphi_{12}(\tau) = \frac{1}{T}\int_{-T/2}^{T/2} f_1(t)\, f_2(t+\tau)\, dt \qquad \text{..... (4.4)}$$

From these expressions, it is noted that both autocorrelation and crosscorrelation involve continuous displacement, multiplication and integration since $f_1(t)$ and $f_2(t)$ are continuous. Although these operations can be carried out by an analog correlator, it is necessary to replace continuous operations by discrete ones when a digital computer is employed to calculate the correlation function. In this case, the process of integration is replaced by one of summation and Eq. (4.1) and (4.3) may be written as

$$\varphi_{11}(\tau_k) = \lim_{N\to\infty} \frac{1}{N} \sum_{n=0}^{N} f_1(nt)\, f_1(nt + \tau_k) \qquad \ldots\ldots (4.5)$$

$$\varphi_{12}(\tau_k) = \lim_{N\to\infty} \frac{1}{N} \sum_{n=0}^{N} f_1(nt)\, f_2(nt + \tau_k) \qquad \ldots\ldots (4.6)$$

where N is the total number of points in the record of $f_1(t)$ or $f_2(t)$, and k and n are integers.

It is known that an autocorrelation function is an even function with a maximum value at the origin ($\tau = 0$), while the crosscorrelation is not necessarily an even function [6]. In general, it is neither even nor odd. Moreover, the value of the crosscorrelation function at $\tau = 0$ need not be the maximum value. The most important difference between autocorrelation and crosscorrelation is the fact that autocorrelation discards all phase information in the given function, but crosscorrelation retains the phase differences of frequencies which are present in both functions being correlated.

4.2 Error Due to Finite Length of Record

4.2.1 Random functions

From the expressions (Eq. 4.1, 4.3, 4.5 and 4.6) it is noted that the exact value of $\varphi(\tau_k)$ can be obtained only by averaging an infinite number of sample products from an infinite length of record. This is impossible if $\varphi(\tau_k)$ is evaluated by any physical apparatus (including the digital computer). Consequently, it is necessary to consider how the correlation function is affected by the finite length of record.

The statistical error associated with the correlation analysis of a finite record of a random function $f_1(t)$, is usually expressed in terms of the normalized standard error, which is the positive square root of the normalized mean square error. For an autocorrelation function, the mean square error is equal to the variance which is given by [4]

$$\mathrm{Var}\,[\varphi_{11}(\tau_k)] \approx \frac{1}{2BT}\,[\varphi_{11}^{\,2}(0) + \varphi_{11}^{\,2}(\tau_k)] \qquad \ldots\ldots(4.7)$$

The normalized mean square error is

$$\epsilon^2 = \frac{\mathrm{Var}\,[\varphi_{11}(\tau_k)]}{\varphi_{11}^{\,2}(\tau_k)} \approx \frac{1}{2BT}\left[1 + \frac{\varphi_{11}^{\,2}(0)}{\varphi_{11}^{\,2}(\tau_k)}\right] \qquad \ldots\ldots\ (4.8)$$

Thus, the normalized standard error in percent is

$$\epsilon \approx \frac{1}{\sqrt{2BT}}\left[1 + \frac{\varphi_{11}^{\,2}(0)}{\varphi_{11}^{\,2}(\tau_k)}\right]^{\frac{1}{2}} \times 100\% \qquad \ldots\ldots\ (4.9)$$

where B is the bandwidth in cps occupied by f(t), T is the record length in seconds, and $\varphi_{11}(0)$ and $\varphi_{11}(\tau_k)$ are the autocorrelation functions calculated at zero lag time ($\tau_k = 0$) and any lag time τ_k, respectively.

This error versus BT product with different values of $\varphi_{11}(0)/\varphi_{11}(\tau_k)$ is plotted in Fig. 4.1. For given values of ϵ, B and $\varphi_{11}(0)/\varphi_{11}(\tau_k)$, the minimum record length Tr could be easily found from either Eq. (4.9) or Fig. 4.1.

Similarly, the normalized standard error for a crosscorrelation function evaluated from a finite record length is given by:

$$\epsilon \approx \frac{1}{\sqrt{2BT}}\left[1 + \frac{\varphi_{11}(0)\,\varphi_{22}(0)}{\varphi_{12}^{\,2}(\tau_k)}\right] \times 100\% \qquad \ldots\ldots\ (4.10)$$

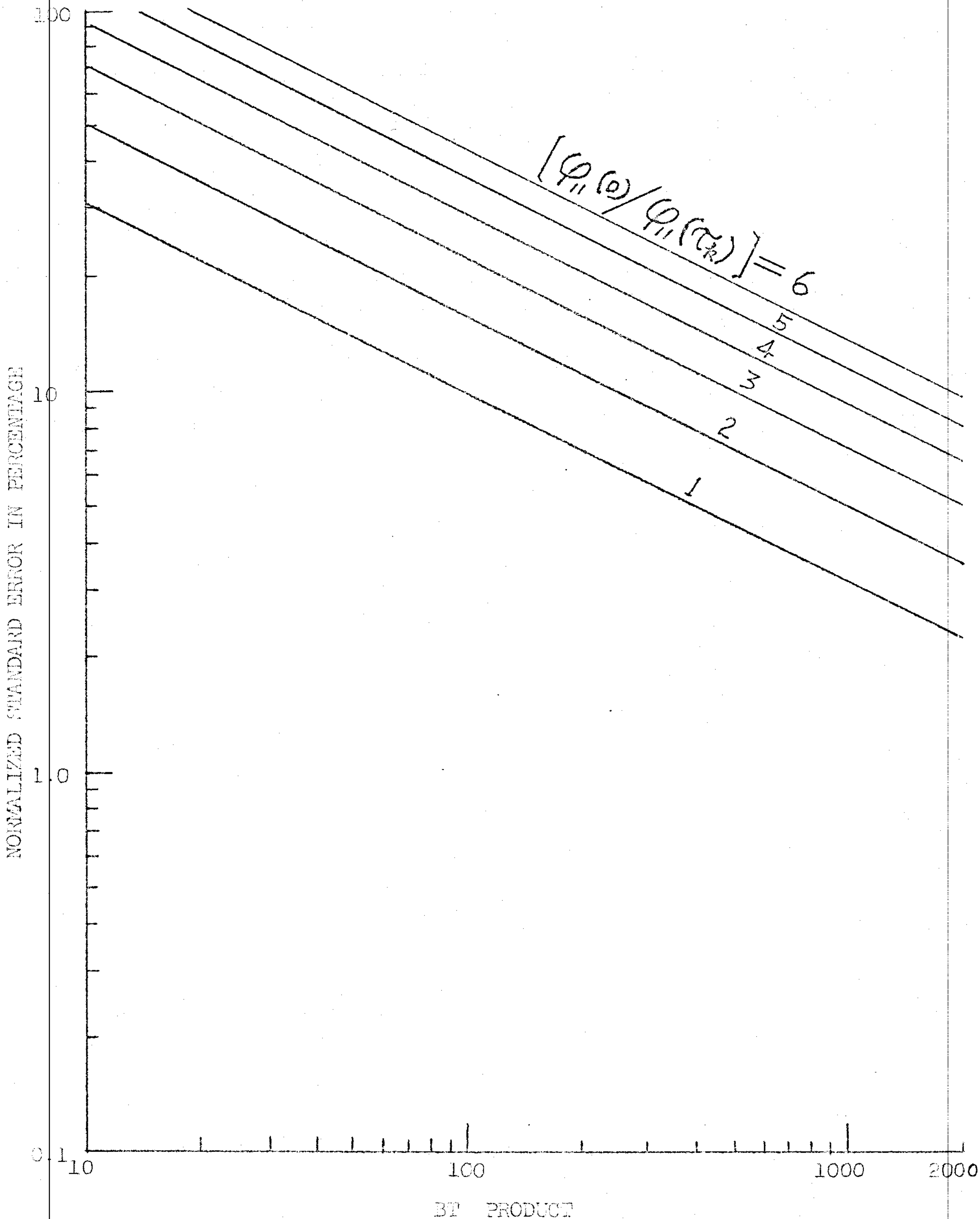


Figure 4.1 Autocorrelation Error Due To Finite Record Length

4.2.2 Periodic functions

The correlation error due to a finite length of record for a periodic function can be derived directly from the correlation definition (Eq. 4.2) if the record length T is not equal to the period or a multiple of the period. Consider the autocorrelation of a cosine function (5).

$$f(t) = E_m \cos(\omega_1 t + \theta) \qquad \ldots\ldots (4.11)$$

$$\varphi_{11}(\tau) = \frac{1}{T}\int_0^T E_m^2 \cos(\omega_1 t + \theta)\cos(\omega_1 t + \omega_1\tau + \theta)\,dt$$

$$= \frac{1}{T}\int_0^T \frac{E_m^2}{2}\left[\cos\omega_1\tau + \cos(2\omega_1 t + \omega_1\tau + 2\theta)\right]dt$$

$$= \frac{E_m^2}{2}\left[\cos\omega_1 + \frac{\sin(2\omega_1 T + \omega_1\tau + 2\theta) - \sin(\omega_1\tau + 2\theta)}{2\omega_1 T}\right] \qquad \ldots\ldots (4.12)$$

When $T \rightarrow \infty$, the exact autocorrelation function is obtained as

$$\varphi_{11}(\tau) = \frac{E_m^2}{2}\cos\omega_1\tau$$

If T does not approach ∞, then the maximum error is:

$$\epsilon = \frac{1}{\omega_1 T} \qquad \ldots\ldots (4.13)$$

where ω_1 is the angular frequency of the cosine function.

In accordance with Eq. (4.13), for a maximum error of 1%, the minimum record length required is about 16 periods of the lowest frequency component contained in the periodic function.

4.3 Error Due to a Finite Number of Samples

4.3.1 Random functions

Consider a random function

$$f_1(t) = S(t) + N(t) \qquad \ldots\ldots (4.14)$$

where S(t) is a periodic function and N(t) is the noise

Let $$S(t) = E_m \sin(\omega_1 t + \theta) \qquad \ldots\ldots (4.15)$$

with the root-mean-square value $E = \frac{E_m}{\sqrt{2}}$, and let the variance of the noise N(t) be σ_N^2.

Then the variance of the autocorrelation function of $f_1(t)$ is given by (6)

$$\text{Var}\,[\varphi_{11}(\tau_k)] = \frac{1}{n}\left[\frac{E^4}{2} + 2E^2\sigma_N^2 + \sigma_N^4\right] \qquad \ldots\ldots (4.16)$$

Since the ideal autocorrelation function of $f_1(t)$ is

$$\varphi_{11}(\tau_k) = E^2 \cos\omega_1\tau_k \qquad \ldots\ldots (4.17)$$

Then the normalized standard error is

$$\epsilon = \frac{\sqrt{\frac{1}{n}\left(\frac{E^4}{2} + 2E^2\sigma_N^2 + \sigma_N^4\right)}}{\frac{E^2}{\sqrt{2}}}$$

$$= \sqrt{\frac{2}{n}\left(\frac{1}{2} + \frac{2\sigma_N^2}{E^2} + \frac{\sigma_N^4}{E^4}\right)} \qquad \ldots\ldots (4.18)$$

Let the input noise-to-signal ratio be

$$\rho_i = \frac{N_i}{S_i} \qquad \ldots\ldots\ldots (4.19)$$

With the sinusoid as the input signal and with the variance of the noise with a zero mean being σ_N^2, then

$$\rho_i = \frac{\sigma_N}{E} \qquad \text{..... (4.20)}$$

In terms of ρ_i, Eq. (3.18) is rewritten as

$$\epsilon = \sqrt{\frac{1}{n}\left(1 + 4\rho_i^{\,2} + 2\rho_i^{\,4}\right)} \times 100\% \qquad \text{..... (4.21)}$$

The normalized standard error in percent versus n with different values of ρ_i is plotted in Fig. 4.2 in solid lines.

Similarly, the normalized standard error for a crosscorrelation function is given by Eq. (4.22) which is plotted in Fig. 4.2 in dotted lines. Clearly the accuracy of the crosscorrelation is much better than that of the autocorrelation for the same number of samples n and input noise-to-signal ratio ρ_i.

$$\epsilon = \sqrt{\frac{1}{n}\left(1 + 2\rho_i^{\,2}\right)} \times 100\% \qquad \text{..... (4.22)}$$

4.3.2 Periodic functions

Michael (7) used the IBM 1620 computer to calculate the autocorrelation function of 1 cps cosine wave which was sampled 12 times per cycle. The result showed that the accuracy of the autocorrelation function can only be determined by Eq. (4.10) if the periodic function was sampled at a rate greater than 10 samples per cycle.

4.4 Resolution of the Correlation Function

As seen from Eq's. (4.5, 4.6), the correlation function $\varphi(\tau_k)$ is evaluated for discrete lag times τ_k. These discrete values of $\varphi(\tau_k)$ are usually plotted through a X-Y plotter to obtain the correlogram. Therefore, the interval between the lag times determines how well the correlation function is resolved. When the interval is

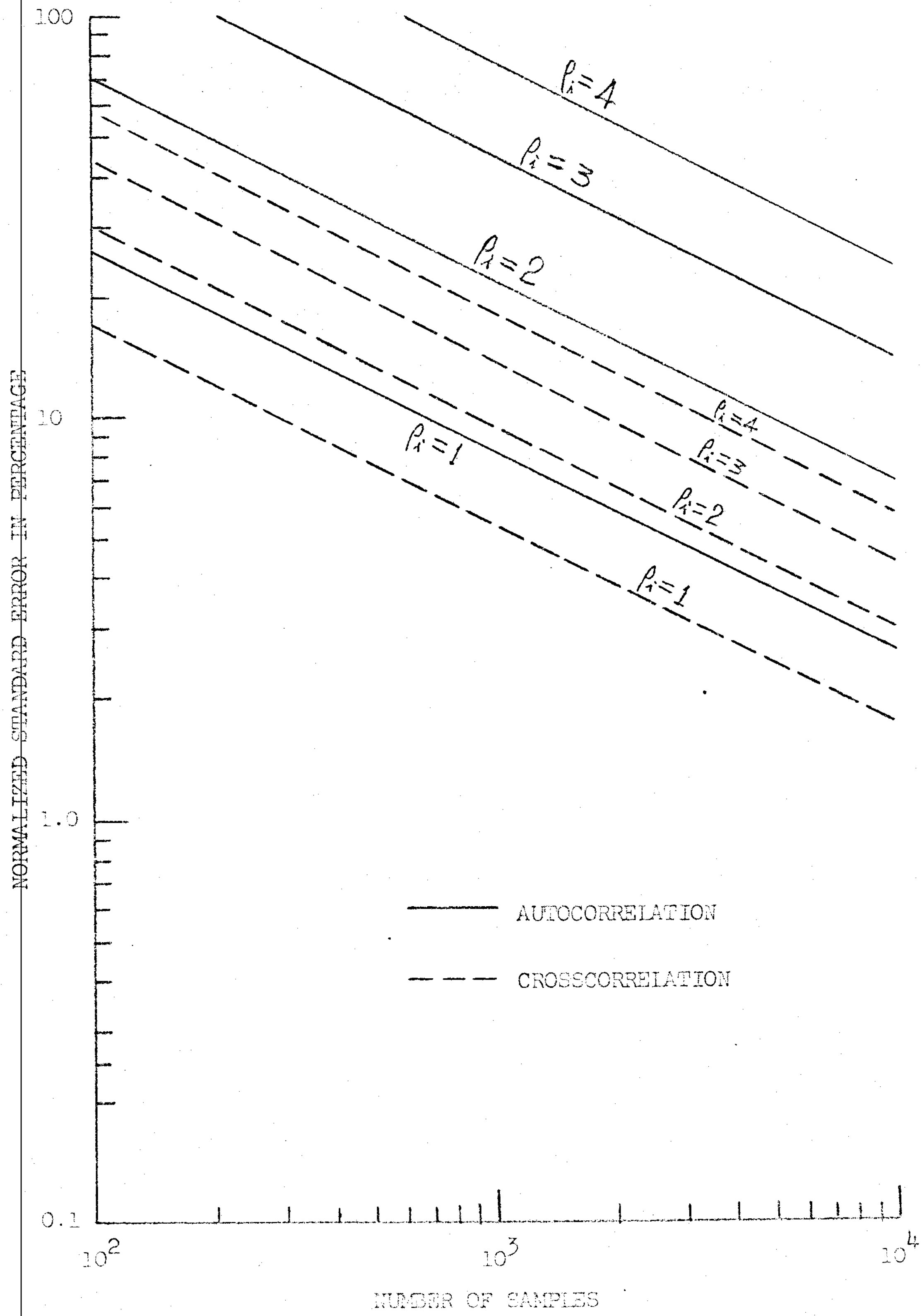


Figure 4.2 Correlation Error Due to Finite Number of Samples

made smaller, the resolution of the correlogram will be improved.

In order to choose a proper interval between lag times, tests were carried out in the laboratory. The experimental setup is shown in Fig. 4.3(a) which consists of a sine wave generator, a sampling gate (Fig. 6.4), a holding circuit (Fig. 6.5), a pulse generator, a trigger circuit (Fig. 6.6) and a wave analyzer.

Different time intervals were used to take discrete samples (Fig. 4.3(c)) from a 50 cps sine wave which was produced by the sine wave generator. A rectangular approximation (Fig. 4.3 (d)) to the sine wave from discrete samples was produced by the holding circuit. The R.M.S. value of the rectangular-approximation sine wave was compared with that of the true sine wave by the wave analyzer. The result was shown in Fig. 4.4.

It is seen from Fig. 4.4 that 10 samples per cycle will adequately specify a continuous waveform. Therefore, 10 correlation values per cycle are sufficient to define a correlogram at any frequency. This result is expressed as follows:

$$\Delta\tau = \tau_k - \tau_{k-1} = \frac{1}{10 f_m} \qquad \ldots\ldots (4.23)$$

where $\Delta\tau$ is the interval between lag times in seconds and f_m is the maximum frequency in cps of the significant information contained in the correlogram.

f_m can never be greater than the maximum frequency of the functions being correlated. If these functions are sampled at a rate which is 10 times their highest frequency component, then the sampling period will be less than $\Delta\tau$ which is expressed in Eq. (4.23). Consequently,

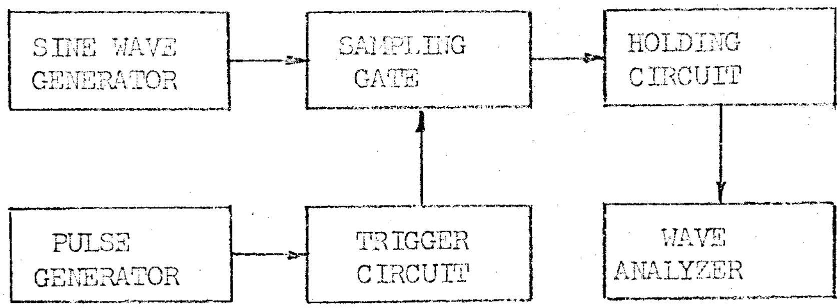


Figure 4.3(a) Experimental Setup

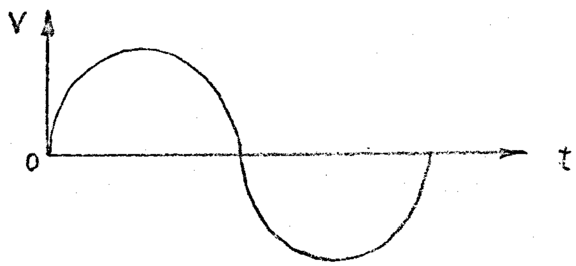


Figure 4.3(b) Sine Wave

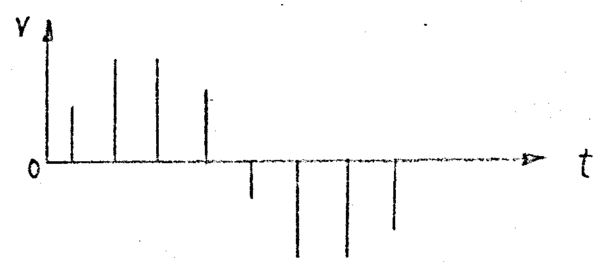


Figure 4.3(c) Output of the Sampling Gate

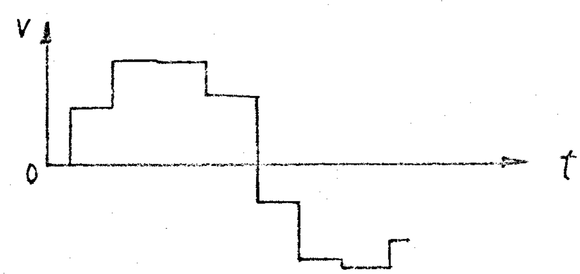


Figure 4.3(d) Output of the Holding Circuit

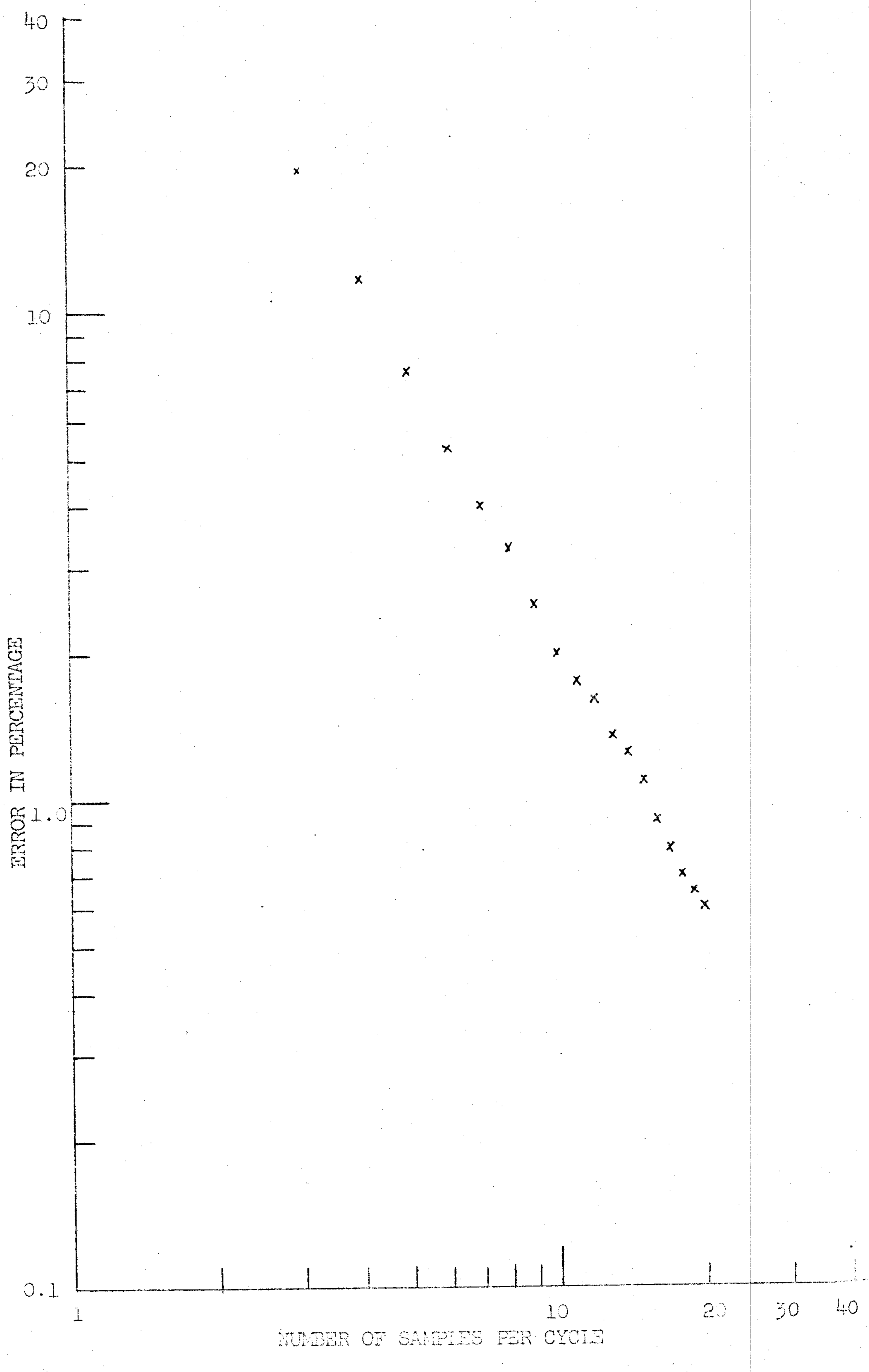


Figure 4.4 Error due to Rectangular Approximation to A Sine Wave

correlation functions calculated at intervals of τ_k equal to the sampling period is adequate to obtain the correlogram.

The maximum lag time τ_m is less than the record length T. In fact, it should be only 5 - 10% of T, or digitally, 5 - 10% of the total number of samples n[4].

4.5 Determination of No. of Samples per Observation Interval for Correlation Analysis of EEG and ECG

4.5.1 EEG

As known from section 2.1, the EEG is a random function with certain periodic signals (the α wave, the β wave and the δ wave) contained in it. Since the α wave, the β wave and the δ wave do not appear simultaneously, it is safe to say that the input noise-to-signal ratio ρ_i is less than 2.

From Fig. 4.2, it is noted that 5,000 samples are required to obtain an autocorrelation function with a normalized standard error of 10% if ρ_i is equal to 2. For the same accuracy and input noise-to-signal ratio ρ_i, only 900 samples are required to obtain the cross-correlation function.

The bandwidth of the EEG is determined by the bandwidth of the devices which are used to detect and record it. These devices are usually designed to have a cut off frequency less than 100 cps. Therefore, the bandwidth B for the EEG is 100 cps.

The autocorrelation function $\varphi_{11}(\tau_k)$ of a random function $f_1(t)$, which contains a periodic signal, is shown in Fig. 4.5. The maximum value of $\varphi_{11}(\tau_k)$ appears at zero lag time $\tau_k = 0$. This is because $\varphi_{11}(0)$ consists of both the autocorrelation of the noise and of the signal. For $\tau_k \gg 0$, the value of $\varphi_{11}(\tau_k)$ is less than that of $\varphi_{11}(0)$ and is approximately equal to the autocorrelation of the signal only. For EEG, the value of $\varphi_{11}(\tau_k)$ required is about one-fourth of that of $\varphi_{11}(0)$ (8), (9).

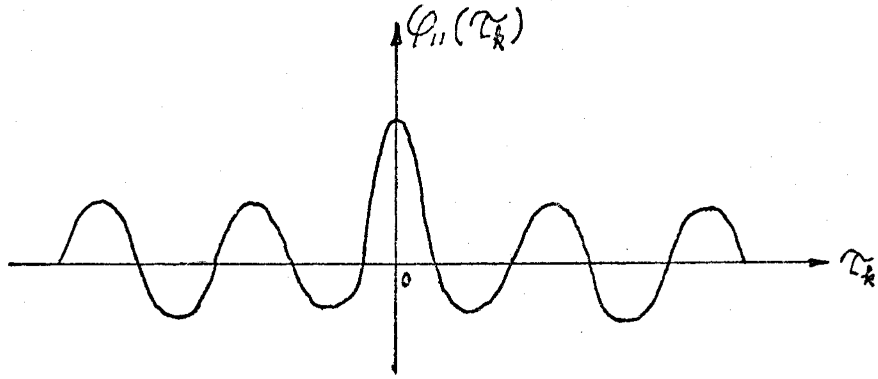


Figure 4.5 Autocorrelation Function of a Random Function with a Periodic Signal

With $\varphi_{11}(0)/\varphi_{11}(\tau_k) = 4$ and B = 100 cps, it is seen from Fig. 4.1 that the minimum record length Tr equal to 10 seconds is necessary in order to obtain an autocorrelation function with a normalized standard error of 10%.

4.5.2 ECG

As seen from section 2.2, the ECG waveform can be considered to be a periodic function with fundamental period equal to 700 milliseconds. In accordance with Eq. (4.13), to obtain an autocorrelation function with 1% accuracy, the minimum record length required is 16 times the fundamental period. Thus, for an ECG, the minimum record length is about 11 seconds. Since the maximum significant frequency component contained in an ECG is less than 50 cps (section 2.2), 500 samples per second are sufficient to calculate the autocorrelation function.

5. THE OVERALL ON-LINE SYSTEM FOR CORRELATION ESTIMATION

5.1 Characteristics of the M3 computer

The characteristics of the M3 (3) computer must be studied in order to make a direct connection of the A-D and D-A converter to it. The first and most important point is to make sure that the memory of the M3 is large enough to store the samples which are required for calculation of correlation functions. Also, the input speed of the M3 must be high enough to read in the data-words which are produced by the A-D converter.

The storage provided on the M3 is 8,192 words. The input speed varies from 60 words per second up to 4000. In case of correlation analysis of the physiological data, the input speed of 500 words per second (section 4.5.1, 4.5.2) and a total of 5000 words (section 4.5.1, 4.5.2) are required. Therefore, the M3 is suitable for correlation analysis of the physiological data.

5.2 The Overall System

Following the requirements which are considered in the previous chapters, an on-line input-output system coupled to the M3 (3) computer is designed and shown in Fig. 5.1. The input system is designed to digitize one or two channels of analog physiological data and to read them into the M3 computer for calculation of the autocorrelation or crosscorrelation function. The output system is designed to plot the autocorrelation or crosscorrelation function graphically. The graphs of these functions are referred to as the autocorrelogram and the crosscorrelogram, respectively.

When an autocorrelogram is required, the input function $f_1(t)$ is applied to channel 1. Alternatively, if a crosscorrelogram is required, the input functions $f_1(t)$ and $f_2(t)$ are applied to channel 1 and channel 2 simultaneously.

Two identical holding circuits are used in order to store simultaneous samples from channels 1 and 2. This is necessary when the value of the crosscorrelation function at zero delay time is required.

The system is composed of two sampling gates, two holding circuits, two multiplex switches, an analog to digital converter, a plot buffer register, a digital to analog converter, an X-Y recorder, and the input and output control networks.

The input control network consists of three main parts: the two ring counters, the write circuit and the head and block switch selector. The two ring counters are used to control the sampling rate. The write circuit, having a counter and writing gates, writes the eight-bit data word contained in the shift register into the M3 memory. The head and block switch selector, having two counter controlled diode matrices, is used to address the word locations in the M3.

The output control network outputs the data from the M3 for plotting.

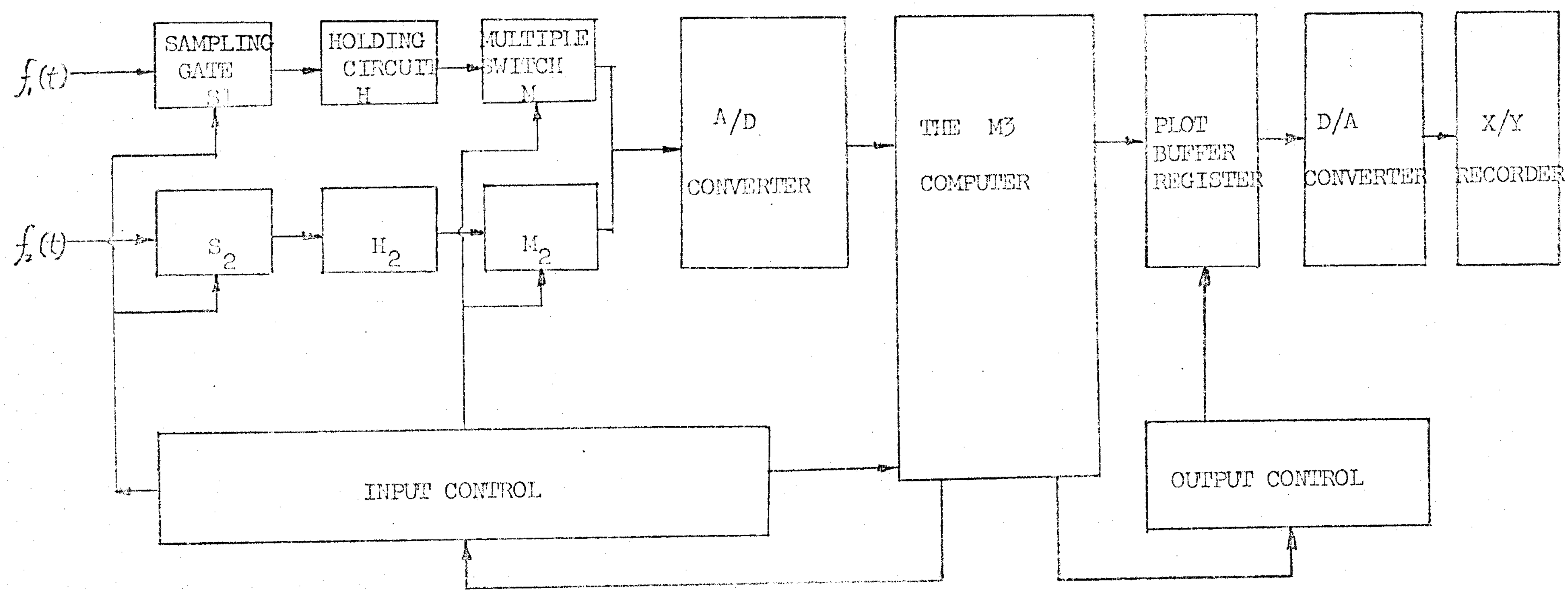


Figure 5.1 The Overall System Block Diagram

6. THE INPUT SYSTEM

6.1 Introduction

The M3 (Appendix I) is a stored program computer. Therefore, the flow of data is controlled by the program stored in the computer. In order that M3 can read external data into its memory, an input program must be stored in its memory first. An optimum input program is considered. Although this program results in a high input speed, it spends the capacity of the memory. Consequently, a technique is developed which feeds data into the M3 without the control of the computer stored program. The details of this technique will be described in the next section.

6.2 The Logic Operation

The input system designed is shown in Fig. 6.1 which is referred to in describing its operation, while the timing diagram of Fig. 6.2 and Fig. 6.3 shows the waveforms at the more important points. Fig. 6.2 shows the timing waveforms if a crosscorrelation function is intended to be calculated by the M3 from the input data, while Fig. 6.3 shows the timing waveforms if an autocorrelation function is intended to be evaluated.

The symbols appearing in the logic drawings are listed under abbreviations on page IX. The subscript number for each symbol is used for identification.

The operation of the A-D converter will be described in section 6.3.3 and the operation of the M3 appears in Appendix I (for more details, see ref. 3).

For crosscorrelation, with reference to Fig. 6.1 and 6.2, the sequence of operation of the input system is as follows:

Push "cross" button so that terminal "A" is connected to terminal "C", "F" to "H", "P" to "R", "T" to "W", -6 volts tests G_9 and G_{10}, and a single start pulse of width 17.5 millisecond sets the start-stop flip-flop (S.S.F.F.) to the "1" state and tests G_1.

At the arrival of a drum marker pulse, G_1 emits a pulse to set Ring Counter No. 1 to the "10000000" state and Ring Counter No. 2 to the "1000" state. The pulse emitted by G_1 also zeros the Head Counter, the Block Counter and sets the Head Flip-Flop (H.F.F.) to the "1" state.

The inhibit gate 1 (IH_1) is used to prevent the 1^{st} drum marker from shifting the "1" in the 1^{st} stage to the 2^{nd} stage of the Ring Counter No. 2. The OS_{11} and the IH_5 are used to prevent the 1^{st} "1000" state of Ring Counter No. 2 from setting Ring Counter No. 1 and counting the head counter.

The "1" state of the 1^{st} stage of Ring Counter No. 1 is differentiated by A_1 and is shaped by OS_1 to form a 10 μS pulse. This pulse opens the sampling gates (S_1 and S_2) to allow the value of $f_1(t)$ and $f_2(t)$ to be stored in the holding circuits H_1 and H_2, respectively. Ten μS later, S_1 and S_2 are closed by the falling edge of the 10 μS pulse, and hence two simultaneous samples have been stored in the holding circuits. The falling edge of the 10 μS pulse also triggers A_2 to form a 30 μS pulse through OS_2. The leading edge of the 30 μS pulse closes the multiplex switch 1 (M_1) and starts the A-D Converter. Then the converter codes the sample which has been stored in H_1.

After 20 μS (the conversion time of the converter), the sample will be converted into an 8-bit word in the output register of the converter. As soon as the conversion is complete, an A-D done pulse is emitted by the converter. This pulse, after being delayed 80 μS by OS_3, shifts the 8 bits simultaneously into the last 8 stages of the shift register (S.R) in the M3.

It takes 52 μS to write 8 bits from the shift register into the memory and 20 μS to convert a sample. Therefore, the 80 μS delay time is necessary to prevent shifting the word from A-D to S.R before the previous word (in S.R) has been written in the memory.

The first word marker pulse, which is emitted by the bit counter in the M3 shifts the "1" in the first stage of Ring Counter No. 1 to the second stage. The "1" state of the second stage, which is differentiated by A_6, zeros the write counter through OR_2 and sets the emit flip-flop (EMT.F.F.) in the M3 to the "1" state through OR_3. When the EMT.F.F. is set to "1", the "32 immediate" (32 IMM) pulses emitted from g_5 test G_4. This gate is controlled by the "0" side of the most significant stage of the write counter and allows the first 8 pulses to pass. The "1" state of the EMT.F.F. also opens G_5 and G_6 to serve as the "write order". The opened G_5 allows the 32 IMM pulses to test G_7 and G_8. At the arrival of an IMM pulse, a "0" stored in the thirty-second stage of the S.R causes G_7 to emit a positive pulse to the pulse shaper in the M3. Consequently, a "0" is recorded in the M3 memory. Similarly, a "1" stored in this stage causes G_8 to emit a positive pulse to record a "1" in the memory. The opened G_6 allows the strobe pulses passing through G_3 to cause the write counter to count and shift the S.R to the right.

When the 8^{th} strobe pulse arrives at the write counter, the most significant stage is switched to the "1" state which zeros the S.R through OS_4 and closes G_3 and G_4. At this time, the 8-bit word has been recorded in the 1^{st} word location of track 1000 and block 0000 which has been addressed by the output from G_1.

The "1" state of the second stage of Ring Counter No. 1 also closes the second multiplex switch M_2 through G_9 and starts the A-D converter through G_9, A_4 and OR_1. Before the second word marker pulse is emitted from the M3, the sample of $f_2(t)$ has been coded and stored in the last 8 stages of the shift register as a binary word. This is because the conversion is completed at the 20^{th} μS after the first word marker and the converted data is shifted into the S.R at the 100^{th} microsecond after the first word marker, but the second word marker pulse is generated at the 266^{th} μS after the first one.

The second word marker pulse shifts Ring Counter No. 1 to the 00100000 state. The "1" state of the 3^{rd} stage of Ring Counter No. 1 writes the word of $f_2(t)$ in the 2^{nd} word location of track 1000 in block 0000.

The 3^{rd} word marker pulse shifts the "1" of the 3^{rd} stage to the 4^{th} stage, the 4^{th} word marker pulse shifts the "1" of the 4^{th} stage to the 5^{th} stage and so on.

The 8^{th} word marker pulse shifts the "1" of the 8^{th} stage of Ring Counter No. 1 back to the 1^{st} stage. This 10000000 state of Ring Counter No. 1 repeats the cycle as above. Consequently, the 2^{nd} data word of $f_1(t)$ is written in the 9^{th} word location and the 2^{nd} data word of $f_2(t)$ is written in the 10^{th} word location of the track 1000 in block 0000.

After one revolution of the drum memory, Ring Counter No. 1 has worked 8 cycles and thus 16 words have been written in this track.

The 64^{th} (0^{th}) word marker pulse shifts Ring Counter No. 1 to the 10000000 state. Three μS later, the next drum marker pulse shifts Ring Counter No. 2 to the 0100 state. The "1" state of the second stage is shaped by OS_7 to close the inhibit gate 2 (IH_2) for 550 μS. Consequently, the 1^{st} and 2^{nd} word marker pulse can not pass through IH_2 to shift Ring Counter No. 1. The 3^{rd} word marker pulse passes through IH_2 to shift the "1" to the second stage of Ring Counter No. 1. Then the same process as the first revolution of the drum memory is going on and another 16 words are written in the word locations of 3,4; 11, 12; 19, 20; 27, 28; 35, 36; 43, 44; 51, 52; 59, 60 of the track 1000 in block 0000.

The 550 μS pulse, after being delayed 17.5 ms by OS_9, closes IH_2 for 550 μS again. This causes Ring Counter No. 1 to write another 16 words in the word locations of 5, 6; 13, 14; ....; 61, 62 of the same track as above.

After four revolutions of the drum memory, the track 1000 in block 0000 has been filled with 64 words. The following drum marker pulse shifts Ring Counter No. 2 in the 1000 state again. The "1" in the 1^{st} stage of Ring Counter No. 2 closes the inhibit gate 3 (IH_3) for a time of one revolution. This "1", which is differentiated by A_3 and delayed 60 μS by OS_{10}, resets Ring Counter No. 1 in the 10000000 state and switches on the head of track 10001 through the head counter and the track selector. Consequently, the next cycle starts and the following 64 words are written in track 1001.

The 60 μS delay time is necessary in order to allow Ring Counter No. 1 to write the 64^{th} word in the 0^{th} word location of track 1000 in block 0000.

After thirty-two revolutions of the drum memory, all the eight tracks in block 0000 have been filled with words. At this time, a pulse generated by OS_5 causes the block counter to count from 0000 to 0001 which switches on block 0001 through the block selector. The following words will be written in tracks 1000 to 1111 contained in this block.

When the last track (track 1000) in block 1001 has been fully filled with words, the block counter counts to 1010 to activate the block selector 1010 line which resets the S.S.F.F. to stop the operation of this system.

After completion of the above operation, 5,120 words have been fed into the M3 memory. These words are stored in 80 tracks which constitute the block 0000 to 1001. The other 48 empty tracks are intended to be used to store the crosscorrelation or autocorrelation program which will operate on these data words. These 48 tracks are also used to store the partial products and summations produced by the correlation programs.

Half of the 5,120 data words are attributed to the function $f_1(t)$ and the other half to the function $f_2(t)$. This number of samples (2,560) is sufficient to obtain the crosscorrelogram since $f_1(t)$ and $f_2(t)$ are EEG's or ECG's (section 4.5.1, 4.5.2).

The input system operation is completed in 5.6 seconds, thus either $f_1(t)$ or $f_2(t)$ is sampled at a rate of 457 samples per second. This rate is approximately equal to 10 samples of the highest significant frequency component (50 cps) of the EEG or the ECG. Again, this sampling rate is sufficient to obtain data for correlation analysis of the EEG or the ECG.

When an autocorrelation function is desired to be calculated, apply the input function $f_1(t)$ to channel 1 and push the "auto" button. Thus, G_9 and G_{10} are closed and terminals A, F, P, T are connected to terminals B, G, Q, U, respectively.

The operation of the input system for autocorrelation is similar to the operation for crosscorrelation. But the eight-stage Ring Counter No. 2 causes the Head Counter to advance one for every eight drum marker pulses. This allows Ring Counter No. 1 to write 64 words in a track after eight revolutions of the drum memory.

The operation of the input system is completed in 11.2 seconds for autocorrelation and 5,120 data words have been input to the M3 memory. This record length (11.2 sec.) and number of samples (5, 120) are adequate to obtain the autocorrelation function of the EEG or the ECG.

6.3 The Components

6.3.1 The sampling gate and the associated trigger circuit

A sampling gate is a transmission circuit in which the output is a reproduction of an input waveform during a selected time interval and is zero otherwise. The time interval for sampling is controlled by the rectangular wave which is produced by the trigger circuit.

The sampling gate used in the input system is a bidirectional

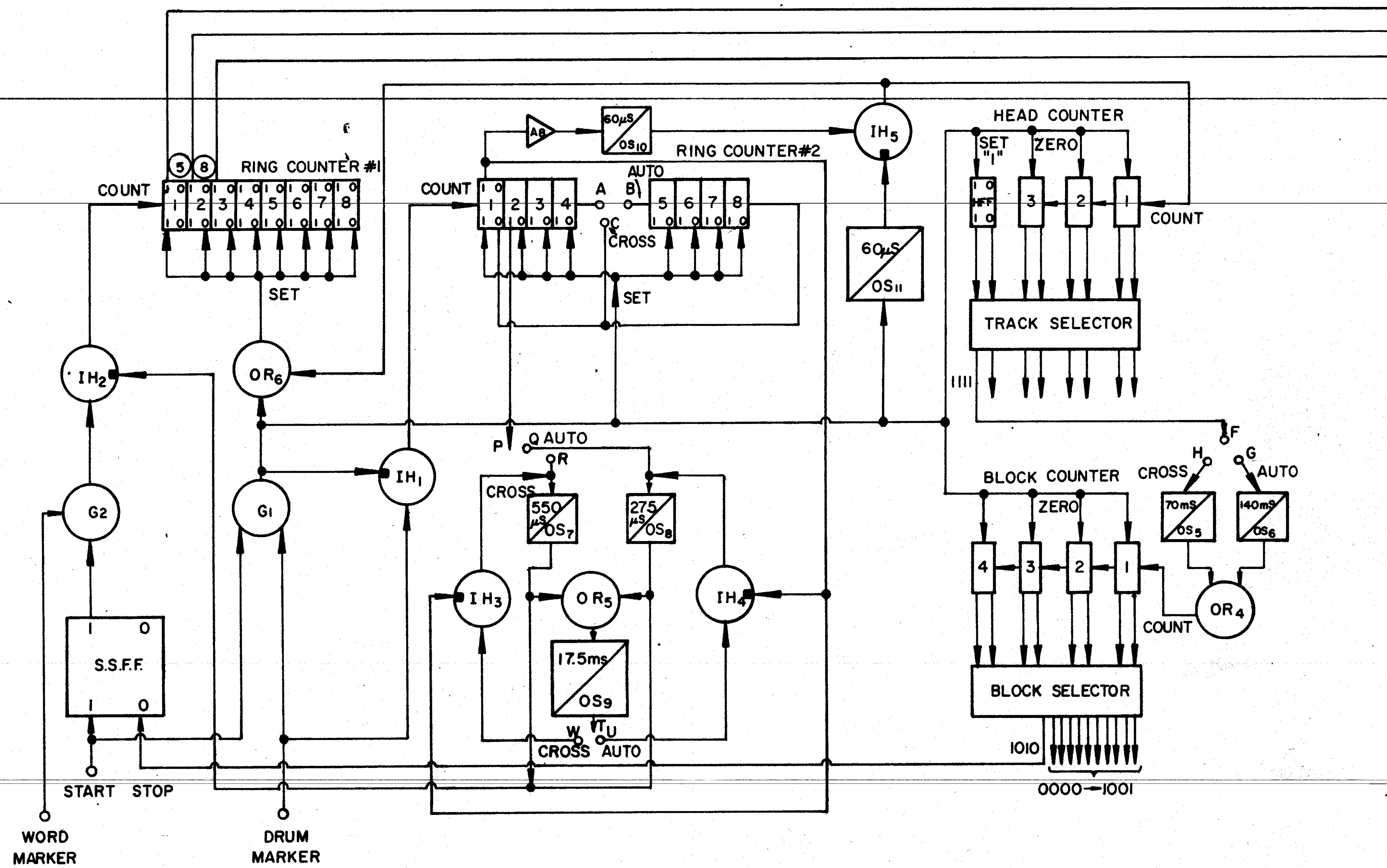
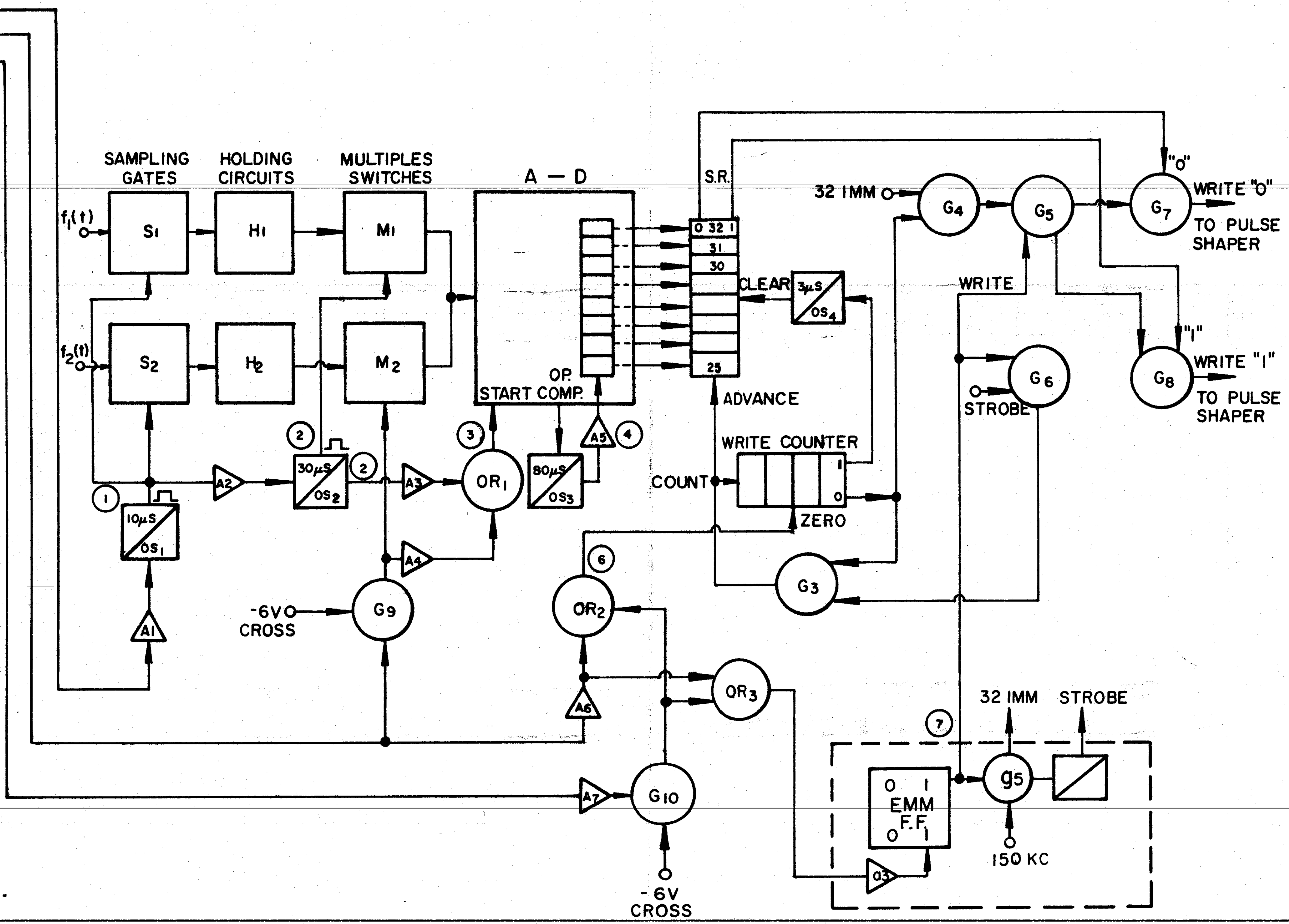


FIGURE 6.1 THE INPUT SYSTEM


SAMPLING GATES
HOLDING CIRCUITS
MULTIPLES SWITCHES
A — D
S.R.
f1(t)
f2(t)
S1
H1
M1
S2
H2
M2
OP. START COMP.
0 32 1
31
30
25
CLEAR
3μS OS4
ADVANCE
WRITE COUNTER
COUNT
ZERO
1
0
10μS OS1
A1
A2
30μS OS2
A3
A4
OR1
80μS OS3
A5
G9
-6V CROSS
OR2
OR3
A6
A7
G10
- 6V CROSS
32 IMM
G4
G5
G7
"0"
WRITE "0"
TO PULSE SHAPER
G8
"1"
WRITE "1"
TO PULSE SHAPER
WRITE
G6
STROBE
G3
32 IMM
STROBE
EMM F.F.
0 1
0 1
g5
150 KC
1
2
3
4
6
7

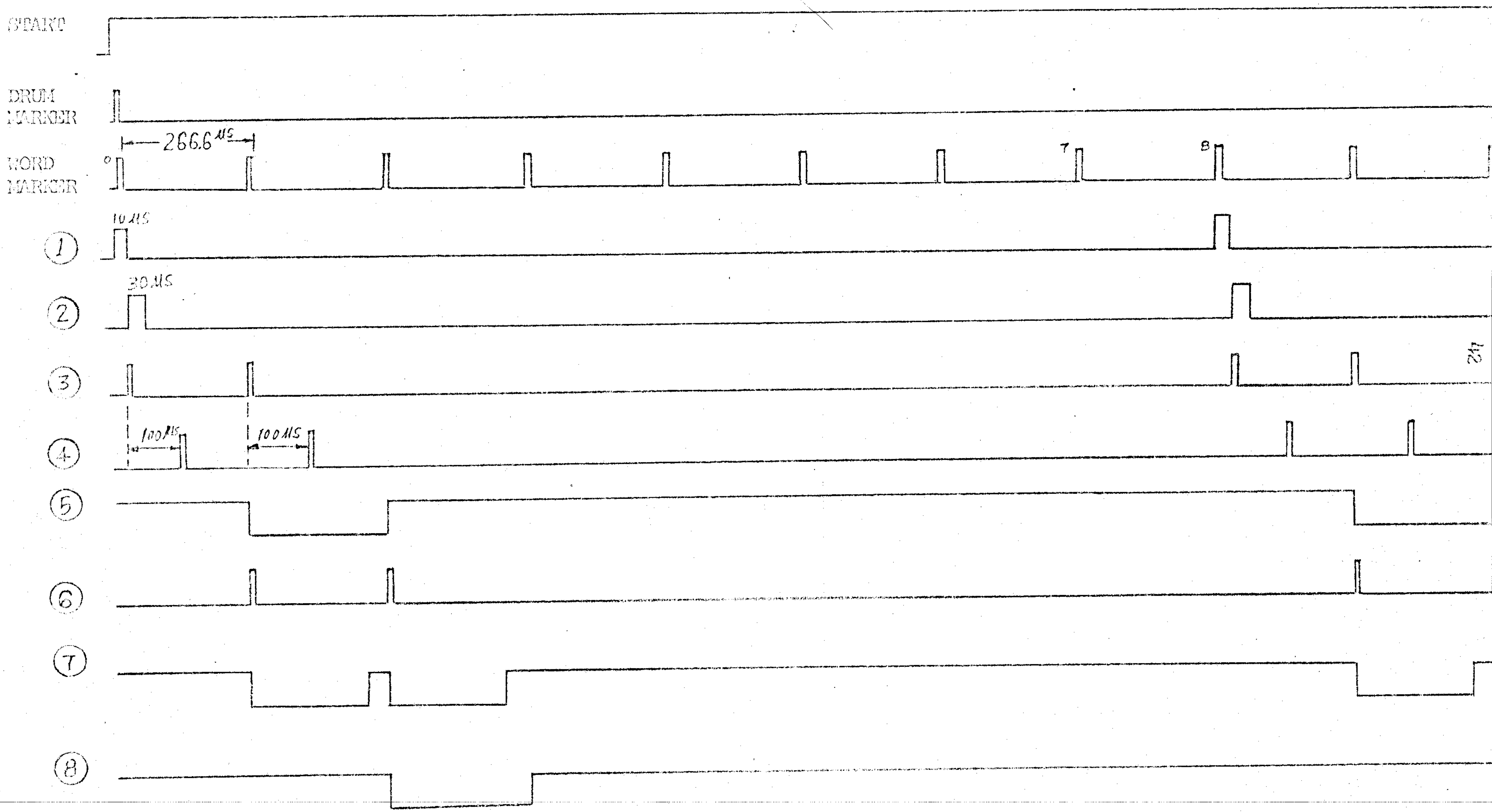


Figure 6 2   The Input System Timing Diagram for Crosscorrelation

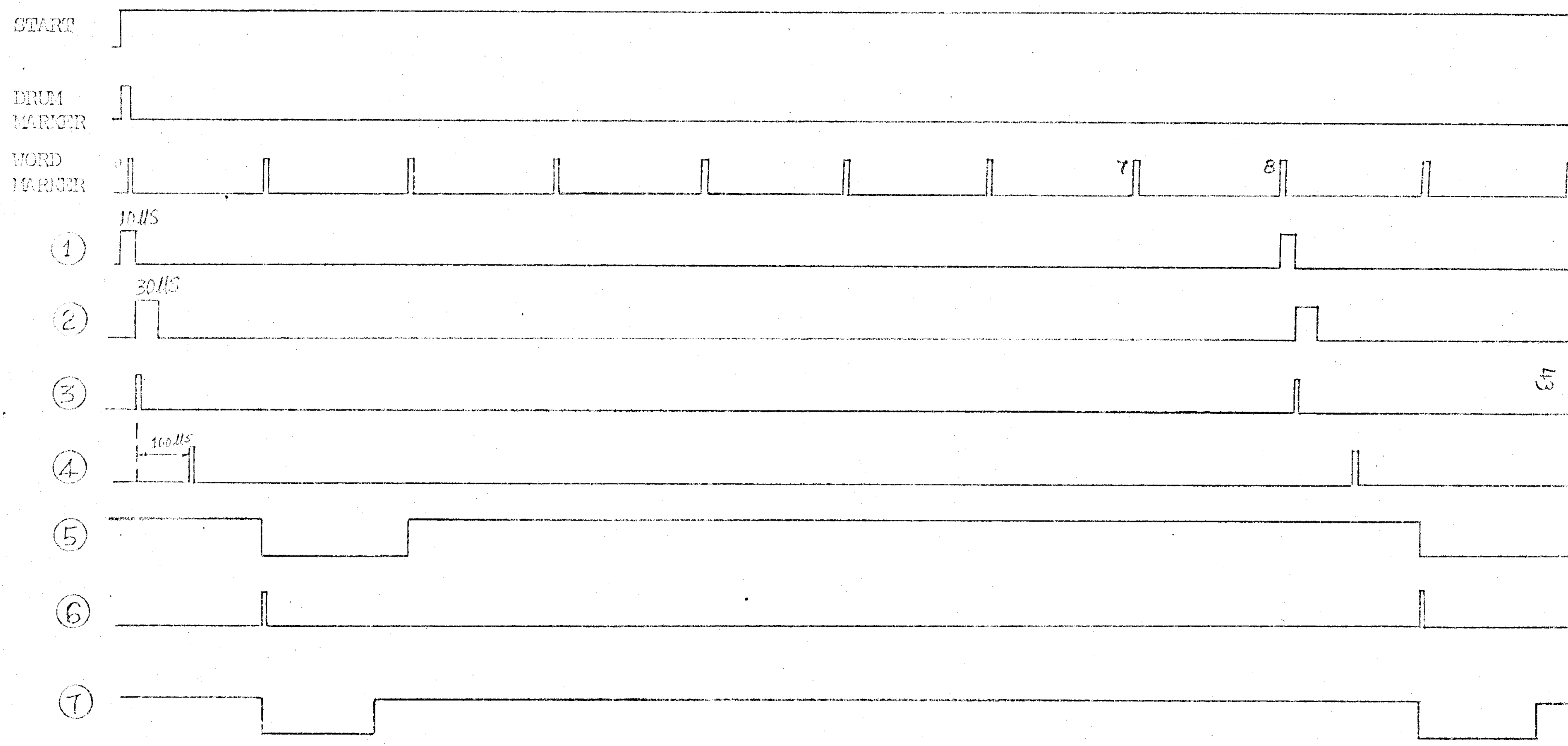


Figure 6.3 The Input System Timing Diagram for Autocorrelation

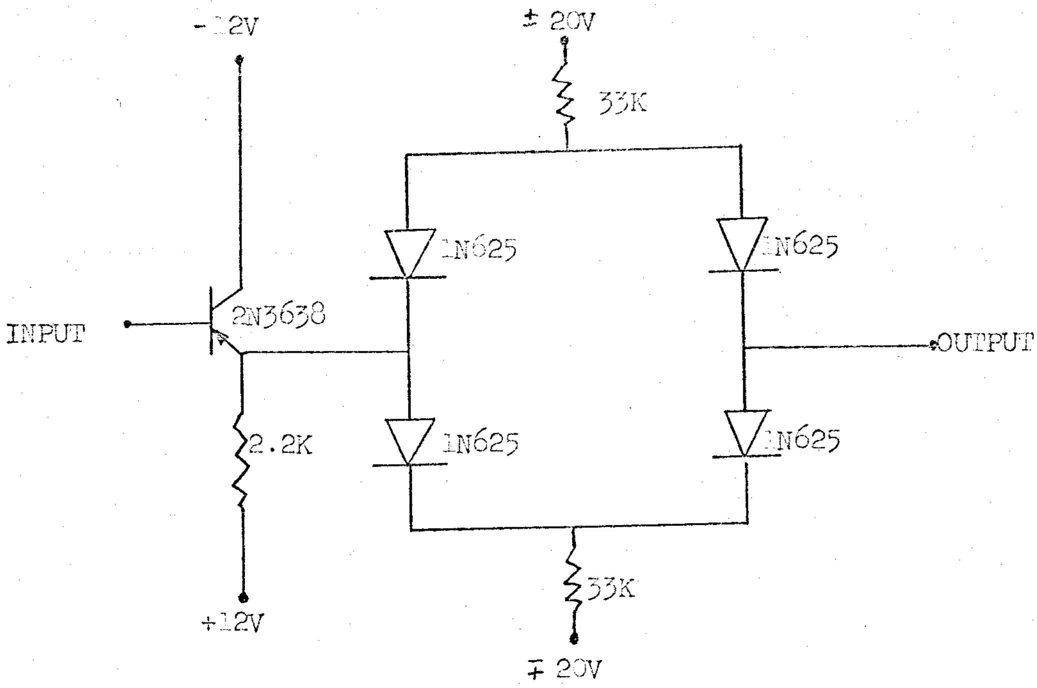


Figure 6.4   The Sampling Gate

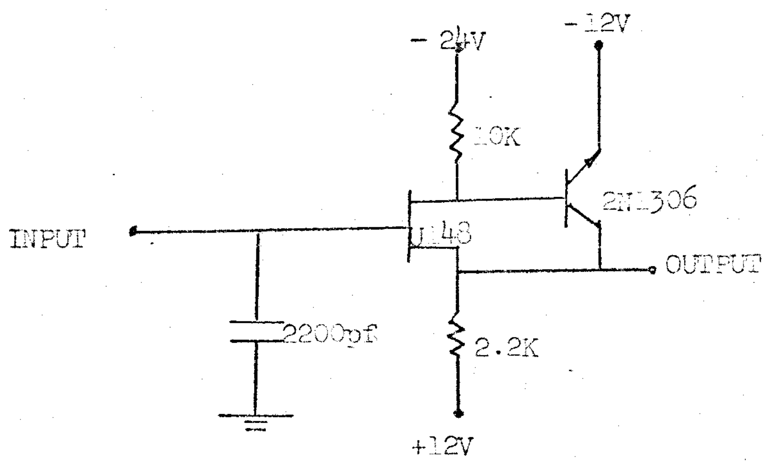


Figure 6.5 The Holding Circuit

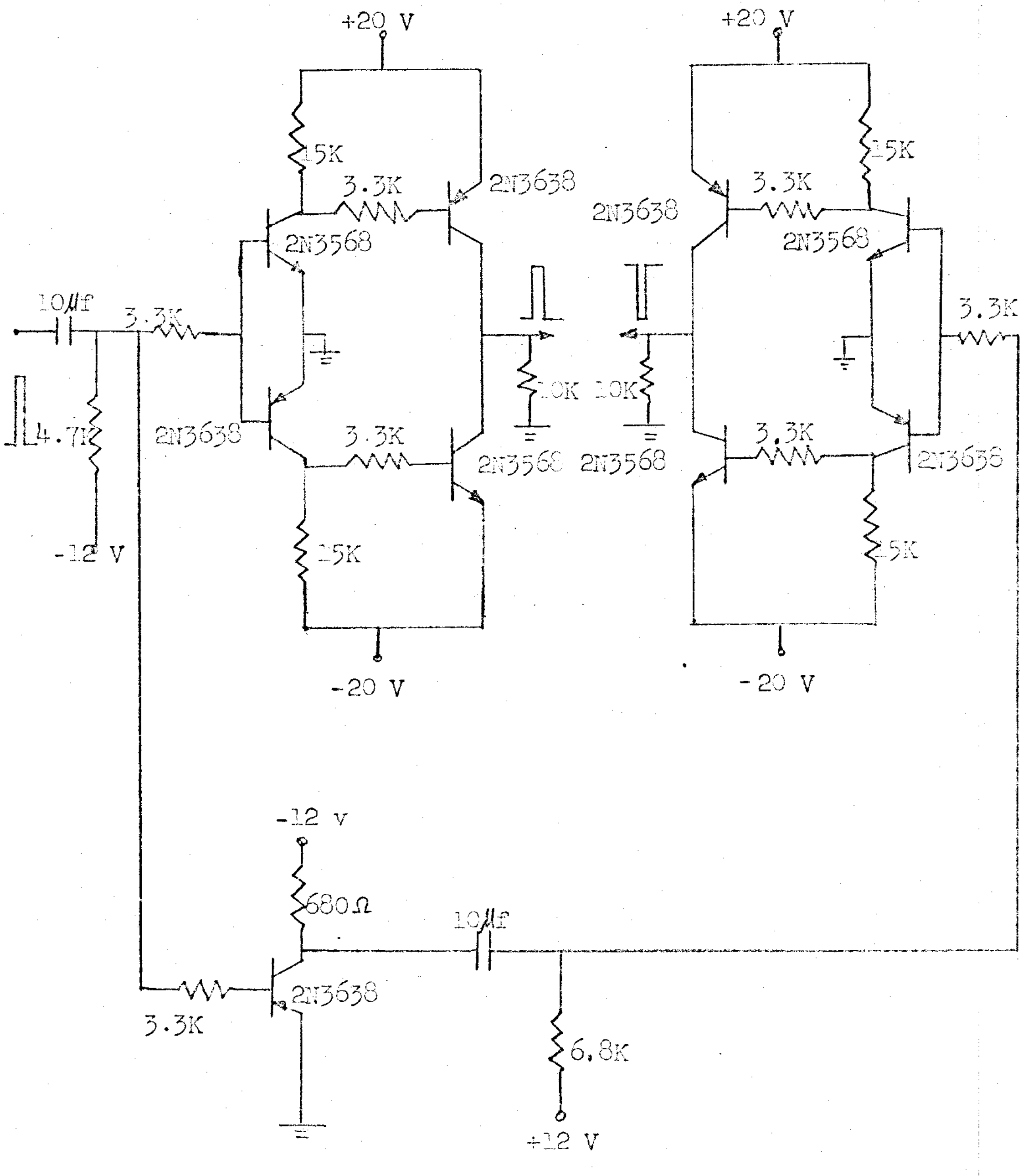


Figure 6 6 Trigger Circuit

four-diode gate as shown in Fig. 6.4. When the trigger voltages are at levels +20 volts and -20 volts, all four diodes are conducting and the input voltage Vi (through the emitter follower) is connected to the holding circuit (Fig. 6.5) through two parallel paths, each consisting of two diodes in series. When the trigger voltages are -20 volts and +20 volts, all four diodes are reverse biased and the input voltage Vi is disconnected from the holding circuit.

The trigger circuit shown in Fig. 6.6 provides two pulses of +20 volts and -20 volts to open the sampling gate when a single positive going pulse triggers this circuit. This circuit also provides -20 and +20 volts to close the sampling gate when the trigger pulse disappears.

6.3.2 The holding circuit and the multiplex switch

The holding circuit shown in Fig. 6.5 is used to store the sample for A-D conversion. The magnitude of the sample is stored in the capacitor as a voltage and the source follower provides a high input impedance to prevent a loss of charge from the capacitor.

The multiplex switch is exactly the same as the sampling gate which is shown in Fig. 6.4.

6.3.3 The analog to digital converter

Fig. 6.7 shows an 8-bit successive approximation A-D converter. This converter uses a digital register with gatable "1" and "0" inputs, a digital to analog converter, a comparison circuit, a control timing loop and a flip-flop distributor register.

At the beginning of the operation, both the digital register and the distribution register are set with a "1" in the most significant

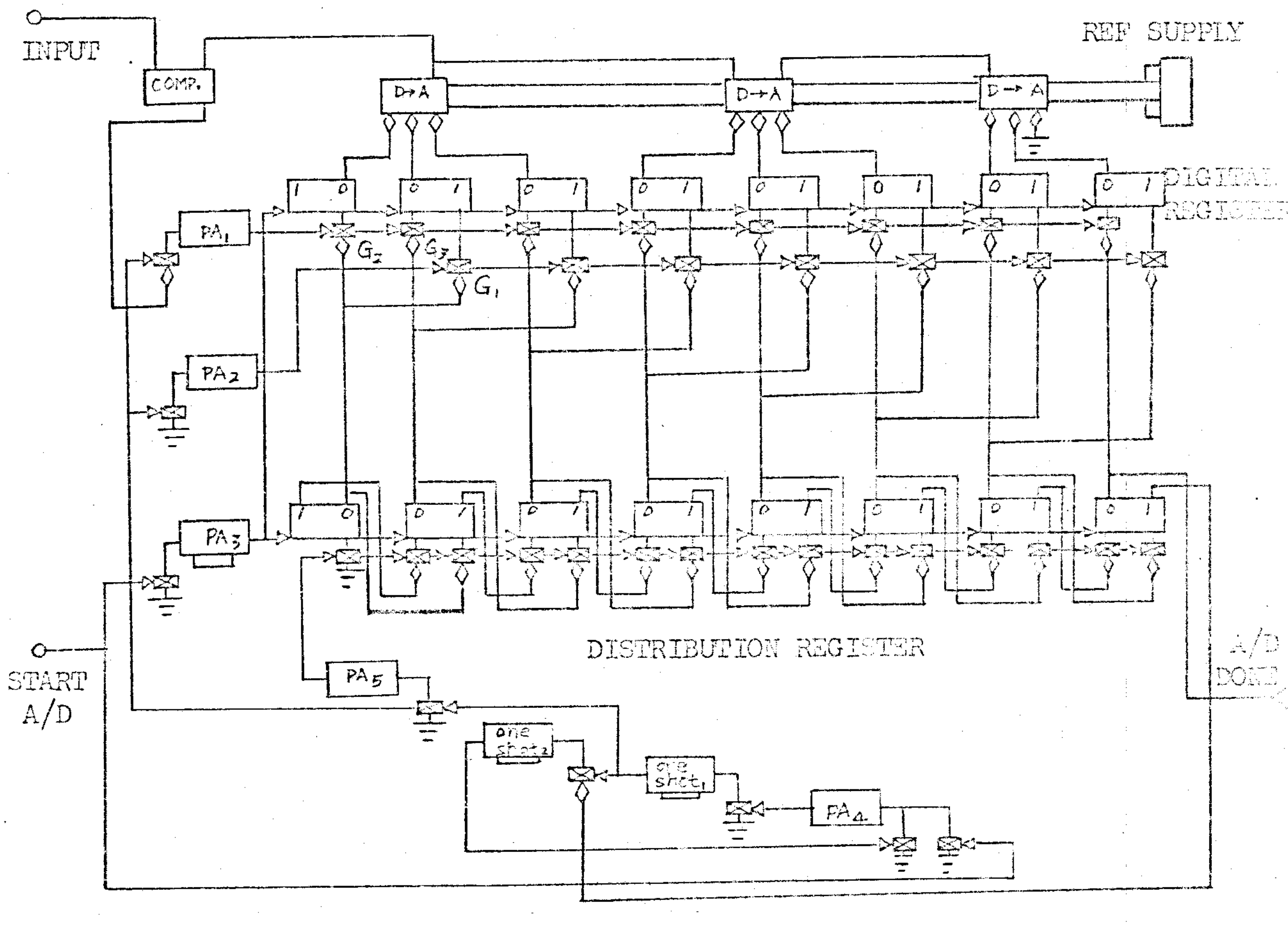


Figure 6.7 8 Bit A/D Converter (Conversion time 20 μsec)

(After Digital Equipment Corporation)

bit and a "0" in all bits of lesser significance by the start pulse. At the same time, the start pulse is amplified by pulse amplifier 4 (PA_4) and is delayed 2.23 μS by one-shot 1. This delay time allows the D-A converter and the comparator to have settled. The output of one-shot 1 amplified by PA_5 shifts the "1" in the most significant bit of the distribution register to the next position. The output of one-shot 1 also sets the second stage of the digital register to "1" since gate 1 (G_1) has been opened by the "0" of the most significant bit of the distribution register. If the output of the D-A converter is greater than the analog input signal, the output of the comparator resets the most significant bit of the digital register to "0" through G_2. If it is not, the most significant bit of the digital register remains in the "1" state.

This procedure is repeated until the least significant bit has been operated. Then an 8-bit data word is present in the digital register. The A-D done pulse shifts the 8 bits out simultaneously. This readout takes only 0.2 μS.

6.3.4 The inhibit gate

The inhibit gate is a logical element which will allow none of the signal to be transmitted through the gate when the inhibit terminal is at a particular voltage.

The inhibit gate is shown in Fig. 6.8. The gate is turned on when input A is at -6 volts and input B is at 0 volt. If input B is at -6 volts, no pulse can pass through this gate.

The characteristics and the symbolic representation of the inhibit

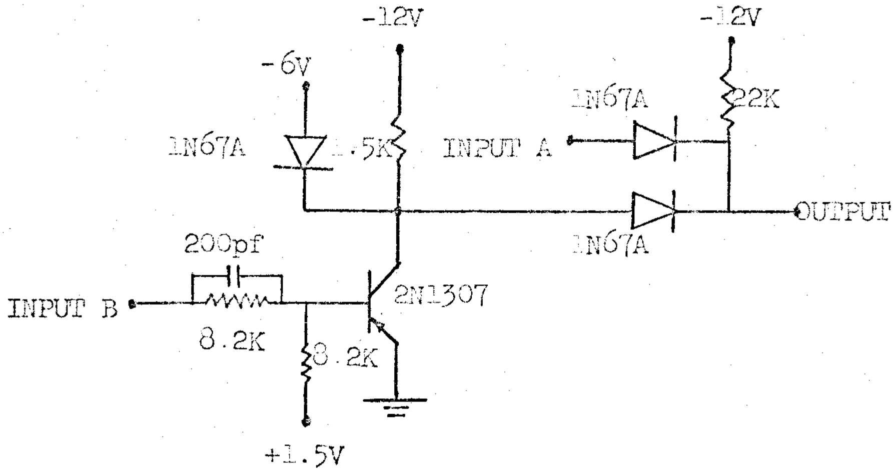


Figure 6.8 The Inhibit Gate

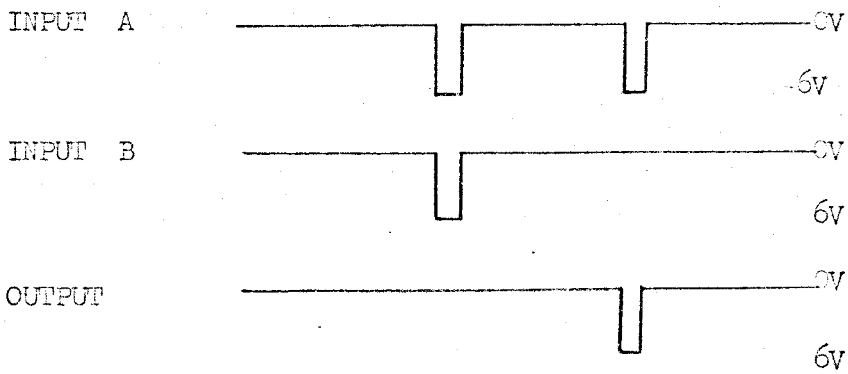


Figure 6.9 Characteristics of The Inhibit Gate

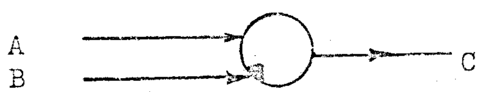


Figure 6.10 Symbolic Representation of An Inhibit Gate

gate are shown in Fig. 6.9 and Fig. 6.10, respectively. In Fig. 6.10, the inputs A and B are represented by arrows pointed into the circle. The output C is represented by an arrow coming out of the circle.

6.3.5 The ring counter and other components

The ring counter is a chain of flip-flops in which the first is coupled to the second, the second to the third and so on, with the last coupled back to the first. In this counter, all stages are triggered simultaneously, and one stage is in the "1" state; all other stages are in the "0" state. With each successive trigger the "1" state moves to the following stage.

A four-stage ring counter is shown in Fig. 6.11. Each stage has four diode gating ciruits, two used for initial setting, and two for shifting.

The characteristics of the four-stage ring counter is shown in Fig. 6.12. It is noted that the output from any stage is a pulse train of period 4T with each pulse of duration T, where T is the period of the shifting pulse.

The other components: the flip-flop, the one-shot, the "and" gate, the "or" gate, the AC amplifier are shown in Appendix II because these circuits are identical to those of the M3 computer.

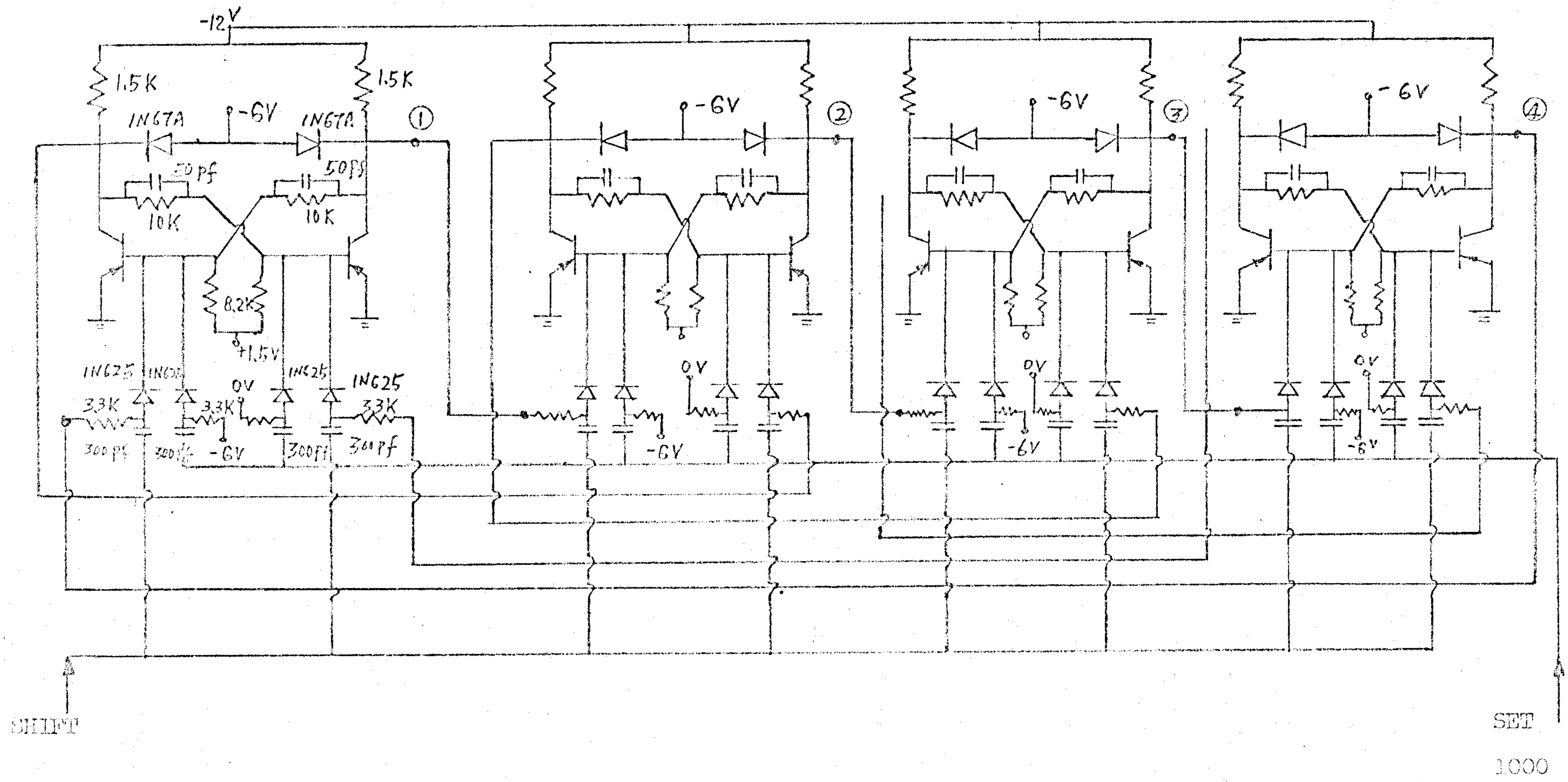


Figure 6.11 Four-Stage Ring Counter

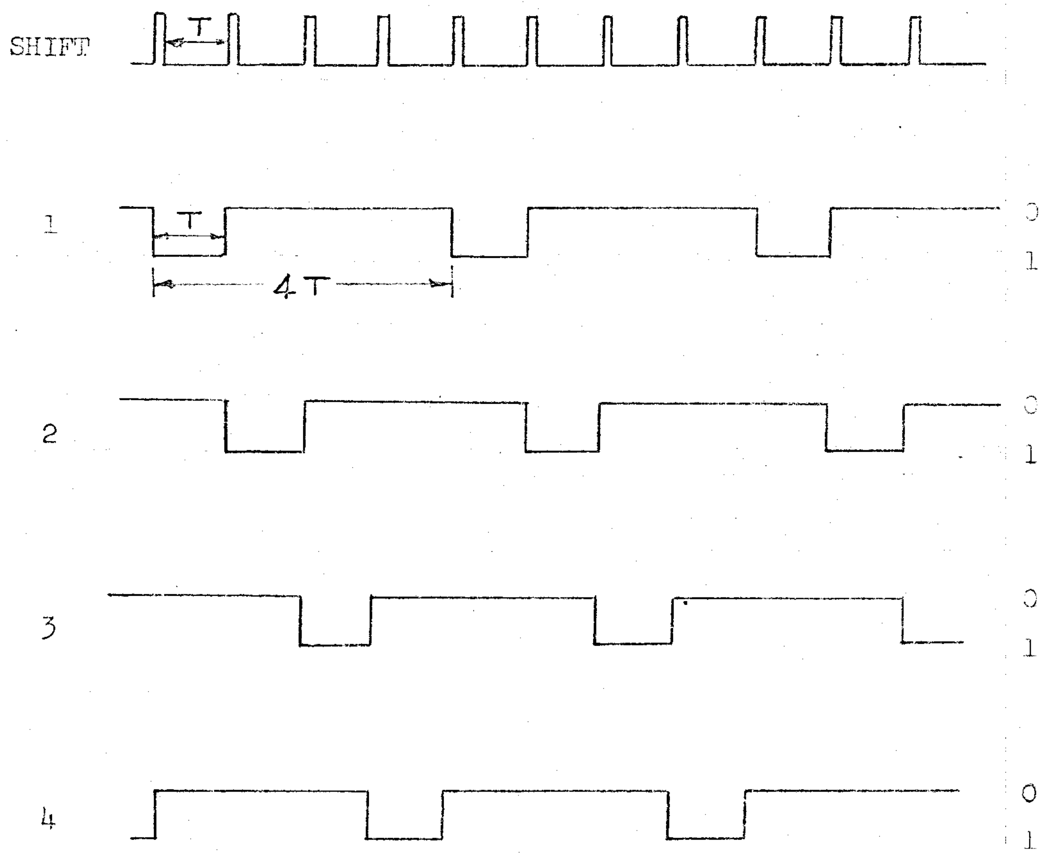


Figure 6.12 Timing Diagram for a 4-stage Ring Counter

7. THE OUTPUT SYSTEM

7.1 Introduction

The M3 makes use of a paper tape punch and electric typewriter as the output devices. Information punched on a paper tape is very difficult for any person to understand directly. Of course, information typed by the typewriter is useful to a person, but if the information represents a continuous variable as a function of time it is better to output the information graphically.

The waveform of the correlation function of an EEG or ECG (the correlogram of an EEG or ECG) is usually interpreted by a physician. Therefore an X-Y recorder is used as the output device to show the autocorrelation function or crosscorrelation function graphically.

In order to use an X-Y recorder as an output device of a digital computer, one should first convert the digital output to an analog voltage; also the time response of the X-Y recorder must be fast enough to record the analog voltages.

The M3 takes 2 milliseconds for multiplication of two 8-bit data and takes 250 microseconds for addition of two data. If a program performs 5,000 multiplications and additions, it will take about 12 seconds to complete the program. If 2,500 multiplications and additions are performed, it will take 6 seconds.

As the value of each point of the autocorrelogram estimated by the M3 is an average of 5,000 products and the value of the crosscorrelogram is an average of 2,500 products, it will take 12 seconds to obtain one value of the autocorrelogram and 6 seconds for crosscorrelogram.

Therefore, the output rate of the M3 for calculation of correlation functions is either 12 seconds per word or 6 seconds per word. Since the maximum recording speed of the Moseley 2D-2 X-Y recorder (section 7.4) is 20 inches per second, this recorder is fast enough to plot correlograms.

7.2 The Logic Operation

The output system which plots correlation functions on a paper automatically is shown in Fig. 7.1. This system is composed of a plot buffer register, a digital to analog converter, an X-Y recorder, a one-shot multivibrator, an A-C amplifier and an inverter.

Before a plot order is initiated, it is assumed that the value of the correlation function to be plotted is in the shift register of the M3.

The plot order generated by the function table of the M3 is inverted by inverter I which transfers all 32 bits of the shift register into the plot buffer register simultaneously. At this time the computer is not needed any longer. The plot order also triggers the one shot OS and after the 10 μ sec. delay, the A-C amplifier A, produces the "operation complete" pulse which resets the control flip-flop of the M3 to "0" state. The output system is then independent of the computer.

As soon as the data-word is fed into the plot buffer register, the significance of the data is weighted by the D-A converter and the magnitude of the output of the D-A converter is plotted by the X-Y recorder.

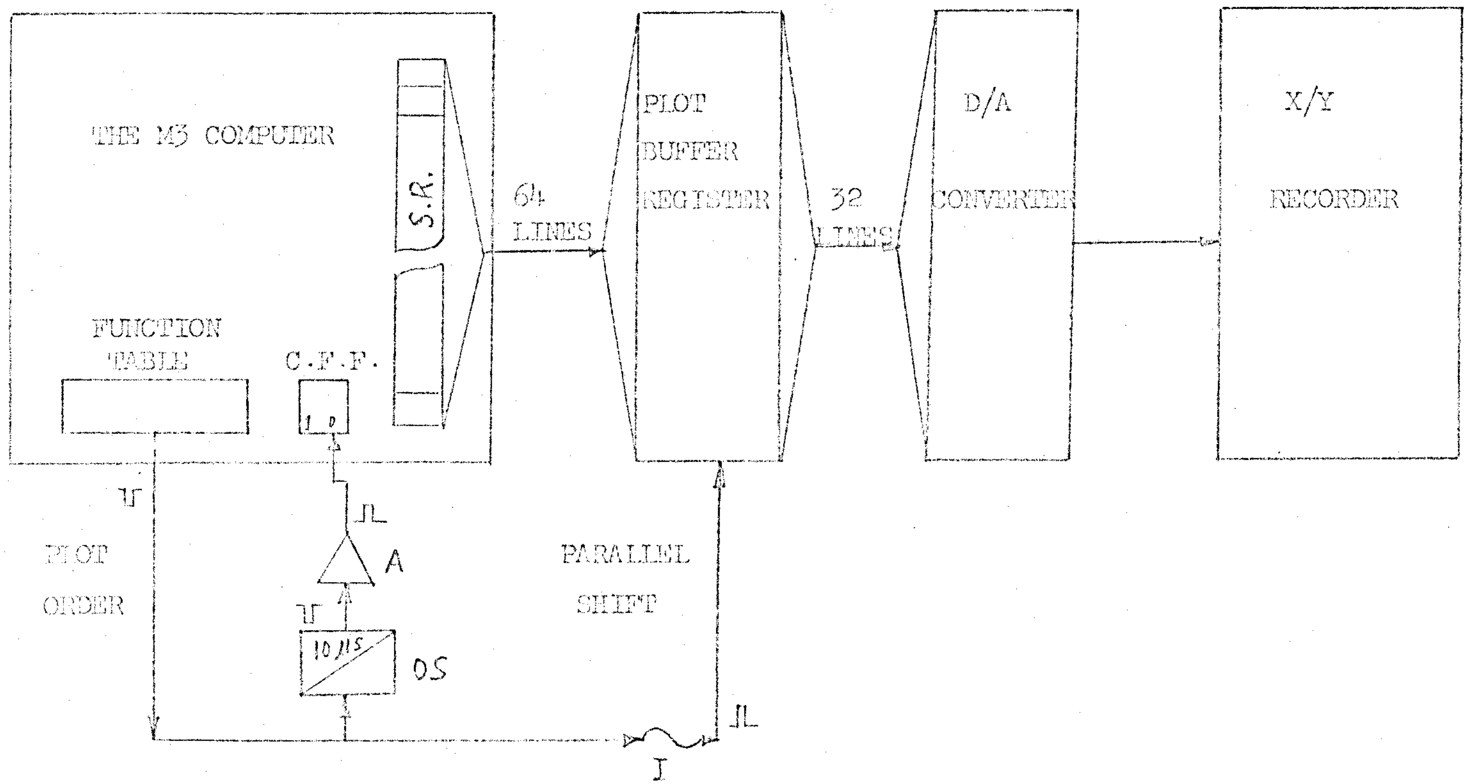


Figure 7.1 The Output System

7.3 The Components

7.3.1 The plot order generator

The order code of the M3 contains 19 orders. Each order is indicated by the 5 bits of stages 21 to 25 of the control register. The function table decodes the 5 bits to generate the order.

In order to obtain the plot order, 6 diodes are added to the function table as shown in Fig. 7.2. When stages 21 - 25 of the control register are in the 00101 state and the control flip-flop is in the "1" state, -6 volts is generated to serve as the plot order. The "1" side of the control flip-flop input to the function table is used to prevent generation of incorrect orders when shifting data into the control register.

The code number for the plot order is 00101 (binary) or decimal 5. This order means that the digits contained in the shift register are plotted on the output X-Y recorder. The digits are not lost from the shift register in so doing. Next order is in location "Y".

7.3.2 The buffer register

The 32-stage plot buffer register is shown in Fig. 7.3. Each stage of the buffer has three input terminals, the "0", "1" and "setting". A positive going transfer pulse applied to the 32 setting terminals shifts all the bits from the shift register to the buffer simultaneously.

7.3.3 The digital to analog converter

The digital to analog converter, which converts the binary number held by the plot buffer register into an analog voltage, is shown in

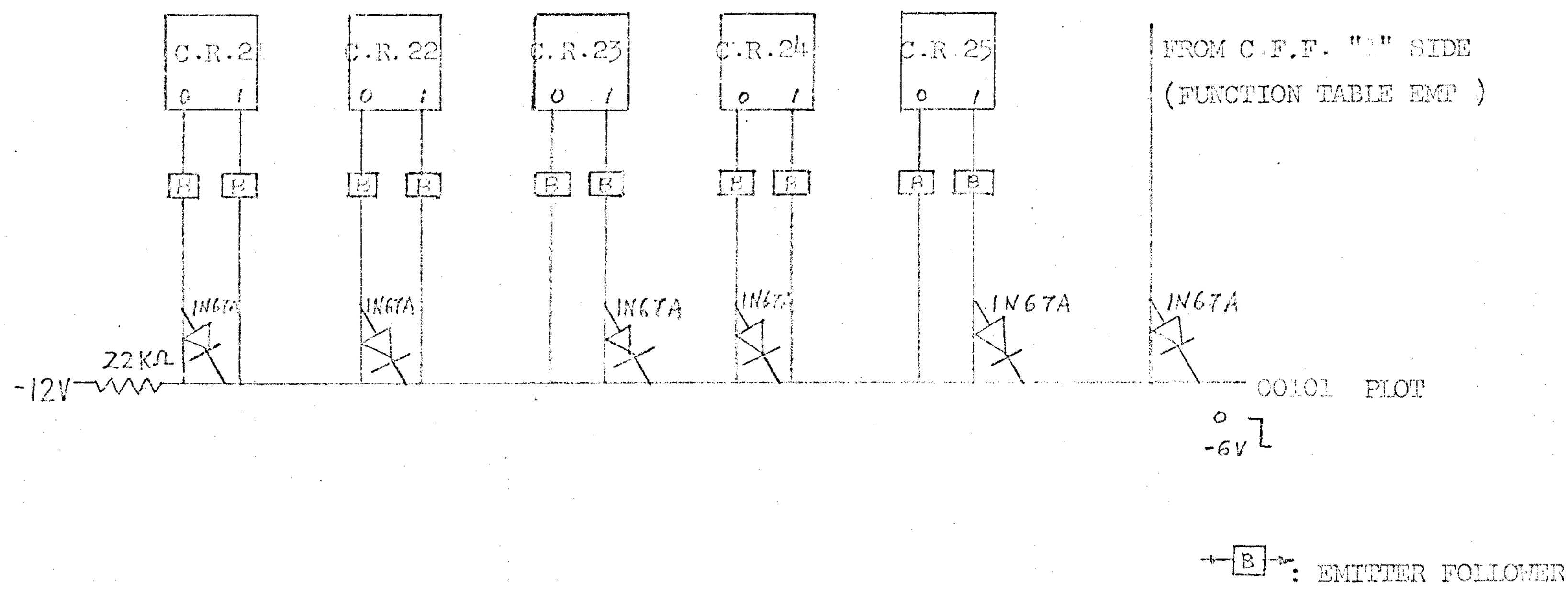


Figure 7.2 The Plot Order Generator

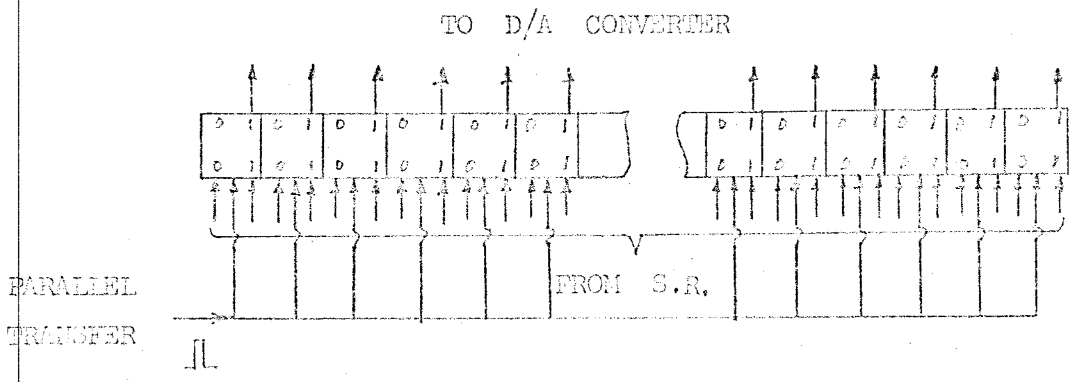


Figure 7.3 The Plot Buffer Register

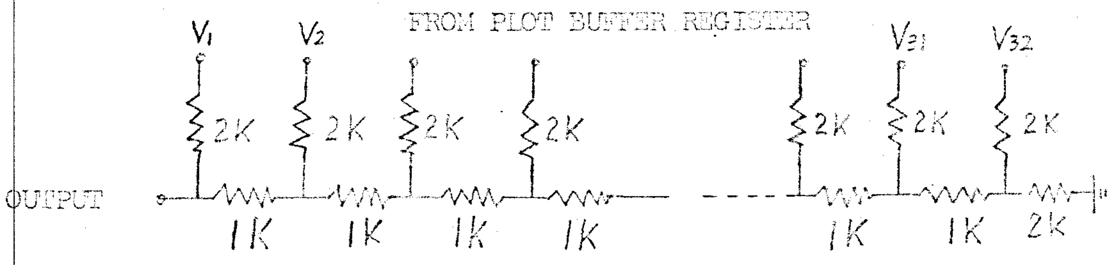


Figure 7.4 The D/A Converter

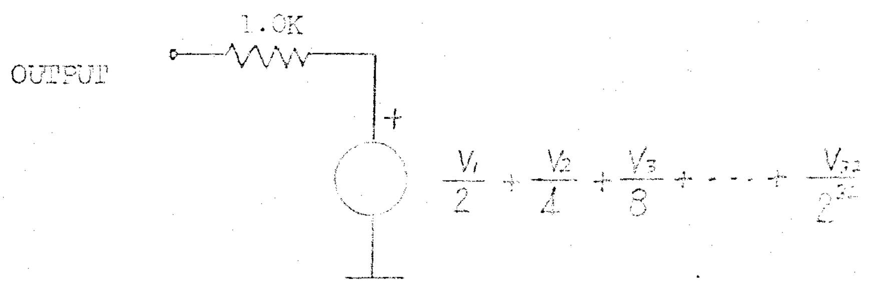


Figure 7.5 Equivalent Circuit of The D/A Converter

Fig. 7.4. The voltages V_1, V_2 ......, V_{32} are obtained from the "1" output of the buffer register stages.

To illustrate that the analog output is proportional to the binary input, the equivalent circuit of the D-A converter is shown in Fig. 7.5 which indicates that the open circuit output voltage is a properly weighted sum of the individual binary bits.

As seen from Fig. 7.5, the output resistance is 1 KΩ. In order to minimize this, the output is fed to an emitter follower.

7.3.4 The X-Y recorder

A commercial Moseley 2D-2 X-Y recorder can be used to plot the electrical waveform produced by the D-A converter. The sepcifications of this recorder are shown in Fig. 7.6.

FUNCTION	DESCRIPTION
Recording Mechanism	Independent servo actuated drives for X and Y axes; isolated and free of ground.
paper size	Standard 11" x 17" graph paper with 10" x 15" recording area.
Recording Speed	20 inches per second maximum pen speed, each axis.
Input Voltage Ranges	From 0 volt to 500 volts for Y axis. 0 to 750 for X axis. Sixteen calibrated ranges for each axis: 0.5, 1, 2, 10, 20 and 50 mv/inch; 0.1, 0.2, 0.5, 1, 2, 5, 10, 20 and 50 volts/inch.
Time intervals	Seven calibrated sweeps on the X - axis: 0.5, 1, 2, 5, 10, 20 and 50 sec/in.
Speed of chart running	Eight calibrated speeds: 2, 5, 15, and 30 seconds/inch; 1, 2, 4, and 10 min./inch.
Input Resistance	200 KΩ /volt full scale (10") through 1.0 volt/inch; 2 MΩ on all higher ranges. One MΩ models provide a 1 MΩ input resistance on all fixed input ranges.
Accuracy	Better than 0.2% of full scale. Time base accuracy better than 5% of full scale. Linearity better than 3%.

Figure 7.6 Specifications of Moseley 2D-2 X-Y recorder

8. CONCLUSIONS

The direct connection of the analog-digital and digital-analog converter to the M3 computer was designed. The analog input is sampled and fed into the computer at a rate of 500 samples per second if one channel of input is used. If two channels of input are used, the sampling rate is the same as that of one channel input, but the computer reads the data at a double rate (1000 samples per second).

The M3 calculates the autocorrelation and crosscorrelation function from 5,000 samples which are stored in its memory. The autocorrelation or crosscorrelation function outputed from the M3 is plotted on an X-Y recorder automatically.

The accuracy of the correlation functions obtained by this method is better than 10% of the normalized standard error.

The great advantage of the direct connection of the digital computer to the patient is that the computer can interpret the clinical waveforms for the physician and statistically analyse physiological data for the biomedical researcher.

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APPENDIX I. THE M3 COMPUTER

In 1964 a general purpose digital computer, The M3, was designed at the Electrical Engineering Department, University of Saskatchewan by Mr. K.E. Cameron (3). The M3 logic is based on the M2 computer designed by Dr. A.D. Booth in 1956 (2), (3). The logical operations required for addition, subtraction, multiplication and division are performed in the M3 by transistor electronic circuits.

The M3 works with 32-bit numbers confined to the range $-1 < x < 1$. The first digit of a number represents the sign, being "0" for a positive number and "1" for a negative number. Negative numbers are expressed in the complementary form Mod. 2. Thus $+\frac{1}{4}$ appears as 0.0100,0000,0000, 0000,0000,0000,0000,000 and $-\frac{1}{4}$ appears as 1.1100,0000,0000,0000,0000, 0000,0000,000.

Instructions are also represented by 32-bit numbers, and "1 + 1 address code" instructions are used. A typical instruction is: Add the number in location "X" into the accumulator and obtain the next instruction from location "Y". The first 10 bits of the instruction contain the "X" address, the next 10 the "Y" address, the next 5 the order to be performed and the next 6 the control counter (C6). The last bit is not used.

The M3 is a stored program machine and, consequently, the flow of data is controlled by the stored program.

The M3 has four main components; the memory which is responsible for storing both instructions and data until required, the control which is capable of receiving and executing instructions stored in the memory, the arithmetic unit which must on command from the control operate on stored data to produce the combinations of ordinary arithmetic and the input-output equipment which communicates the M3 with outside information.

1. The memory

The M3 memory consists of an aluminum alloy cylinder which is driven by an induction motor at 3,424 rpm. The surface of the cylinder is coated with a thin homogeneous layer of ferrous oxide and plastic. One hundred and twenty eight recording heads are spaced on individual tracks along the side of the cylinder. The spacing between the drum surface and the head is approximately 0.0005 inch.

Three timing tracks are engraved on one end of the drum. The first track is engraved with a single slot to generate a single "drum marker" pulse in a read head each drum revolution. The second track is the "word marker track", but it is not used to generate the "word marker" pulses. The third track is the "bit marker track". It has 1280 equally spaced slots. The output from the read head on this track is amplified to form the basic 75 KC/S. continuous clock of the computer.

The "word marker" pulses are obtained by using the bit counter to count the clock pulses. A "word marker" pulse is resulted after counting every twentieth clock pulse. Thus, there are 64 word locations per track and the total capacity of the memory is 8,192 words.

These 8,192 word locations occupy 128 tracks, each having a recording head. The heads are divided into 16 blocks with each containing 8 heads. In order to store or receive information, the computer must be able to address any one of these heads. This is done through the block and head selectors.

The M3 is a serial machine in which data transferred between the memory and the rest of the computer become available one bit at a time starting with the least significant bit. To transfer information to a memory location, the control register addresses the "X" track location and a comparison is made between the "X" word location (stored in the control register) and the word location shown by the word marker counter. When these are equal (coincidence), the memory emits 32 bit markers.

If the least significant bit of the word being recorded is a "1", the first bit marker pulse is gated to cause a 1 amp. current to pass in one direction through the recording head winding. The resulting magnetic field magnetizes a small spot on the drum surface.

If a bit in the word is a "0", the corresponding bit marker produces a 1 amp. current which passes through the recording head winding in the opposite direction. This produces a magnetized spot with opposite polarity to the spot recorded by a "1".

The memory generates an "operation complete pulse" (op. comp. pulse) after emission of the thirty-second bit marker pulse. This indicates to the control and arithmetic unit the completion of any operation in which information is transferred to or from the memory.

Access time to this type of memory is inherently slow as the drum must rotate to the proper word location before information can be recorded or received from the memory.

Information no longer needed can be erased from the memory by recording new information over the old. If recorded information is not removed in this manner, it will be retained for many years with negligible deterioration.

2. The Control

The M3 control consists of four main sections: the control register which stores an instruction until it is executed, the function table which interprets the instruction in the control register, the control counter which has been incorporated into the control register to control the number of basic operations performed in an instruction, and the control flip flop (C.F.F.) controls the operation of the computer. When in the "0" state, the C.F.F. causes a new instruction to be shifted into the control register; when in the "1" state, it causes the instruction to be executed.

The computer must execute three basic types of instruction: instructions which shift a single word to or from the memory, instructions which require more than one basic operation and the branch instructions.

With instructions requiring transfer of information between memory and arithmetic unit, the C.F.F. change to the "1" state shifts the "X" track location from control register stages 1 to 4 (C.R. 1 - 4) through the "and" gate, g_4, to the track selector and permits the function table to issue the order stored in C.R. 21 - 25 to the arithmetic unit (see Fig. A.1). When coincidence occurs between the available word location and the "X" word location (C.R. 5 - 10), 32

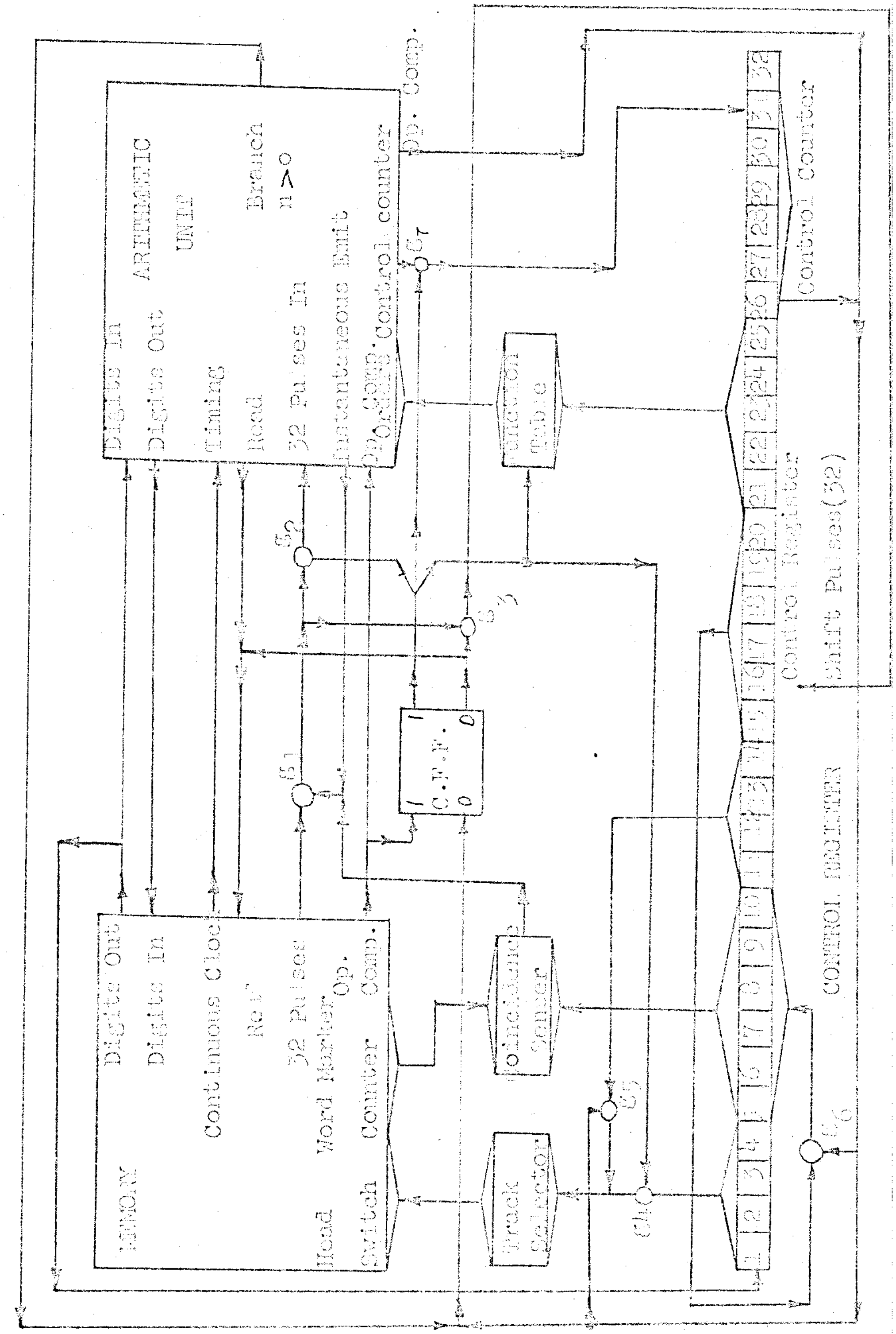


Figure A.1 M5 Control Schematic

shift pulses from the memory cause the execution of the order. Following the thirty-second shift pulse, the op. comp. pulse generated by the memory passes through the arithmetic unit to zero the C.F.F., shift the "Y" track location (C.R. 11 - 14) through g_5 to the track selector and shift the "Y" word location (C.R. 15 - 20) through g_6 into C.R. 5 - 10 locations. Zeroing of the C.F.F. instructs the memory to read and opens g_3 to allow the 32 shift pulses emitted by the memory on coincidence to shift next instruction into the control register. Following the thirty-second pulse, the op. comp. pulse generated by the memory returns the C.F.F. to the "1" state ready to execute the next instruction.

With instructions requiring the completion of more than one basic operation, the C.F.F. changes to the "1" state, shifts the "X" track location into the track selector, and permits the function table to emit an instruction. As this type of instruction does not require coincidence with a word location, operation starts immediately. Each basic operation performed passes a pulse through g_7 to the control counter (C6). When the required number of operations have been performed, the most significant stage of C6, C.R. 26, generates an op. comp. pulse to zero the C.F.F., shift the "Y" track location into the track selector and shift the "Y" word location into C.R. 5 - 10. When coincidence occurs, the zeroed C.F.F. shifts a new instruction into the control register in a manner similar to that described in the previous paragraph. The op. comp. pulse following the thirty-second pulse resets the C.F.F. to unity, ready to execute the new instruction.

With branch instructions, the next instruction shifted into the control register is determined by the sign of a number stored in the arithmetic unit. When the C.F.F. switches to the "1" state, the "X" track location is set into the track selector by g_4 and a gating pulse from the function table tests the sign of the number in question. If the sign bit is "1" indicating a negative number, the arithmetic unit emits an op. comp. pulse which zeros the C.F.F. and opens g_5 and g_6 to shift the next instruction into the control register from the "Y" memory location. If the sign bit is "0" indicating a positive number, the arithmetic unit emits a pulse on the branch $n > 0$ line which zeros the C.F.F. but does not open g_5 or g_6. This results in the new instruction being shifted into the control register from the "X" memory location. Following the instruction shift, the operation complete pulse generated by the memory will set the C.F.F. to a "1" state ready to execute the new instruction.

3. The Arithmetic Unit

The arithmetic unit is composed of four units: the arithmetic network, the accumulator, the shift register and the cycle register.

Operation of the arithmetic unit is governed by the Control unit mentioned in the previous section. When instructed, the arithmetic unit will perform (1) transfer of a number from memory location "X" to the shift register, (2) transfer of a number from memory location "X" to the cycle register, (3) right shift, (4) left shift, (5) addition, (6) subtraction, (7) multiplication and (8) division. The addition or subtraction requires 250 microseconds. Multiplication requires 250 to 8000 microseconds and division requires 8,000 microseconds.

4. The Input Equipment

The input device is used to accept information from outside and feed it into the computer. The input device used with the M3 is a paper tape reader. The paper tape has 7 holes as data channels and a small guide hole at each row. The guide hole is used to locate the character along the length of the tape.

The reader has a reading station to sense all the hole positions across the tape, a driving mechanism to move the tape past the sensing station, and some index mechanism which generates a signal when the character is in a position to be sensed.

The operation of the tape reader is controlled by a logic circuit called the "tape reader control". The maximum speed of this reader is 500 characters per second.

5. The Output Equipment

The output device is used to translate and display information received from the computer; the devices used with the M3 are a paper tape punch and a typewriter.

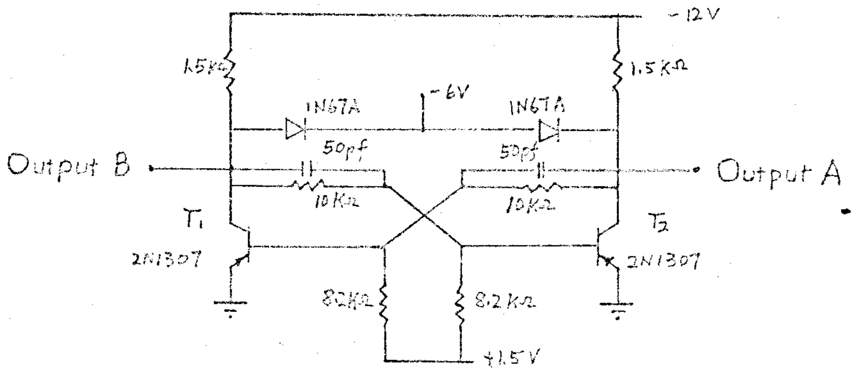
The paper tape punch has a mechanism to perforate the data holes and guide hole across the tape, a driving mechanism to move the tape one character at a time, and an index mechanism to emit pulses when punching can begin.

The operation of the tape punch is controlled by the "tape punch control" logic and its speed is 100 characters per second.

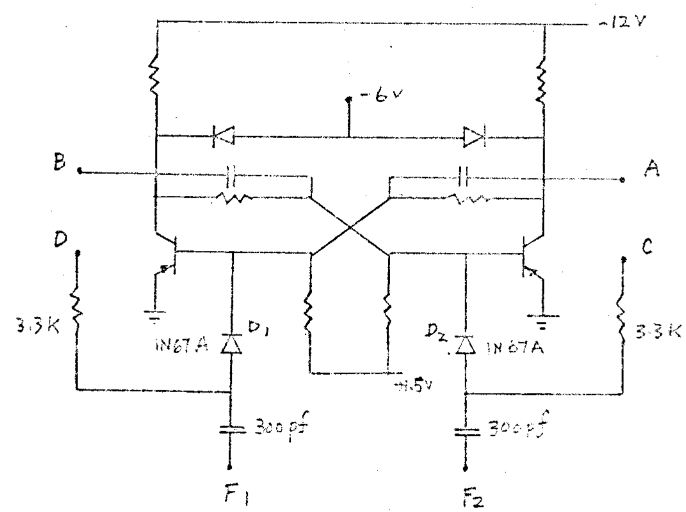
The electric typewriter has 48 separate input lines. Each of them is connected to a solenoid which in turn operates the key mechanically for each alpha-numeric character or symbol.

To control the operation of the typewriter, the logic used is referred to as the "typewriter control". The speed of this typewriter is 10 characters per second.

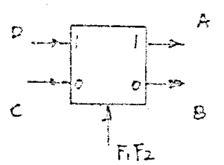
APPENDIX II BASIC CIRCUITS



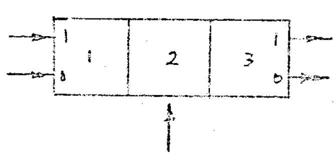
The Basic Flip Flop



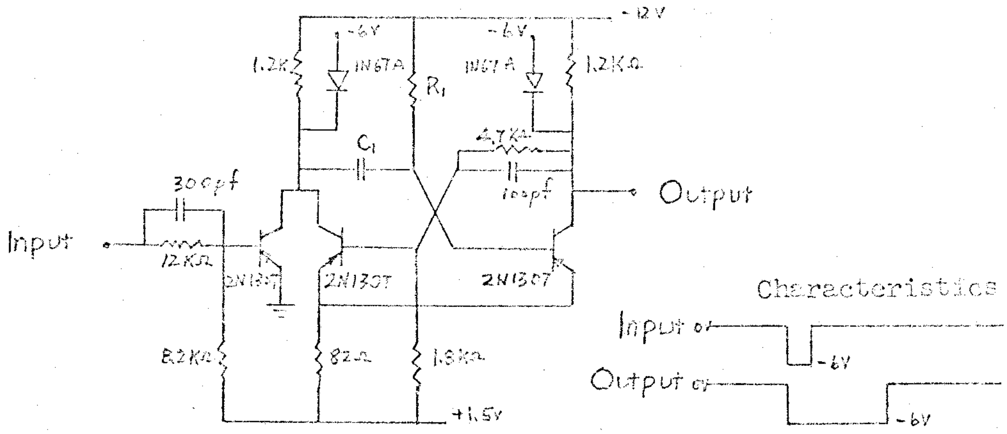
Basic Flip Flop Showing Input Gating



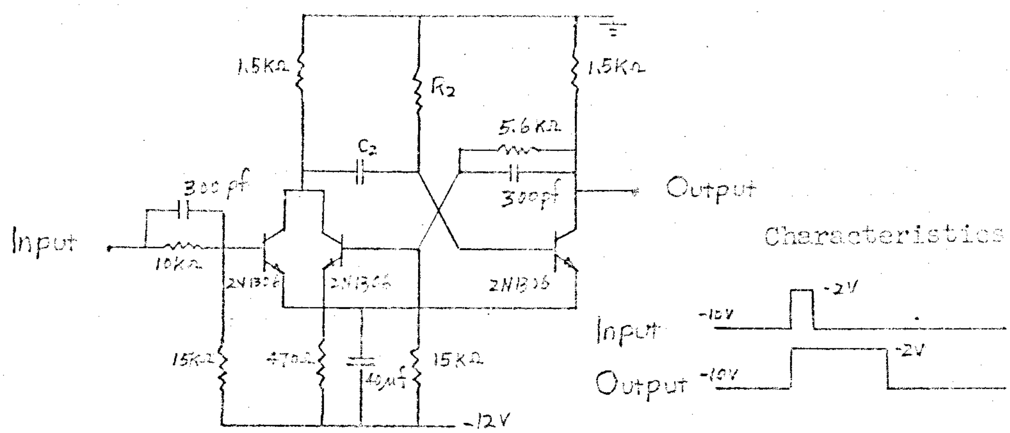
(a) Single Shift Register Stage



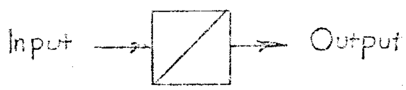
(b) Stage Shift Register



(a) Negative Pulse Generating One Shot

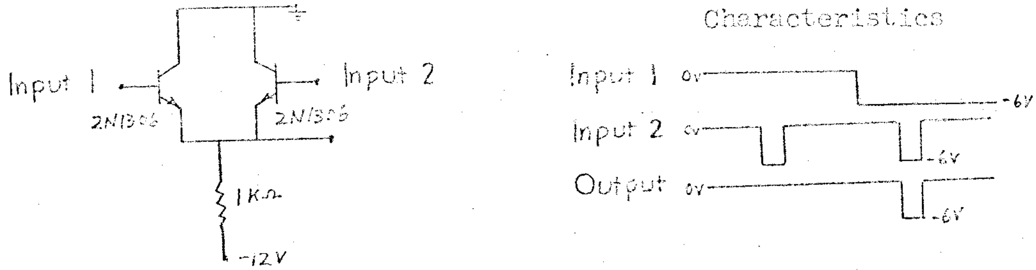


(b) Positive Pulse Generating One Shot

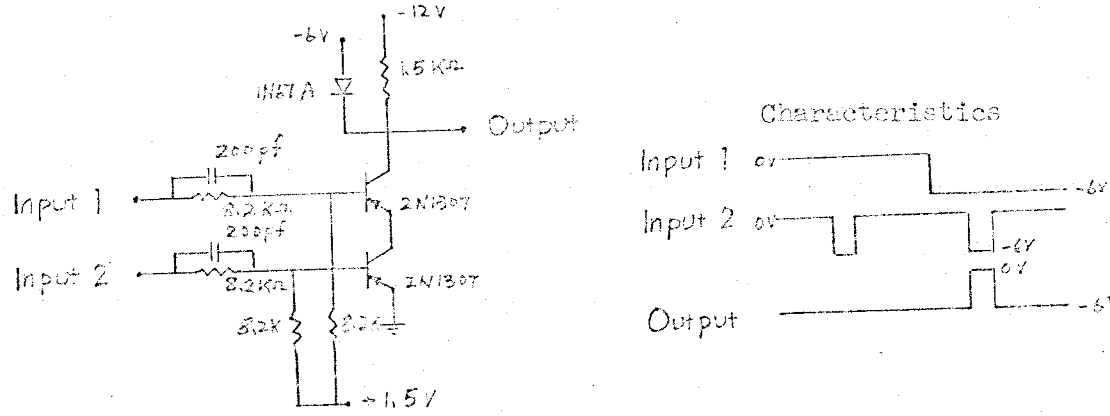


(c) Symbolic Representation of One Shot

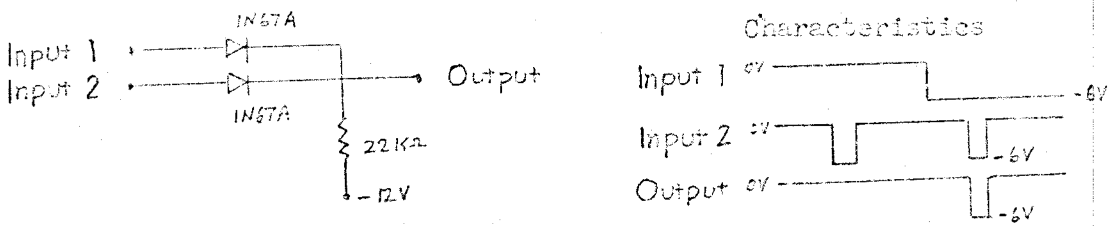
Basic One Shots



(a) Transistor "And" Gate



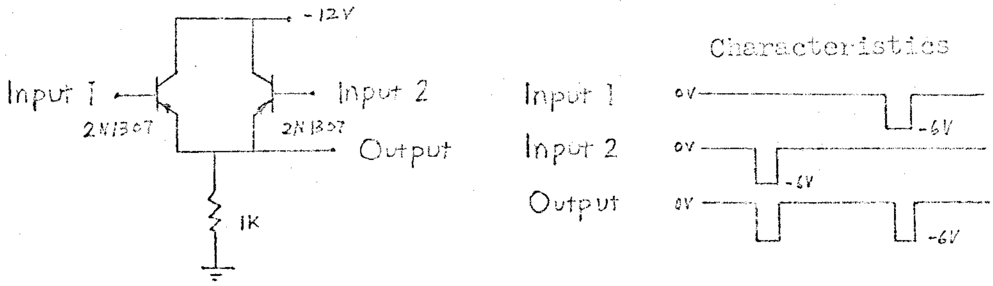
(b) Inverting "And" Gate



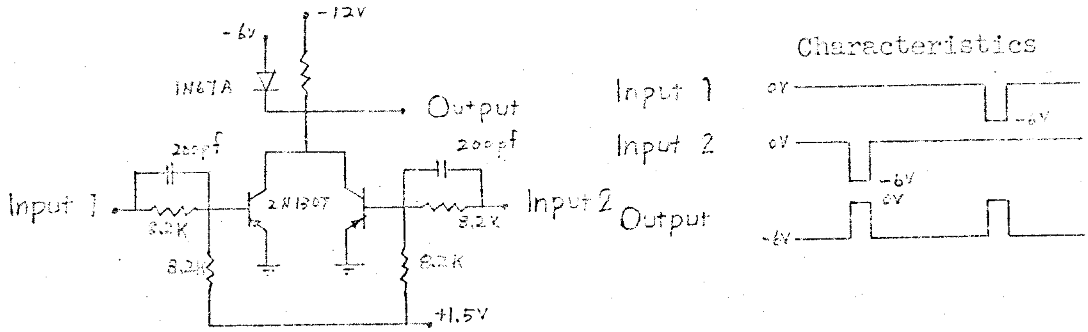
(c) Diode "And" Gate

Symbolic Representation of an "And" Gate

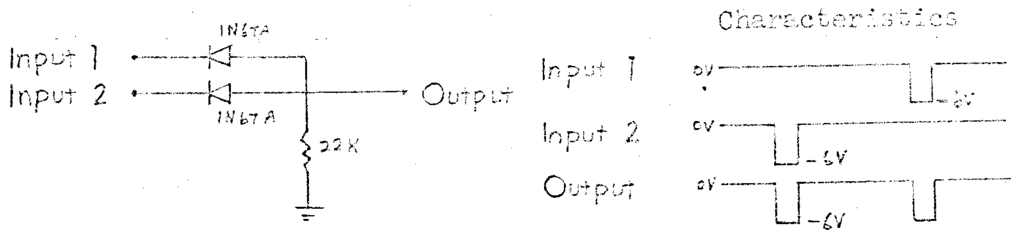
Basic "And" Gates



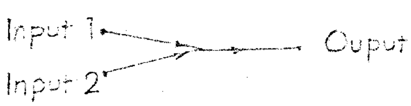
(a) Transistor "Or" Gate



(b) Inverting "Or" Gate

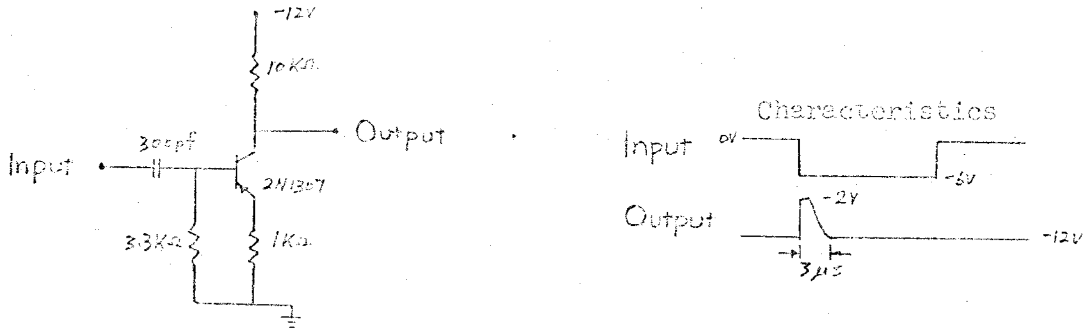


(c) Diode "Or" Gate

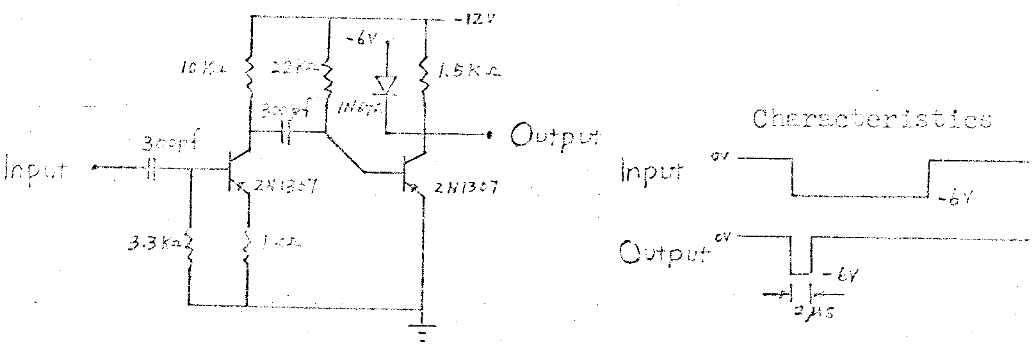


Symbolic Representation of "Or" Gate

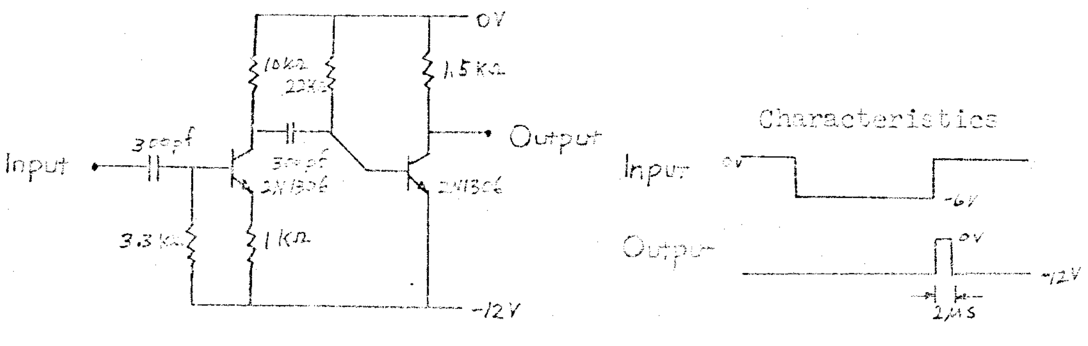
Basic "Or" Gates



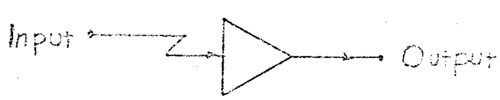
(a) Inverting A.C. Amplifier (Negative Trigger)



(b) A.C. Amplifier(Negative Trigger, Negative Output)



(c) A.C Amplifier (Positive Trigger, Positive Output)



(d) Symbolic Representation of A.C. Amplifier

Basic A.C. Amplifiers