A QUANTIZED DELAY-LOCK DISCRIMINATOR

BY

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ABSTRACT:

A new radar tracking detector using fixed delay lines in place of continuously variable delay lines is described. The fixed delays are switched in and out depending on the output of a correlator. Results of a working system are shown using bang-bang feedback and analog-to-digital feedback, for tracking a time--varying delay.

PREFACE

This work has aimed at the continuation of research on the delay-lock discriminator, an optimum radar detector. Much of the work of this thesis was of a practical nature. A working model of the radar tracker was constructed. Not having a transmitter, antenna, nor a suitable target, it was necessary to simulate these elements. Therefore the words transmission and echo contained in the thesis refer to the pseudo-transmission and the pseudo-echo. Many words are used interchangeably, notably delay and distance. The distance output coming out of the detector is called the delay estimate or simply estimate. The transmission waveform is called the reference and the two terms transmission and reference are used interchangeably. The radar tracker of this work is thought of as co-existing with its transmitter and therefore the reference may be brought to the detector by a wire. The word correlator refers to an analog multiplier followed by a low-pass filter.

Because of the evolution of the final form of the project, the thesis has been written in a chronological order.

AKNOWLEDGEMENTS

The largest step in improving this topic came as the result of a suggestion by Dr. S.S.Haykim, the project super--visor, that a switch be made from continuous to quantized delay. A large amount of unclear thinking was redirected by Dr. Haykim and by Alan Delamere, then of Canadian Westinghouse in Hamilton. Thanks go to Mr. Delamere for the delay lines used in the discriminator constructed.

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LIST OF GRAPHS AND PHOTOGRAPHS

Note:

Many dozen small hand drawn diagrams illustrate the points of the text and clarify the connection of the apparatus. These will not be listed as they are generally found in that section of the text to which they provide clarity.

CHAPTER ONE

A PRELIMINARY DISCUSSION AND LITERATURE SURVEY

1-1 The Historical Aspect

The historical aspect of the delay-lock discriminator was deeply imbedded in the furor in the last two decades directed toward solutions to the optimum detection of signals in noise. The detection process generally involved a filter to maximize the signal-to-noise ratio. In 1943 D.O.North[1] devel--oped a theory of filters now called "North Filters". A cent--ral result in North"s theory was that in the case of white additive noise the signal-to-noise ratio was maximized by a filter whose impulse response had the form of the image of the signal to be detected. Van Vleck and Middleton[2] independently formed a similar result called "matched filters". Filters of

1 D.O.North,"Analysis of the Factors which Determine Signal /Noise Discrimination in Radar",Report PTR-6C,RCA Laboratory June 1943

2 J.Van Vleck and D.Middleton,"A Theoretical Comparison of Visual,Aural,and Meter Reception of Pulsed Signals in the Presence of Noise", Journal Applied Physics Vol.17,pp.940-970, November 1946

this kind eventually became so important to signal detection that an entire issue of the "Proceedings of the IRE on Information Theory" was devoted to them.[3] These sophisticated approaches to detection required certain "a priori" know-ledge of the statistics of the signal and the noise. Optimum filters of the Wiener type required that the frequency spec-trum of the signal and the noise be known. Many different optimum filters were possible, each for defined initial expect-ations of the statistics. In radar detection banks of "matched filters" were used, with each filter designed for a different delay and doppler shift of the specific transmitted signal. On the basis of known "costs" of false alarms the outputs of the filters could be examined to determine in the best poss-ible fashion, the most likely received message.

Correlation could be used to perform the required filtering. Lee, Cheatham and Wiesner[4] described a system of

3 Trans. PGIT-IRE, MATCHED FILTER ISSUE, Vol.IT-6, No.3, June 1960

4 Y.W.Lee, T.P.Cheatham and J.B.Wiesner,"Application of Correlation Analysis to the Detection of periodic signals in Noise," PROC. IRE, Vol.38,pp1165-1172,Oct.1950.

detection of a periodic signal buried in additive noise by an electronic correlator. In their summation they clearly draw the parallel between filtering in the frequency domain with networks and filtering in the time domain with correl--ators. Their final remarks are here repeated verbatim for clarity.

" It is well to emphasize that theoretically no claim can be made that the method of correlation is superior to conventional filtering in the frequency domain in the sense of accomplishing in the time domain what is impossible in the frequency domain. Such a claim would be false, since it has already been stated that the correlation function and the power-density spectrum of a stationary random process are uniquely related by a Fourier transformation, (the Wiener-Kintchine Theorem), and since it is known that a similar relationship holds for periodic phenomenon. Nevertheless, from an engineering point of view, many equivalent operations may be more practicable and feasible in the time domain."

With this equivalence in mind a bank of radar matched filters may be a set of possible signal returns stored in some fashion for later correlation with received echoes. These stored or delayed signals will henceforth be referred to as " references ".

The storage of references in optical film density on a revolving glass disc record has been described.[5]

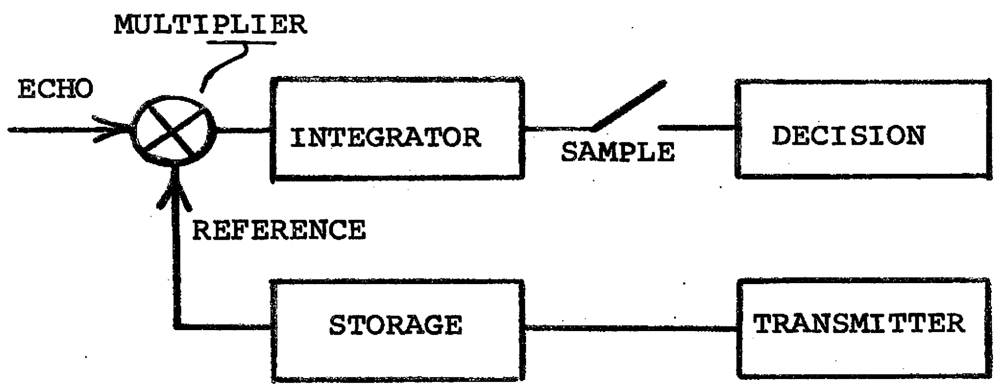


fig.1 A radar matched filter by the correlation method

All optimum radar detectors or filters require a replica of the transmission or certain statistical knowledge of the signal and the noise. This thesis concerns detection of the first kind where a noise free delayed version of the transmission is available to the receiver for correlation.

Definition: where f(t) is a stationary process of constant average power the autocorrelation function $R(\tau)$ is defined by

$$R(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)\, f(t-\tau)\, dt$$

5 A.J.Talamini and E.C.Farnett,"New Target for Radar:Sharper Vision with Optics," ELECTRONICS, December 27, 1965.

The noise is assumed small and uncorrelated with the signal and the integration time T is long. The output of the int--egrator of the system of fig.1 will approximate the value T R(τ), where τ is the delay difference between the delays of the echo and the reference. In practice the integration time T is fixed by the bandwidth of the low-pass filter which carries out the integration.

1-2 The Phase-Lock Loop

We have now arrived at a point at which we may con--sider the dynamic control by feedback of the parameters of the reference signal. The first device of this kind was the phase-lock loop detector.

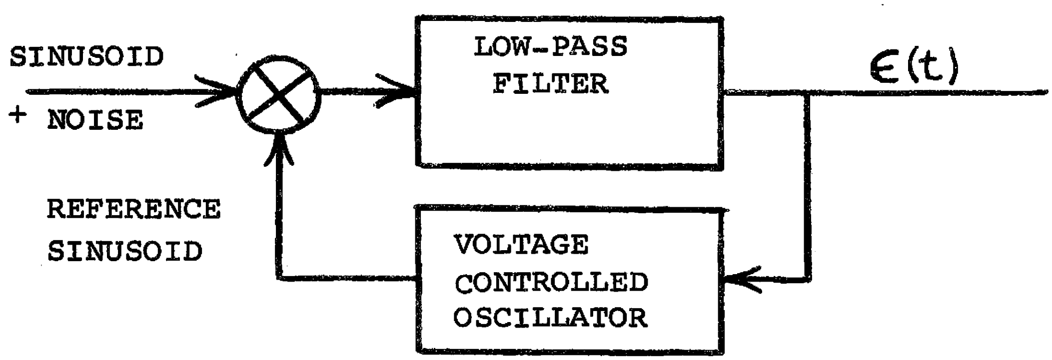


fig.2 The Phase-Lock Loop

The voltage controlled oscillator produces a frequency which is a linear function of the applied voltage. We may also consider the oscillator output as a phase which is the integral of the applied voltage. The noise is assumed to be uncorrelated

with the sinusoid and to be of zero mean value. If the ref-
-erence and the returned sinusoid are of the same constant frequency then the output of the multiplier will consist of many high frequency terms plus additive noise of zero mean and a constant term $\overline{\epsilon(t)}$. The bar over $\epsilon(t)$ indicates aver-
-age value. This constant term will be proportional to the strength of the incoming sinusoid and to the cosine of the phase difference between the echo and the reference as shown in fig.3.

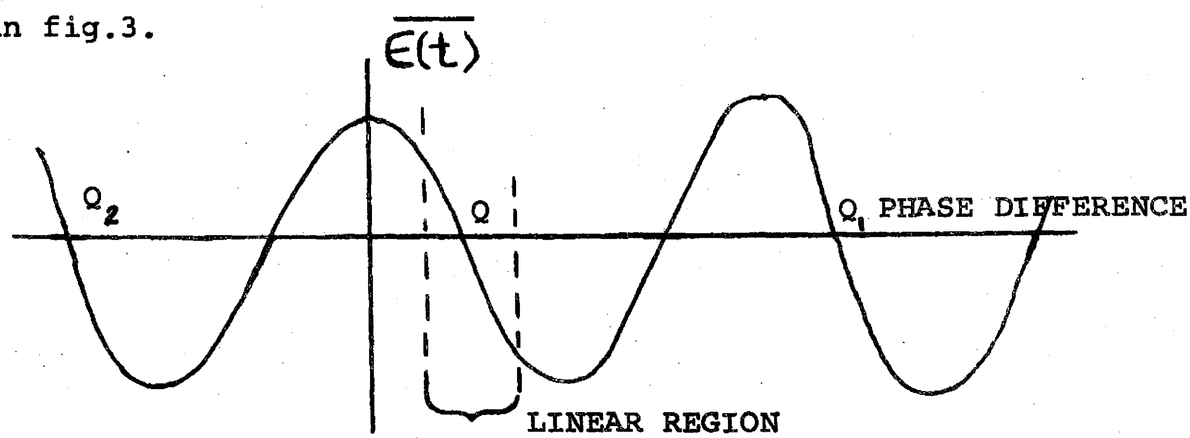
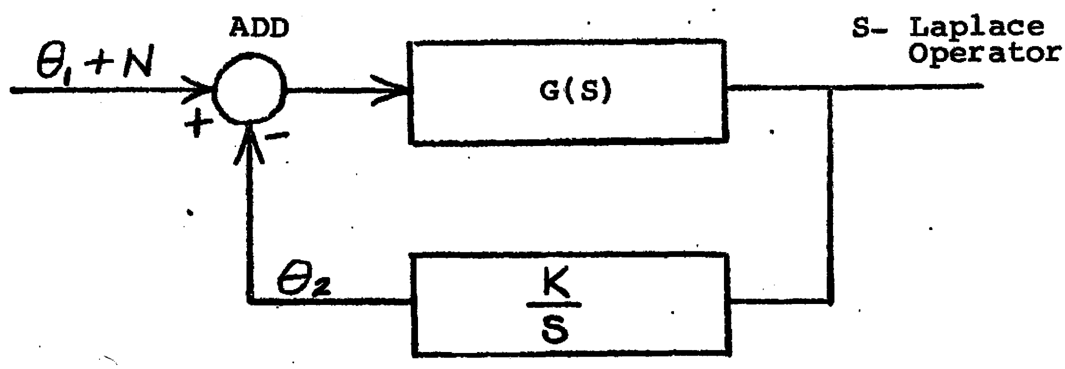


fig.3 The Autocorrelation Function of a Sinusoid

By a suitable arrangement of the signs of polarity around the feedback loop the point Q of fig.3 may be established as a stable point. A small perturbation linear model of the system can be drawn as in fig.4. The region over which this model has application is shown on fig.3 and is called the " linear region ". This model applies for a constant amplitude of input signal which is now represented only by its phase θ_1.



<u>fig.4</u> <u>A Small Perturbation Phase-Lock Model</u>

The system must remain locked-on, that is, near to Q of fig.3. Notice other stable points Q_1 and Q_2 exist. These other possible lock-on regions are called " ambiguities." A complete analysis of the model of fig.4 has been made and many optimum filters G(S) derived.[6]

1-3 <u>Linear Model Optimization</u>

The following analysis is similar to that of many previous authors on the phase-lock loop and appears in cond--ensed form in Gupta and Solem.[7] With anticipation of Chapter Four of this thesis, the symbols θ_1 and θ_2 will be replaced by D_1 and D_2 respectively.

6 R. Jaffe and E. Rechtin, " Design and Performance of Phase--Lock Circuits Capable of Near-Optimum Performance, " IRE TRANS. INF. THRY. Vol. IT-1, pp.66-76, March 1955.

7 S.C.Gupta & R.J.Solem,"Optimum Filters for Second- and Third--Order Phase-Locked Loops," IEEE TRANS. SPACE ELECTRONICS and TELEMETRY, pp.54-62, June 1965

Several symbols will now be defined:

σ_n^2 - the mean squared noise error within the loop also called output jitter.

E_T^2 - the total squared transient error = $\int (D_1 - D_2)^2 \, dt$ where the change in D_1 is applied at t = 0 and D_2 is the noiseless transient response of the system.

λ - a Lagrangian multiplier

$H(s) = \dfrac{K\ G(s)}{S + K\,G(s)}$ the system transfer function.

$\Phi_n(s)$ - the input noise spectral density assumed flat.

The Wiener optimum filter is calculated from the Wiener criterion which seeks to minimize the sum of the mean squared noise jitter and the total weighted squared transient error.

$$\Sigma^2 = \sigma_n^2 + \lambda\, E_T^2$$

$$\sigma_n^2 = \frac{1}{2\pi j}\int_{-j\infty}^{j\infty} H(s)\, H(-s)\, \Phi_n(s)\, ds$$

$$E_T^2 = \frac{1}{2\pi j}\int_{-j\infty}^{j\infty} D_1(s)\, D_1(-s)\,[1-H(s)][1-H(-s)]\, ds$$

It has been shown[6] that the system transfer function can be derived from,

$$\Psi(s)\,\Psi(-s) = \lambda^2 D_1(s)\, D_1(-s) + \Phi_n(s)$$

$$H(s) = \frac{\lambda^2}{\Psi(s)}\left[\frac{D_1(s)\ D_1(-s)}{\Psi(-s)}\right]_+$$

The loop noise bandwidth B_n is defined by:

$$2B_n = \frac{1}{2\pi j}\int_{-j\infty}^{j\infty} H(s)\,H(-s)\;ds$$

First Order Input

The first order system has zero steady state error for a step of input phase. Because a step of phase is a non--physical target motion it is summarily dismissed. It has been shown[6] that G(S) consists of a constant gain only, that gain dependent on the input step size and the noise intensity.

Second Order Input

The second order system has zero steady state error for a ramp of input phase. $D_1(t) = \alpha_2 t$

The solution has been derived as:[7]

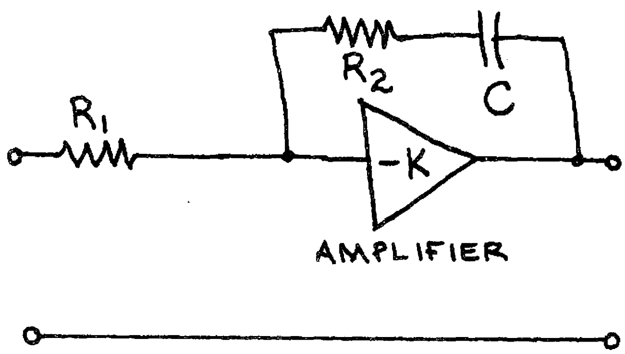
$$H_2(s) = \frac{\sqrt{2}\,B_2 S + B_2^2}{s^2 + \sqrt{2}\,B_2 s + B_2^2}$$ and therefore

$$G_2(s) = \frac{\sqrt{2}\,B_2 S + B_2^2}{K s}$$ where B_2 is defined

$$B_2^4 = \frac{\lambda^2 \alpha_2^2}{\Phi_n(0)}$$ and the noise bandwidth is

$$B_{n_2} = \frac{3\,B_2}{2\sqrt{2}} \quad \text{Hz.}$$

It is well to emphasize that this solution is only useful for the exact $\Phi_{in}(S)$ specified. An implementation of the second order filter is shown in fig.5.



$$G_2(S) = -\frac{R_2}{R_1}\left[\frac{S + \frac{1}{R_2 C}}{S}\right]$$

$K >> 1$

$$\frac{R_2}{R_1} = \sqrt{2}\, B_2 \qquad R_2 C = \frac{\sqrt{2}}{B_2}$$

fig.5 The Second Order Wiener Optimum Filter $G_2(S)$

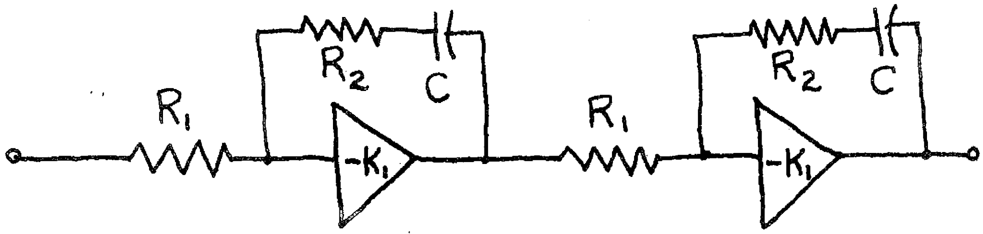
Third Order Input

The third order system has zero steady state error for a parabola of input phase. The transfer function $H_3(S)$ has been derived[7] as:

$$H_3(s) = \frac{2B_3 S^2 + 2\sqrt{2}\, B_3^2 S + B_3^3}{S^3 + 2B_3 S^2 + 2\sqrt{2}\, B_3^2 S + B_3^3}$$

$$G_3(S) = \frac{2B_3 S^2 + 2\sqrt{2}\, B_3^2 S + B_3^3}{K S^2}$$

The exact filter proves to have unsuitable values of components and therefore an approximate filter, shown in fig.6 is used.



$$G_3(s)_{\text{APPROX.}} = \left(\frac{R_2}{R_1}\right)^2 \left[\frac{s^2 + \frac{2}{R_2 C} s + \frac{1}{R_2 C}}{s^2}\right], \quad \begin{array}{l} KR_2^2 = 2B_3 R_1^2 \\ R_2 C B_3 = 2 \end{array}$$

fig.6 The Approximate Third Order Filter

Thus we see that the first order optimum filter contains a constant, the second order filter contains a single amplifier which operates as an integrator, and the third order system contains two integrators.

1-4 The Delay-Lock Discriminator

Whereas the phase-lock loop might be called an automatic feedback correlator for sinusoids of unknown phase, there exists another similar system, which will operate upon many general kinds of waveforms, which might be called an automatic feedback correlator for general waveforms of unknown delay. Such a device has been built and first investigated by Spilker and Magill in 1961.[8]

8 J.J.Spilker and D.T.Magill,"The Delay-Lock Discriminator An Optimum Tracking Device," Proc. IRE, pp. 1403-1416, September 1961.

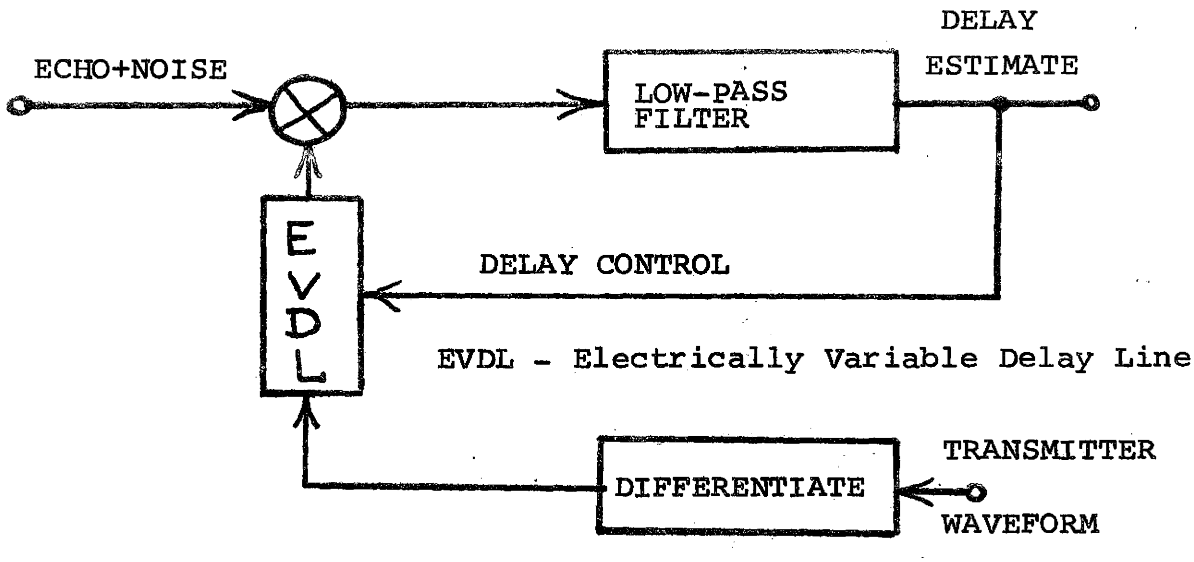
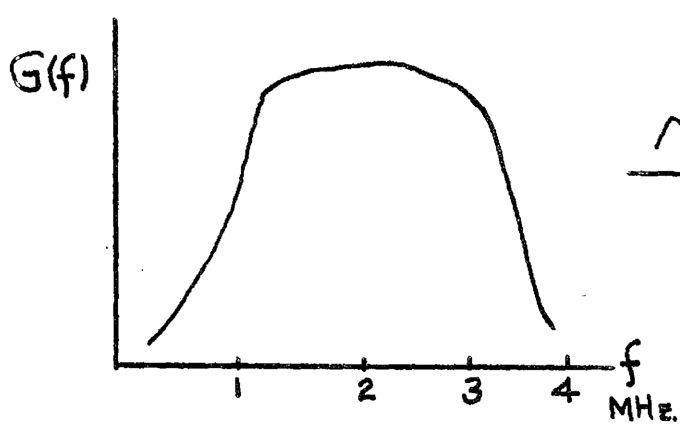


fig.7 The Delay-Lock Discriminator

The waveform they transmitted was a bandpass spectrum of filtered random noise approximately 2 MHz. wide centered at 2 MHz. The autocorrelation of such a waveform is given by the Wiener-Klintchine Theorem which states that the autocorrelation function and the power spectral density are mutual Fourier transforms.



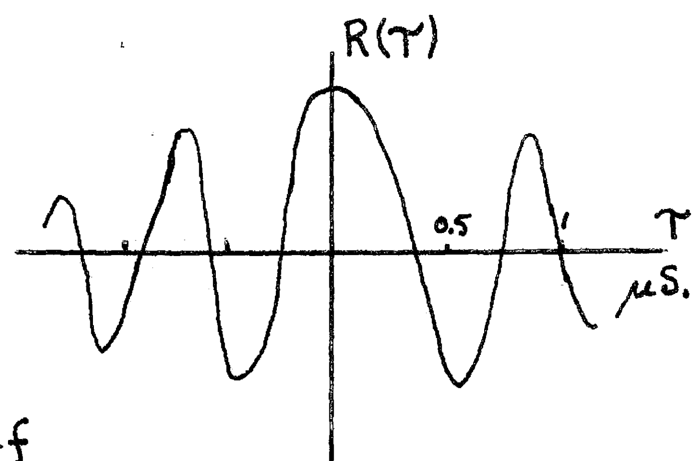


fig.8 Power SpectralDensity fig.9 Equivalent Autocorrelation

The system contains a time differentiator in order that the output of the multiplier will have a mean value proportional to the differential with respect to τ of the autocorrelation function $R(\tau)$. A simple proof of this fact is found in the form of a theorem in the Appendix.

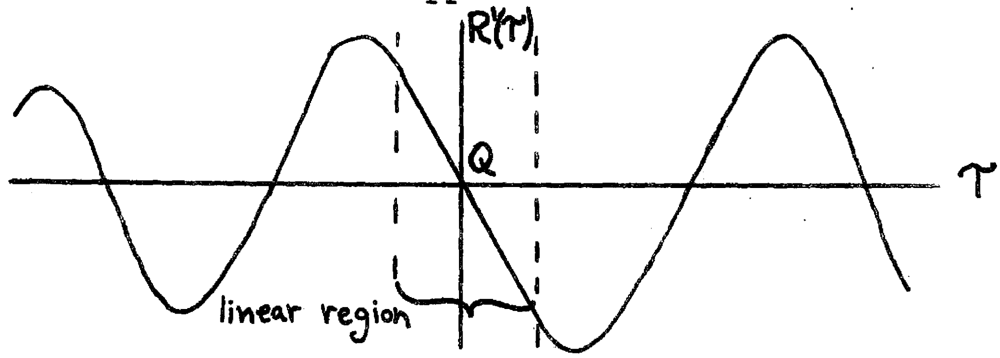


fig.10 The Differentiated Autocorrelation Function

It is seen from fig.10 that the differentiator allows a stable operating point Q to be set up and the system to be locked-on at zero delay difference between the reference and the echo. Assuming that the system remains locked-on in the linear region marked on fig.10 then a linear model exists similar to that of the phase-lock loop.

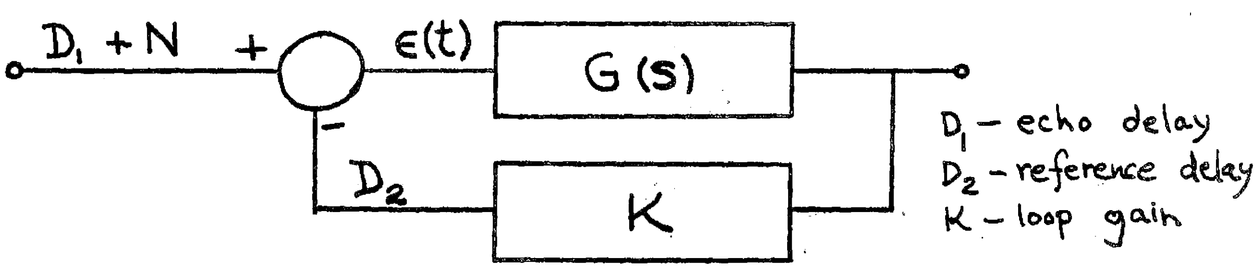


fig.11 Linearized Delay-Lock Model

Using this linear model Spilker and Magill have taken over results derived for the phase-lock loop by Jaffe and Rechtin and produced several optimum filter transfer functions G(S) for the delay-lock discriminator. Calculations were also made by Spilker and Magill of the time required to lock-on the system if the delay was initially outside the linear region. The minimum tolerable signal-to-noise ratio was also calculated. Operation at signal-to-noise ratios of -40 db. was claimed.

In their construction the delay line used was a coaxial delay cable having a high permeability ferrite core which was saturable by a direct current control, thus reducing the series inductance of the line. Nonlinearity of control and dynamic distortion were noted.

In 1962 M.R.O'Sullivan described[9] a proposed radar system employing the phase-lock loop and the delay-lock loop for range and angle tracking. The combination used the advant--ages of both systems of detection, the phase-lock loop for its great accuracy and the delay-lock discriminator because of its freedom from ambiguities. The proposed system would cover long distances, up to 500 miles, with great accuracy, up to one foot relative, using modest transmitter power of 100 milliwatts.

9 M.R.O'Sullivan,"Tracking Systems Employing the Delay-Lock," IRE TRANS. SPACE ELECTRONICS and TELEMETRY Vol.SET.8, pp.1-7 March 1962.

Later that year Spilker returned[10] with an advanced new digital system employing binary coded signals. The delay of the reference was accomplished by reproducing the transmitted code inside the receiver from a feedback shift register.

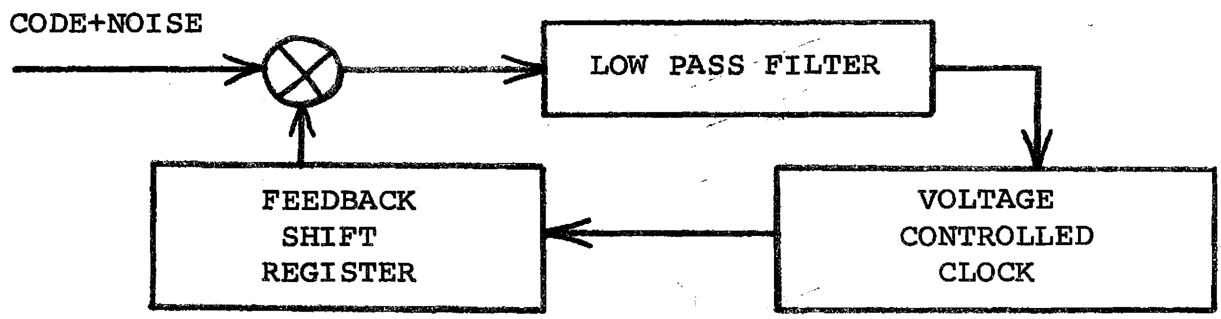


fig. 12 The Binary Delay-Lock Discriminator

The multiplication of binary numbers was greatly simplified compared to the multiplication of analog* form voltages. The shift register accomplished long delays with no distortion, a feat not technically feasible with LC delay cable. By the use of a suitable binary code only one peak appeared in the autocorrelation function and thus only one lock-on region existed for delays up to a complete code length. Solutions to the phase-plane trajectories of the control system transients during search and acquisition of lock were obtained and calcula-tions of the effect of noise on accuracy were shown.

10 J.J.Spilker,"Delay-Lock Tracking Binary Signals",IRE TRANS. SPACE ELECTRONICS and TELEM.,Vol.SET-9,pp.1-8,March 1963.

* "Analog" will be used for signals having a smooth and continuous value, variable over all values in some range.

In 1964 R.B.Ward proposed a system[11] using binary delay--lock tracking for use in communicating with spacecraft on a mission to Mars. The Earth station would have used interfero--meter techniques on the recieved code from the spacecraft transponder and the spacecraft would have used a delay-lock detector to recieve commands from Earth. Various calculations of range, range rate, and angle accuracy and power requirements were shown.

In 1965 P.A.Wintz described a strategy[12] for the increase of the linear range of dynamic response (the widening of the linear portion of the correlation curve as in fig.10) of the analog delay-lock discriminator. This improvement involves the correlation of the signal received against a reference composed of the weighted sum of signal derivatives.

In 1966 W.J.Gill made a comparison[13] of the three tech--niques of delay-lock tracking shown in the following three diagrams of fig.13.

11 R.B.Ward," Application of Delay-Lock Tracking Techniques to Deep Space Tasks," IEEE TRANS. SPACE ELECTRONICS and TELEM. Vol.SET-10,pp.49-65, June 1964.

12 P.A.Wintz," A Strategy for Obtaining Explicit Estimators of Signal Delay," IEEE TRANS. SPACE ELECTRONICS and TELEM. pp.23-28, March 1965.

13 W.J.Gill," A Comparison of Binary Delay-Lock Loop Tracking Implementations," IEEE TRANS. AEROSPACE and ELECTRONIC SYSTEMS, Vol.AES-2,No.4, July 1966.

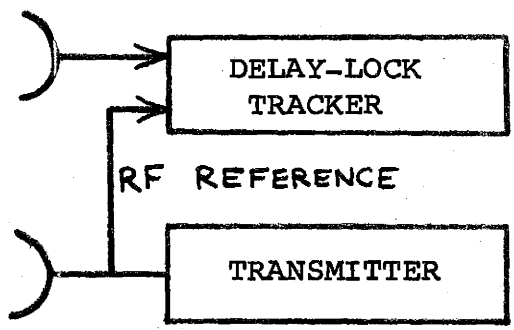


fig.13a Phase Coherent Correlation

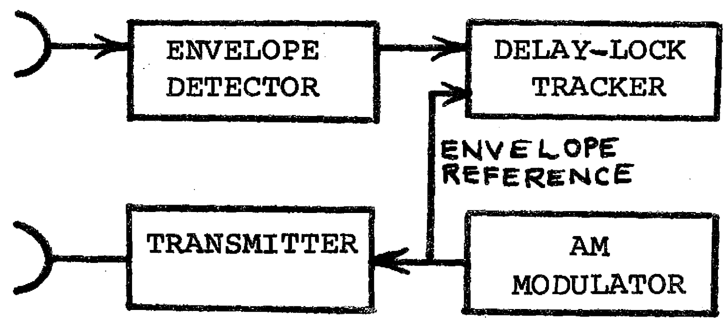


fig.13b Envelope Correlation

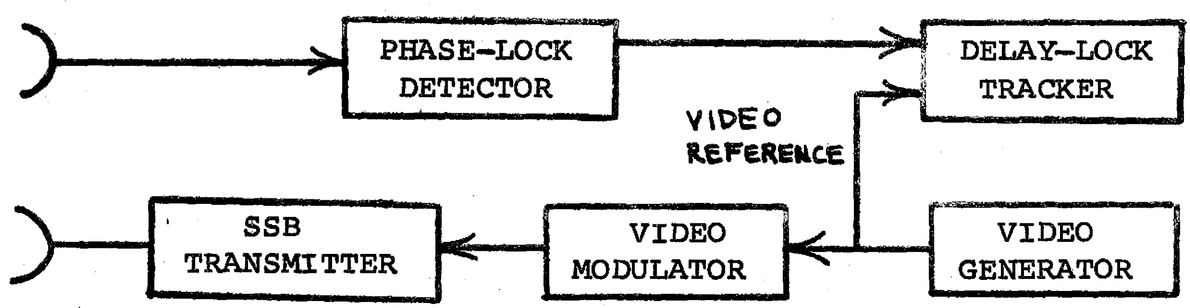


fig.13c Phase-Lock Demodulation and Video Correlation

CHAPTER TWO

INITIAL RESEARCH

2-1 Attempts at a Continuously Variable Delay Line

The heart of the delay-lock discriminator is the electrically variable delay line, abbreviated EVDL. Many different approaches are possible. Spilker and Magill used a miniature ferrite delay cable. The binary signal method used a shift register with the clock period controlled. A variable speed video tape recorder might be used for exceptionally long delays of analog signals, such as occur in sonar. Two other EVDL methods were explained and working examples shown in a publication on a different topic.[14] The first system was similar to the binary shift register except that samples of an analog signal were held and cascaded through a series of " sample and hold " circuits. The rate of progression of the sample down the " bucket brigade line " was controlled by a variable rate clock. The second EVDL was the familiar lumped LC delay

14 W.J.Hannan, J.F.Schanne, and D.J.Woywood," Automatic Correction of Timing Errors in Magnetic Tape Recorders," IEEE TRANS. MIL. ELECTRONICS,pp.246-254, July-Oct. 1965.

network using variable capacitors in the form of varicap diodes. The performance of a 60 section line containing 120 varicap diodes was discussed. A delay variation of 100 nanoseconds

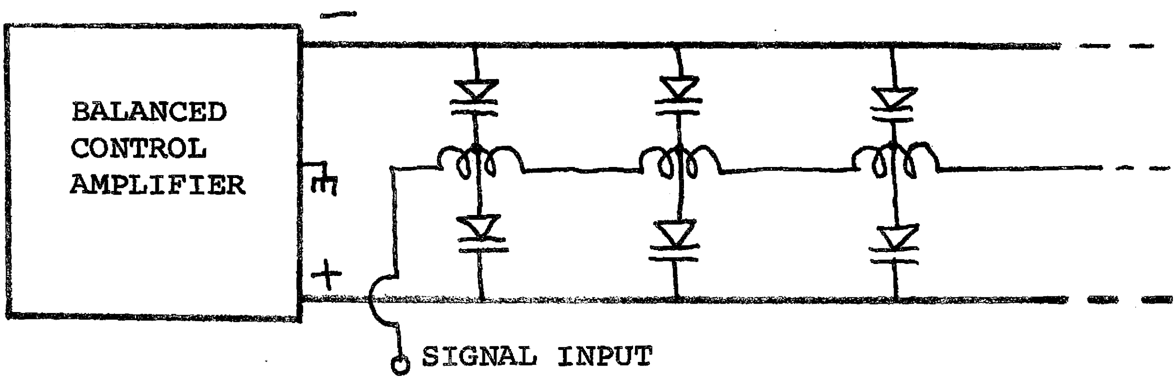
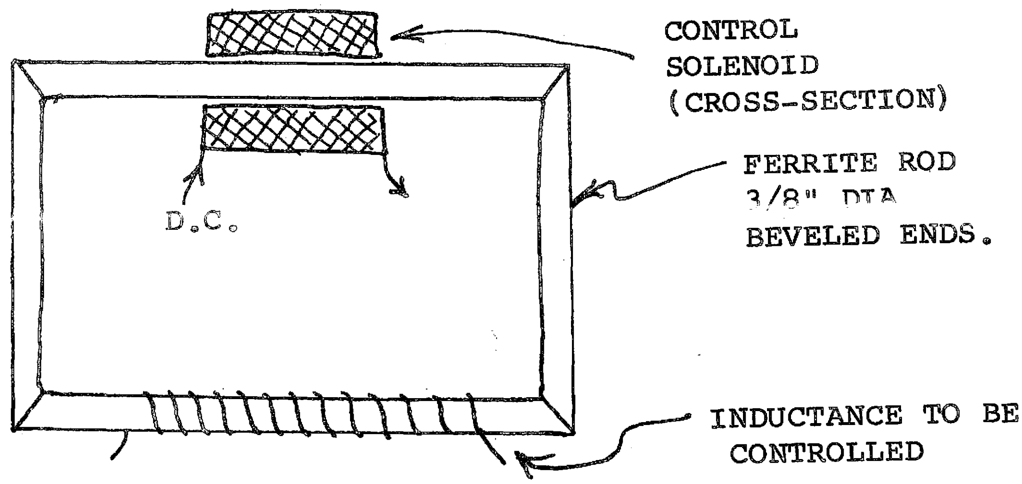


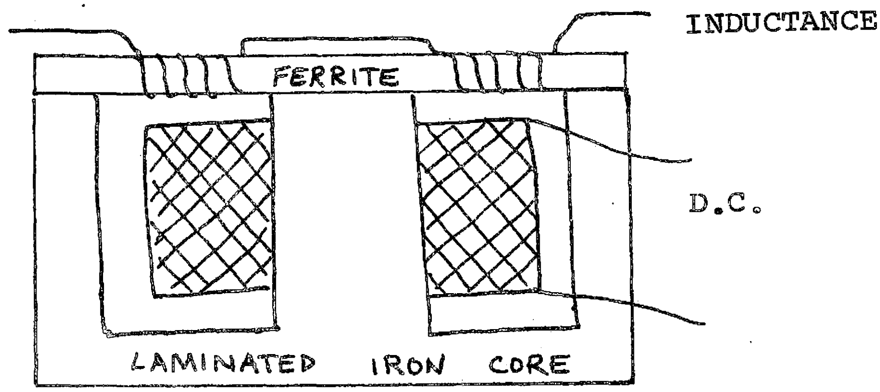
fig.14 A Varicap Delay Line

and a phase linearity of 5% was claimed for a bandwidth of 16 MHz. The bucket brigade EVDL provided a 100 microsecond delay variation with a bandwidth of 80 kHz.

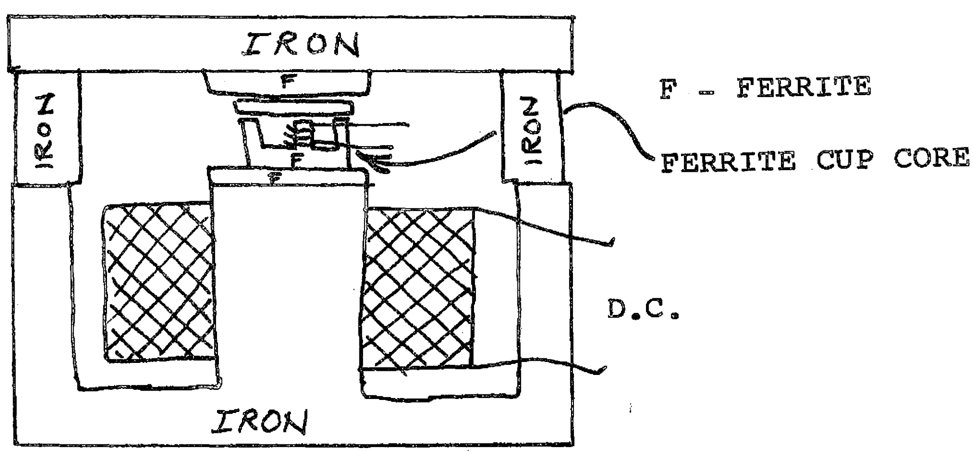
The proposed research required an EVDL to be constructed as none were known to be commercially available. The initial effort was placed in the area of the work of Spilker and Magill and a lumped delay network containing saturable inductors was attempted. Initial prototypes of a suitable saturable inductor using ferrite cores and electrical solenoids were a disappointment. Each prototype is drawn in chronological order in fig.15 and a note indicates its disadvantage.



insufficient saturation available due to low permeability of the ferrite material to direct flux



good range of control of inductance (2:1) but very poor Q factor due to extreme RF losses in the iron



good Q of the inductance (25 @ 2 MHz.) but small range of control (about 10%)

<u>fig.15</u> <u>Three Saturable Inductor Prototypes</u>

Many disadvantages became evident in this approach. The large iron content of the inductance control set an upper frequency limit to the dynamic response of the delay control. There was also the difficulty of matching many sections of controllable inductors in cascade. A nonlinear control of delay versus solenoid current and slight hysterysis would inevitably occur. In addition the linearization of delay with respect to frequency presented itself. Finally all delay lines having controllable L or C suffer from a variation of characteristic impedance,

$$Z_0 = \sqrt{\frac{L}{C}}$$

L - inductance per section

C - capacitance per section

Only the simultaneous variation of both L and C can prevent reflections from a constant terminating impedance.

2-2 The Stepped Delay Idea

At this time consideration was given to the use of constant L and C per section and bringing out taps at even intervals along the delay line. The desire was to implement an all electronic version of the system shown in fig.16.

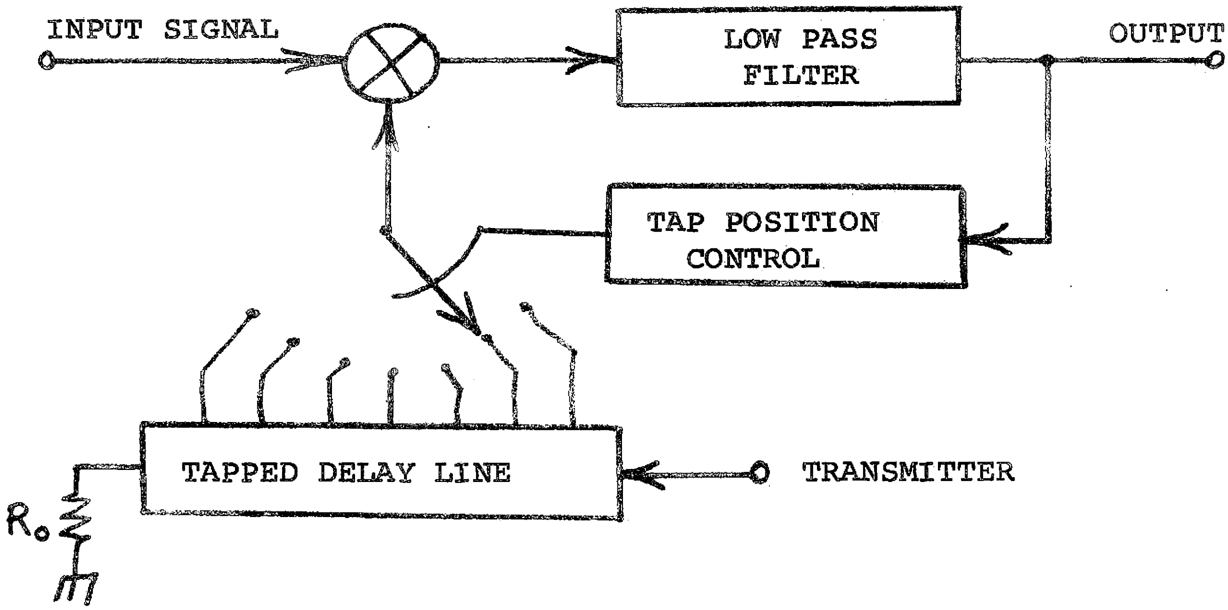


fig.16 The Stepped Delay-Lock Discriminator

The first proposed electronic switching system was as shown in fig.17.

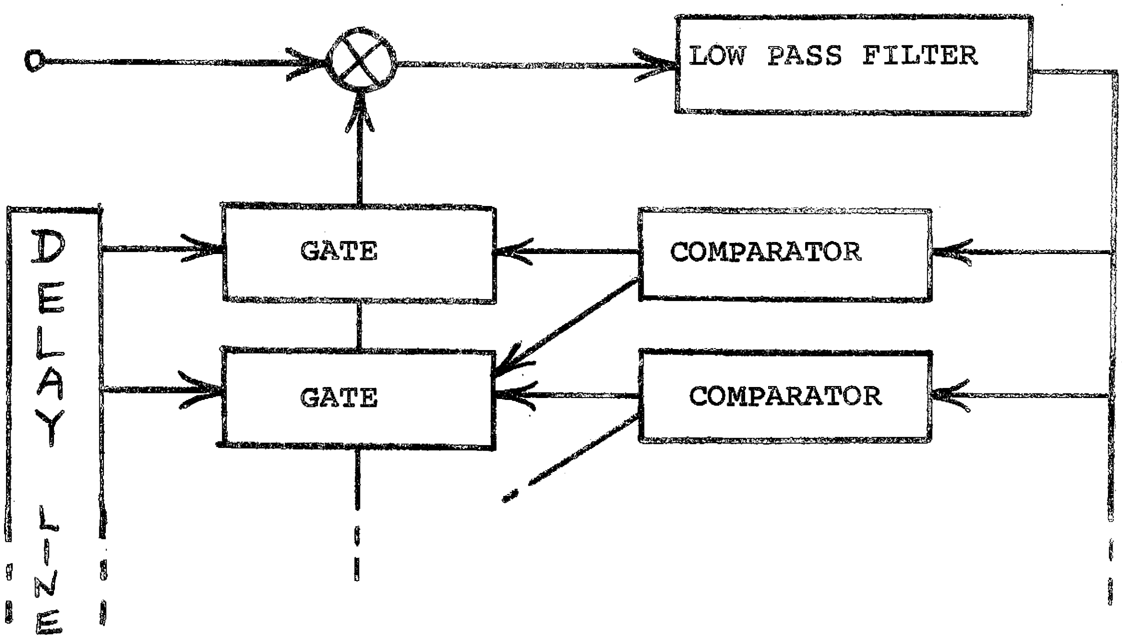


fig.17 An Initial Electronic Switched Proposal

The system of fig.17 has the disadvantage of requiring "N" gates and "N" comparators for an "N" tap delay line. The complexity and expense increases linearly as the number of taps on the delay line. An alternate scheme, more compact and giving the same results, is as follows using the cascade of delay line lengths weighted in a binary manner.

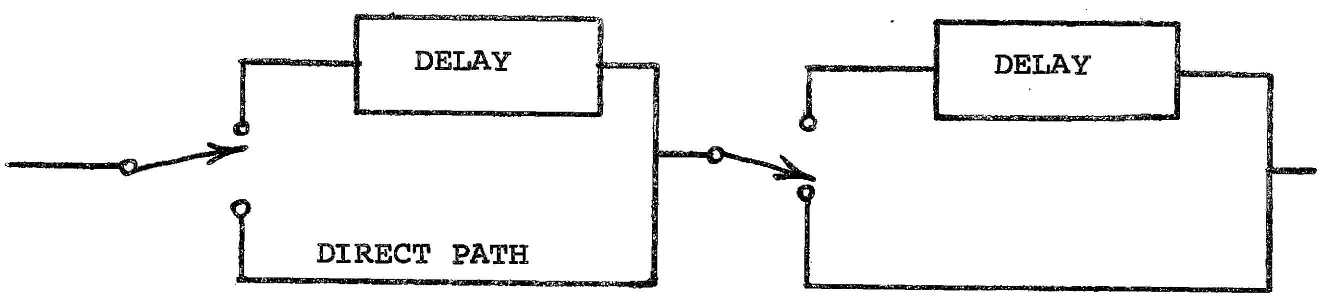


fig.18 Sections of Cascade Delay

In a system with "n" sections of delay, by closing the switches in 2^n possible combinations, there are thus 2^n delays generated. Such a cascade is explained and results shown in a recent correspondence.[15] The system constructed for this thesis used the cascade delay principle.

2-3 The Multiplier

The second most difficult project was to construct a workable multiplier to handle wideband high frequency analog

15 J.B.Payne, "Wide Bandwidth Electronically Controlled Digital Delay Line," Correspondence IEEE TRANS. AEROSPACE and ELECTR. SYST., Vol.AES-2, No.5, September 1966.

signals. The multiplication operation may be considered as a frequency conversion from the frequencies of the signal to baseband. Most analog multipliers operate on zero mean value RF waveforms by the double modulation and low-pass filtering method.

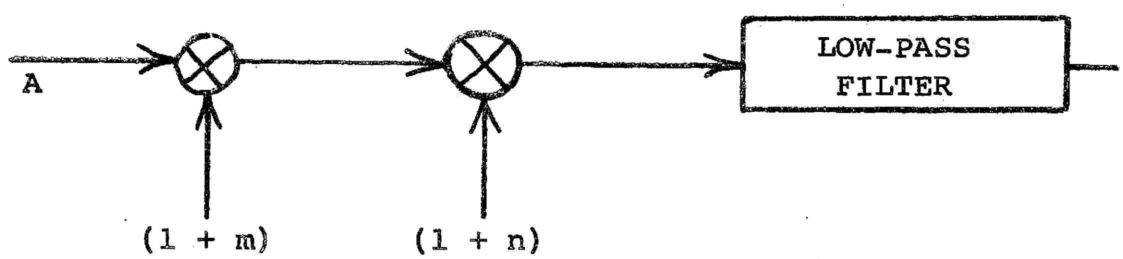


fig.19 The Method of Operation of the Multiplier

Let A be a positive constant which is linearly modulated.

Let m and n be zero mean value RF signals normalized in amplitude so that:

$$|m| < 1 \qquad |n| < 1$$

First amplitude modulation of A by m yields,

$$(1 + m)A > 0$$

Second amplitude modulation by n yields,

$$(1+n)(1+m)A = nA + mA + nmA + A$$

The first two terms of the double modulation are zero mean value terms having the same frequency spectrum as n and m respectively. The last term is a constant which can be subtracted. The low-pass filter which follows the analog multiplier must be chosen to reject the lowest frequency components of n and m.

The term nmA has a non-zero mean value only if n and m are correlated.

The circuits of two correlators constructed appear in the Appendix. The first circuit used pentagrid vacuum tubes. It was less than satisfactory because of a weak correlation output and DC drift. A second circuit used transistors and was somewhat more dependable.

CHAPTER THREE

THE SYSTEM IMPLEMENTED

3-1 The System Components

To understand the operation of the system it is necessary to understand the operation of each part. In the following explanations the separate parts are discussed. Comp--lete circuits appear in the Appendix.

3-1 (a) The Quantized Delay Line

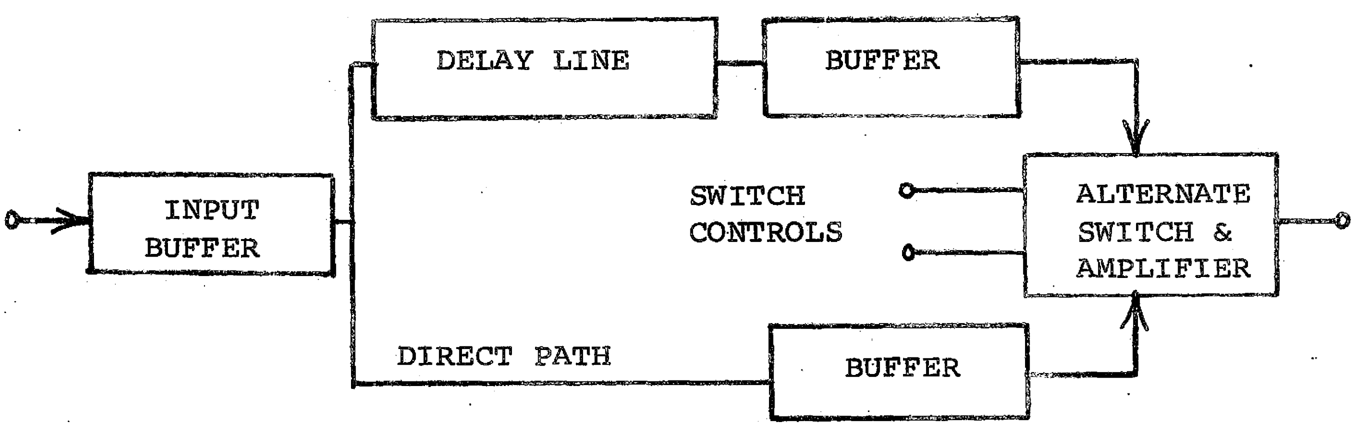


fig.20 One Section of Digital Delay

The delay lines available were 16 identical units of 0.5 microsecond each, with 60 nanosecond risetime and a char--acteristic impedance of 1200 ohms. Initially four sections as in fig.20 were made up having " lengths " of 0.5 μS., 1 μS., 2 μS., and 4 μS. By suitable switch actuation 16 different evenly spaced values of delay were available, in 0.5 μS. steps, from zero to 7.5 μS. Each section was balanced for identical gain by either path and the pedestal (DC level) was also equalized. Approximately 0.5 μS. was required to switch the delay and a switching transient of the same duration was gener--ated . This transient was not found to be a serious shortcoming. Although the delay lines themselves had 16 MHz. bandwidth the finished quantized delay line had only 2 MHz. bandwidth due to limitations of the transistors used in the signal path. Seven transistors were used per section of delay. A previously mentioned paper[15] indicates that proper care in selection of transistors and delay lines can result in 450 MHz. bandwidth at the present state of the art.

3-1 (b) The Binary Counter

A binary counter was required to suitably actuate the switch controls of the delay sections. In order to approach the correct delay as directly as possible, it was necessary for the counter to be able to both increment (count up by ones) and decrement (count down by ones) at will. This was accomplished by gates inserted between each flip-flop stage. The up-down gates were controlled by a Schmitt Trigger circuit.

The up-down control voltage was applied in analog form to the input of the Schmitt trigger which exhibited a hysteresis of 30 millivolts. This amount of hysteresis was generally much smaller than the applied voltage and could be ignored. When the quantized delay line and the complete binary counter were connected, the binary number stored in the counter would appear in the delay line as that number of half-microseconds of delay.

3-1 (c) The Multiplier, Filter and DC Amplifier

The first multiplier used pentagrid converter tubes, type 6BA7 in a balanced configuration with 12AU7 triode diff--erential DC amplifiers to increase the correlation output voltage. Provision was made to subtract any constant quantity of voltage so that the output could vary about zero volts. About one volt of variation was available after amplification. The filter was conveniently chosen to be an RC low-pass filter with a cutoff frequency of approximately 800 Hz. No claim is made that this filter is optimum.

3-1 (d) The Delayed " Echo " Generator

The testing of the constructed system required a delayed signal to be detected. To test the linearity of the estimate, a delayed and an undelayed signal were applied to the tracker. The use of a random noise signal would have required a device for delaying a noise waveform. This was judged to be too diffi--cult a task initially and therefore a periodic two level waveform was used. Transistor monostable delay circuits pro--vided the test delay.

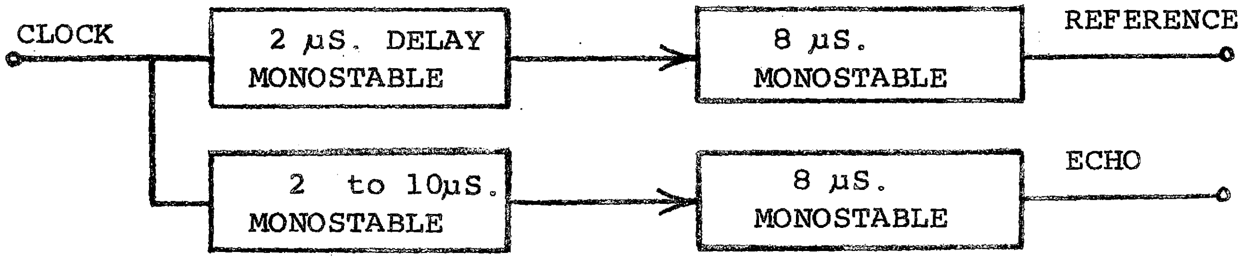


fig.21 Test Echo Generator

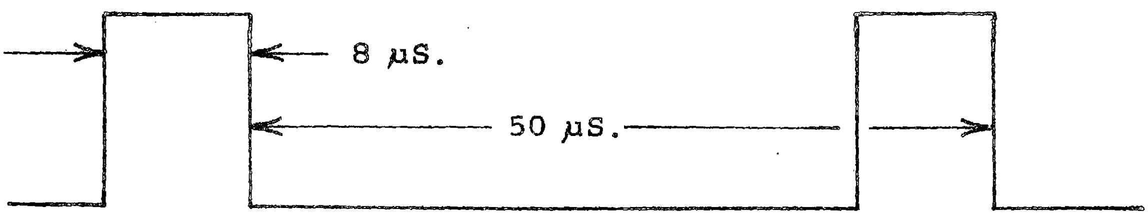


fig.22 The Transmission Waveform

The transmission was a rectangular periodic wave and the echo was adjustable by hand continuously from zero to 10 µS. delayed with respect to the transmission wave. The autocorrel--ation function of such a signal would have the shape of fig.23.

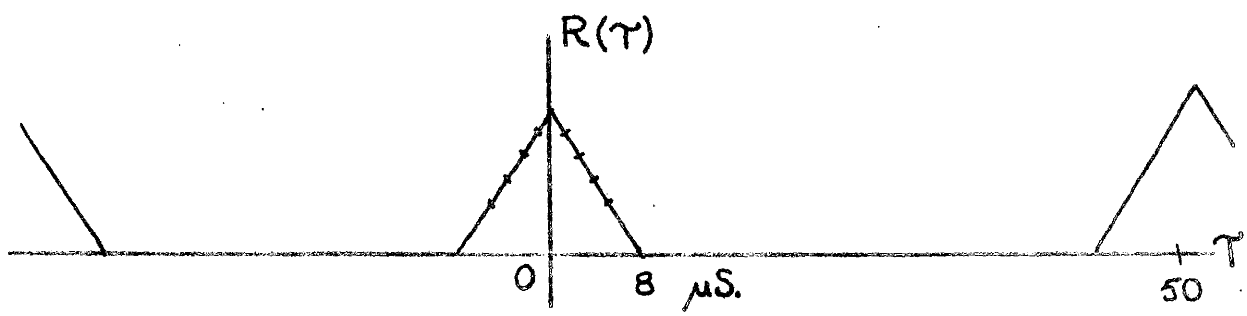


fig.23 The Autocorrelation Function for the Wave of Fig.22

The second triangle appearing at a positive delay of 50 μS. in fig.23 was not within the range of the system and there--fore no ambiguities were possible during operation.

3-2 Open Loop Trial of The Correlator

All the elements discussed were connected as in fig.24 and an open loop trial was made of the ability of the corre--lator to produce the autocorrelation function theoretically expected.

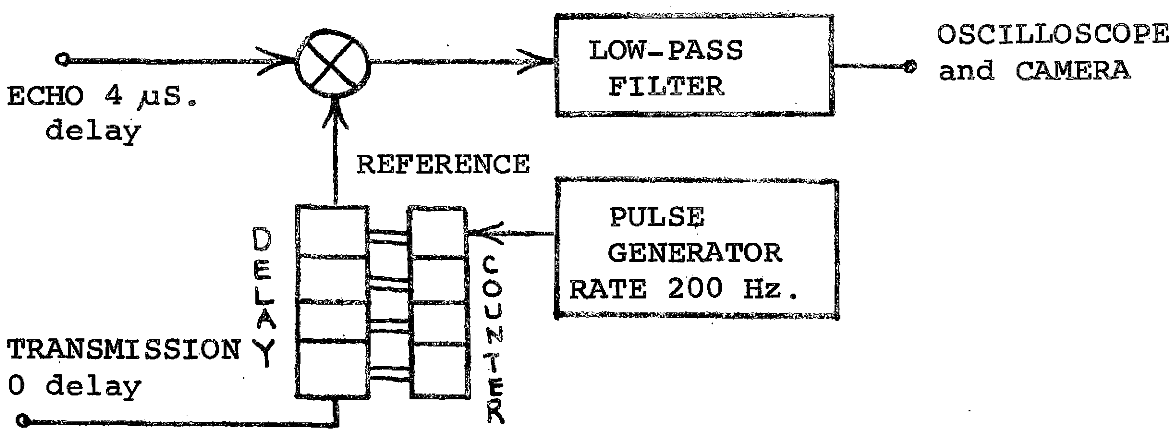
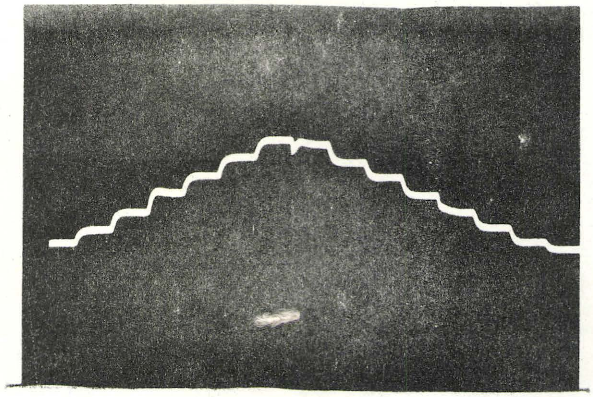


fig.24 Open Loop Trial of The Correlator

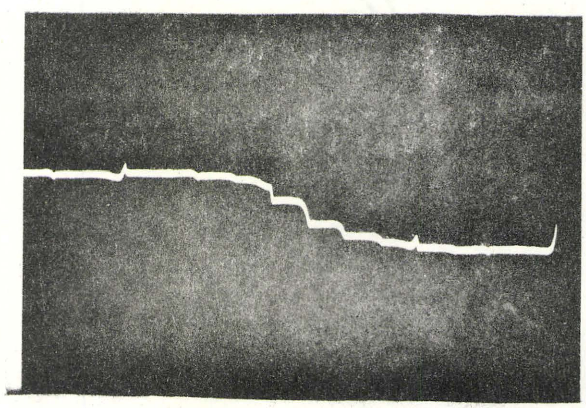
The delay was allowed to increase at the rate of 200 steps per second moving the reference through all delays from zero to 7.5 μS. The delay difference τ at the correlator inputs went from minus 4 μS. to plus 3.5 μS. by steps of 0.5 μS. In the photograph of fig.25 the triangular shape of the auto--correlation function is evident and the similarity to a series of points drawn near the origin of fig.23 is obvious.



HORIZONTAL SCALE:
10 mS./ cm.

VERTICAL SCALE:
0.5 volts / cm.

fig.25 The Quantized Autocorrelation Function



HORIZONTAL SCALE:
10 mS. / cm.

VERTICAL SCALE:
0.5 volts / cm.

fig.26 The Differentiated Autocorrelation Function

The test was repeated with a series RC differentiator inserted into the reference line of fig.24. Due to bandwidth limitations of the delay line circuits and inaccuracy in the RC differentiator, the waveform of the delayed differentiated rectangular wave was not alternate up and down spikes but alternate up and down bumps of about one microsecond width. Therefore the differentiated autocorrelation function experi--mentally recorded in fig.26 showed the positive and negative constant expected, but the discontinuity between became more gradual.

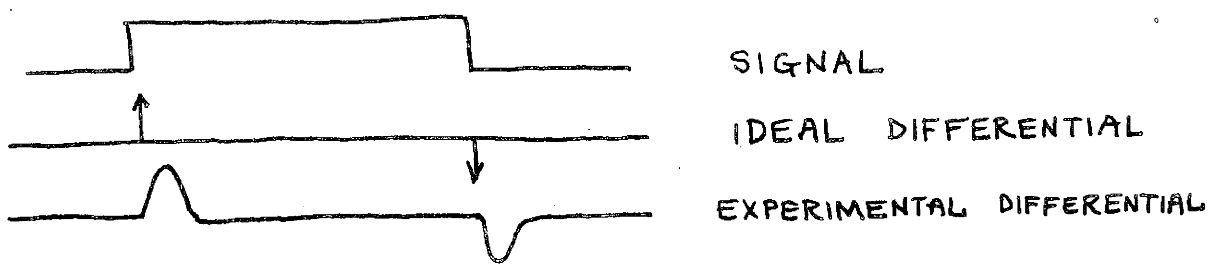


fig.27 The Ideal and Experimental Differentiated Signal

3-3 Closed Loop Static Linearity Test of the Relay System

The loop as drawn in fig.24 was closed by connecting the output of the filter to the counter directional control, the Schmitt Trigger circuit. The reference differentiator was used.

3-3 (a) The Static Test

Many different setting of the echo delay were tried and the system estimate was recorded and compared to the echo delay. No provision was made to stop the input of pulses to the counter. The results are plotted in fig.28.

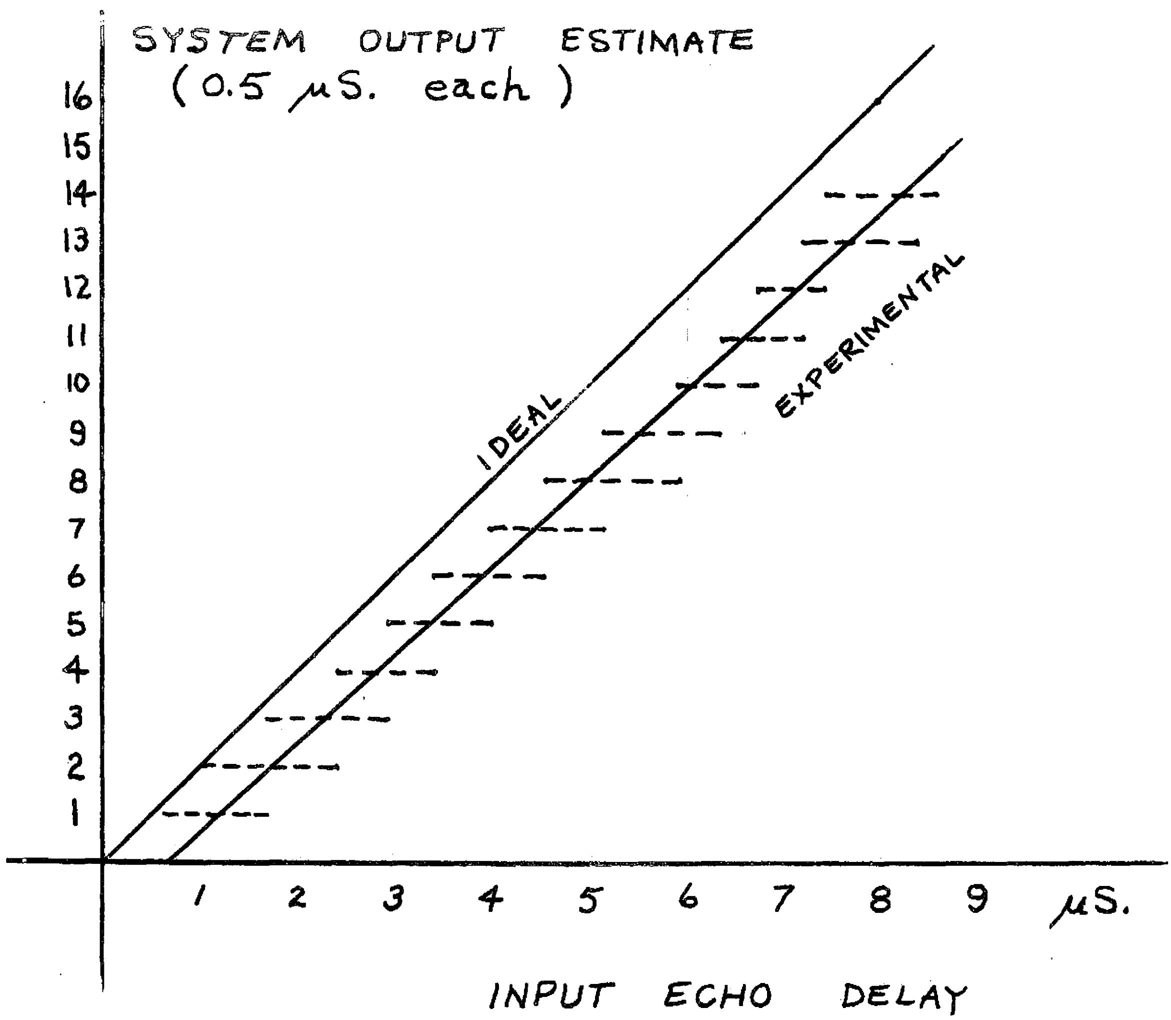


fig.28 Static Linearity Test of Quantized Delay Tracker

The inability of the system to stop was evident by a cont--inuous flicker at the counter rate between the two discrete estimates adjacent to the correct delay. The general trend of fig.28 showed the output to follow the input delay. A small offset was explained by examining fig.27 which showed that the derivative of the reference lagged the transmitted waveform by a constant amount.

3-3 (b) The Deadband Stop Device

In order not to be plagued with a constant flicker between two adjacent taps on the delay line, a stop count device, actuated by the filter output, was constructed and inserted into the loop between the counter pulse input and the pulse generator.

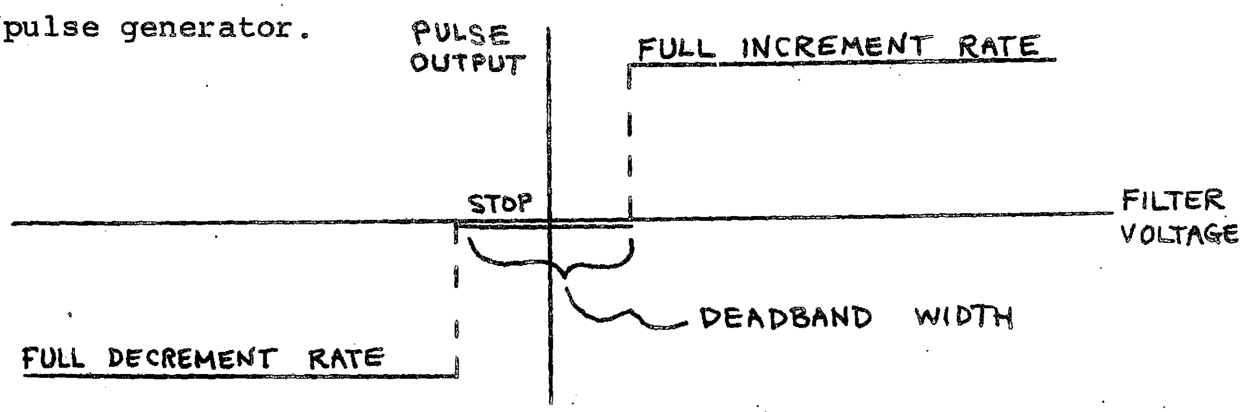


fig.29 Characteristics of the Deadband Stop Device

For correct operation the deadband width was adjusted to be equal to the voltage shown between steps in fig.26. Another graph of static linearity is shown in fig.30.

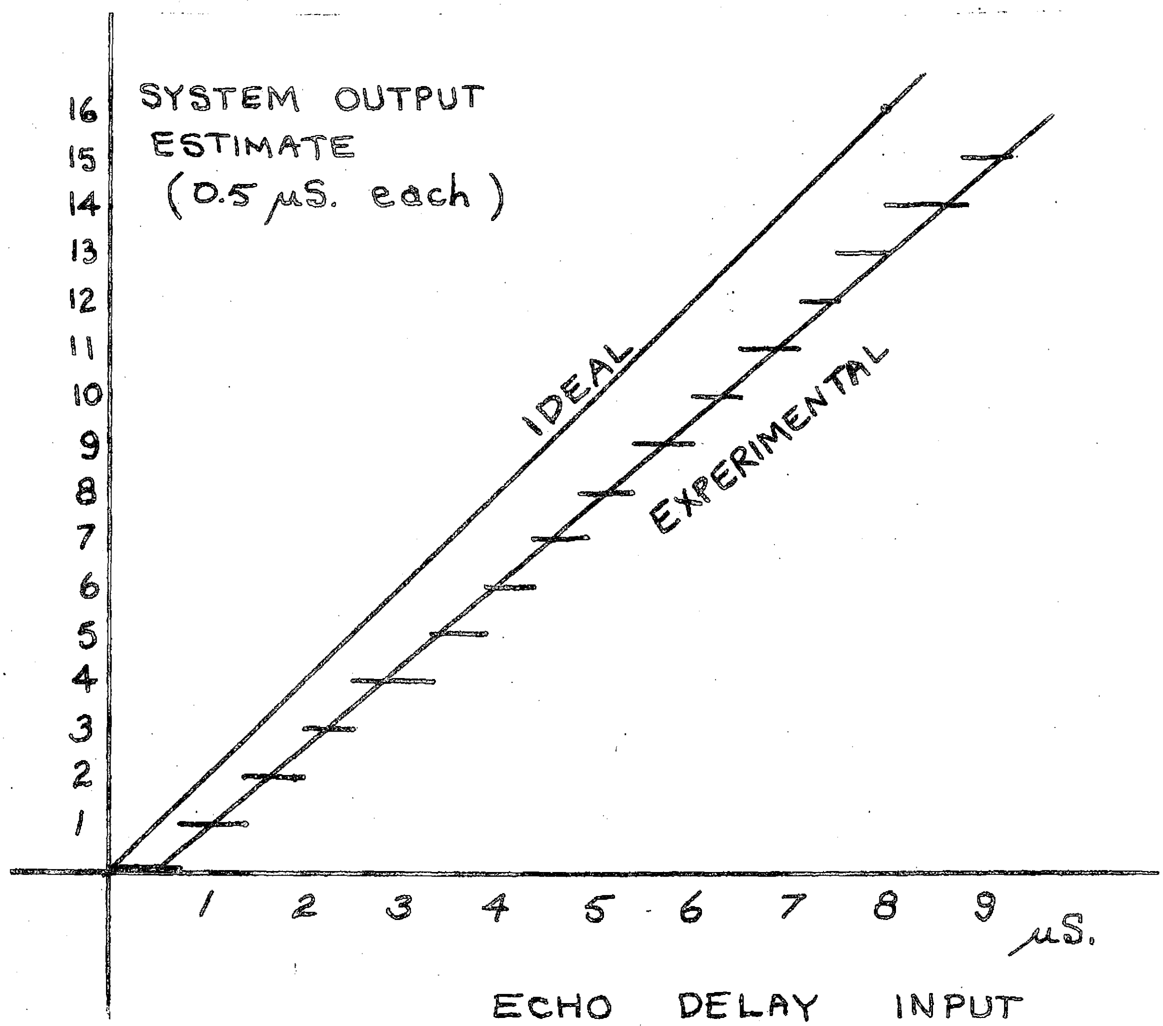


fig.30 Static Linearity Test with Deadband Device

The success of the deadband device is shown in fig.30 by the existence of only one output for one input, whereas the graph of fig.28 exibits two alternating outputs for one input. The uneven spacing of the steps was due principally to DC drift of the correlator during the time taken to plot the graph. This drift also explains the different slope from that expected. The points were plotted left to right during which time the correlator drifted downward.

3-4 A Demonstration of the Relay System with Noise Added

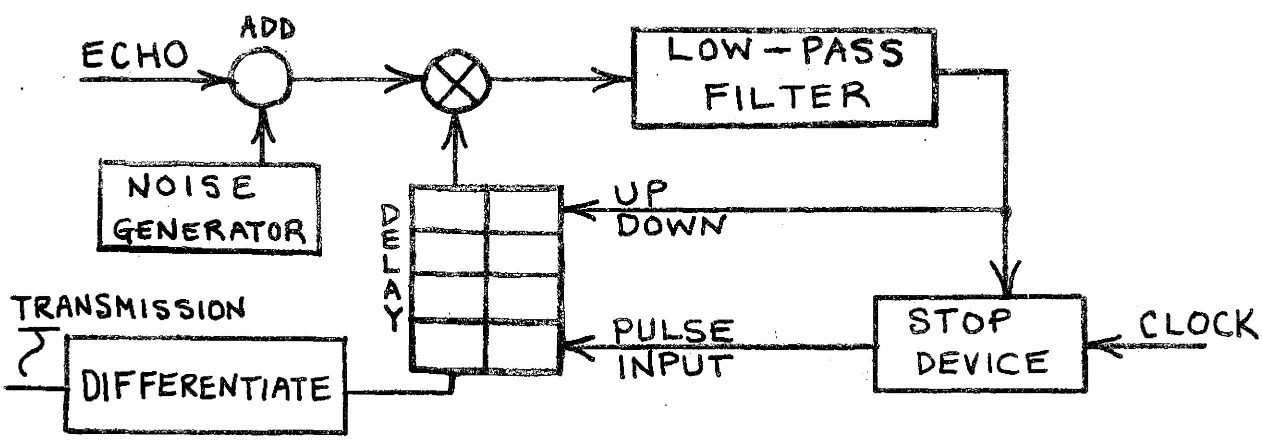
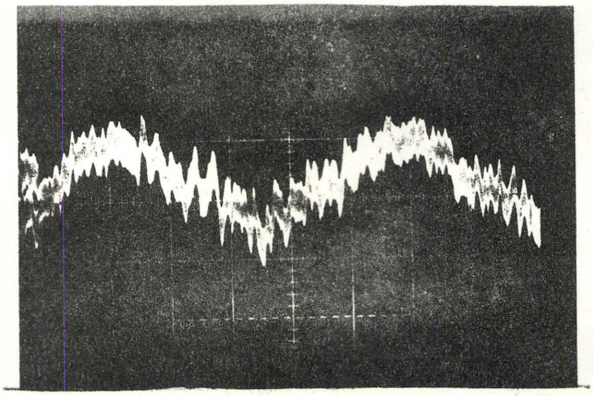


fig.31 The System with Noise Added

The noise output from a random noise generator was filtered by a high-pass filter to remove those frequency components which were outside the range of components of the signal. The strength in terms of true RMS voltage of signal and noise were recorded. The correlator was able to discriminate against the wideband noise added to the periodic signal. Locking-in was observed at RMS signal-to-noise ratios as low as 1 : 5. The noise rejecting performance of the system was essentially a function of the bandwidth of the low-pass filter and correspondingly the time of integration.

In fig.32 an example of the noise contaminated auto-correlation function is shown. Recall that the autocorrelation function was triangular in shape. The delay was changed at the rate of 100 steps per second and a low-pass filter with 100 Hz. bandwidth was used. The signal-to-noise ratio for fig.32 was one to one. The triangular shape is clearly shown and evidently even more noise could be removed by a narrower low-pass filter.

In fig.33 the loop was closed and the system was locked-on. The echo plus noise and the reference are exhibited. The vertical alignment between the two correlator inputs, at an RMS signal-to-noise ratio of 6 : 1, indicates the locked-on condition.

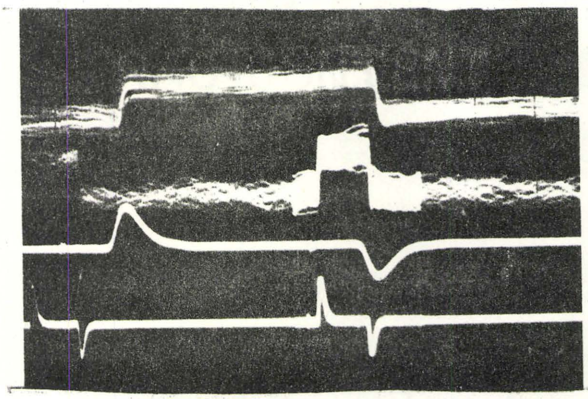


HORIZONTAL SCALE:
0.1 second / cm.

VERTICAL SCALE:
0.5 volt / cm.

fig.32 Noisy Autocorrelation Function

note: In the following photograph the first and third traces are expanded views of the second and fourth traces which are the noisy echo and the reference respectively.



HORIZONTAL SCALE:
5 μS. / cm.
2 μS. / cm. expanded

VERTICAL SCALE:
1 volt / cm. signal
5 volt / cm. reference

fig.33 Signal Plus Noise and Reference Waveforms

3-5 An Improved Dynamic Tracker with A-D Converter Feedback

The previous system was demonstrated to lock-on to a static signal, that is one having a constant delay. It was decided to perform tests on the ability to track dynamic motion, that is delay which was changing in time. The new dynamic system incorporated several additional refinements which are discussed in turn in the following. Circuits are found in the Appendix.

3-5 (a) Additional Circuits

A Transistorized Correlator

The vacuum tube analog multiplier proved rather diffi--cult to adjust to cancel DC drift and gave a weak correlation output. Therefore a new multiplier was built using transistors striving for a maximum of correlation output with a minimum of additional DC gain required. At this time a new filter was installed using an LC low-pass ladder network in order to remove all traces of high frequencies, due to the signal, from the correlator output. A considerably sharper cutoff was employed compared to the previous RC filter although the bandwidth remained similar at approximately 800 Hz.

A Dynamic Echo Generator

In order to have dynamic motion of the echo along the delay axis it was necessary to build an electronically variable delay generator in which delay was linearly and continuously related to an applied voltage. A block diagram of the new delay generator is shown in fig.34.

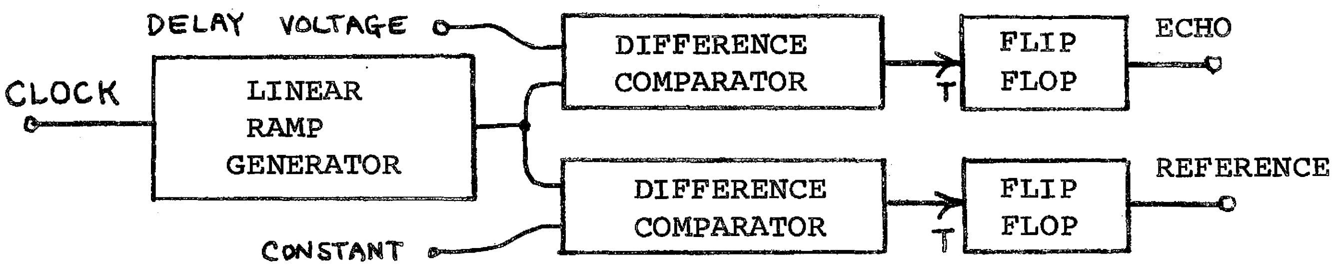


fig.34 Electrically Variable Delay Generator

The use of flip-flops at the output of the delay gen--erator was necessary to produce two identical waveforms but resulted in the signal taking the form of a two level square wave. Two 30 kHz. square periodic waveforms with a slowly vary--ing relative delay were produced.

The autocorrelation function of a square wave of repet--ition frequency 30 kHz. is a triangular wave which is periodic along the delay axis with period 33 μS.

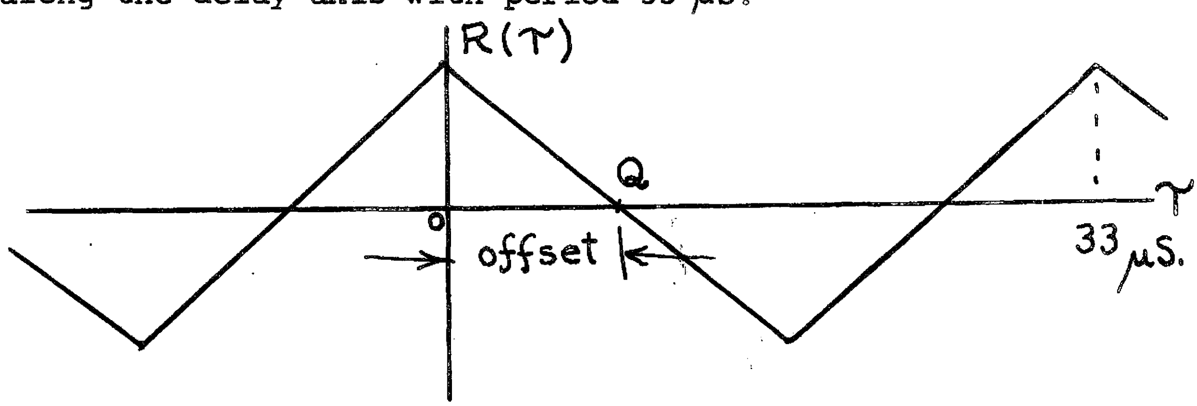


fig.35 The Autocorrelation Function of a Square Wave

In this case stable operation was set up about point Q of fig.35. This method of operation was called " offset operation " because the stable lock-on condition allows a constant differ--ence to exist between the delay of the echo and the reference.

A Refinement and A Convenience

By the construction of an additional delay section of 0.25 μS., the 16 step system was refined to a 32 step system. A corresponding additional flip-flop stage was added to the binary counter.

Nowhere in the system was an analog form voltage avail--able which was proportional to the absolute delay setting of the quantized delay line. In order to check that the dynamic delay variations of the tracker were indeed following the input delay variations of the echo, it was convenient to be able to exhibit the two, input and estimate, simultaneously on an oscilloscope. For this purpose an analog voltage was derived from the number stored in the binary counter. This operation was a form of D-A conversion.

3-5 (b) The Analog-to-Digital Converter

In order to more closely approach a linear type of control system operation, the rate of pulse input to the counter was made proportional to the filter output. For this purpose a serial A-D converter was built. This converter allowed the advantage that whenever the filter output was zero the counter would stop. In addition a sudden step of delay on the part of the echo would produce a sudden burst of pulses to the counter great enough to completely follow the delay step if the converter gain were correctly set. One may also think of the action of the A-D converter as giving a variable rate of incrementing or decrementing delay, this rate being prop--ortional to the size of the delay error. The A-D converter was set to sample the correlator filter output at 0.005 second intervals and to issue from zero to four pulses depending on the magnitude of that error. Fig.36 shows the A-D transfer characteristic.

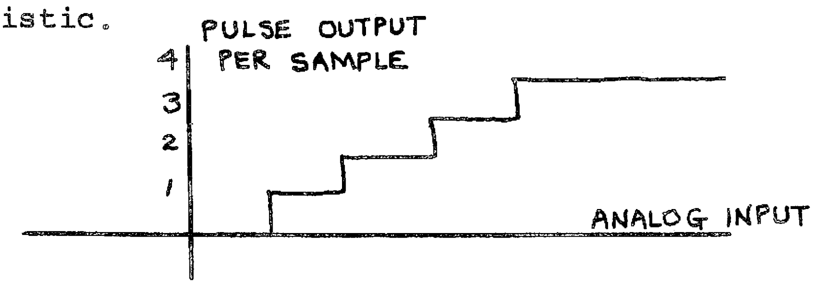


fig.36 A-D Converter Transfer Characteristic

Since only positive voltages could be converted full wave rectification of the filter output was necessary before application to the converter. The reversal ability of the counter enabled negative errors to cause correction in the suitable direction.

3-6 Dynamic Tracking Tests with A-D Converter and Relay Feedback

The system of parts described was assembled in the form shown in fig.37. A motion generator was built using filtered relaxation oscillations of frequency 2 Hz. and was used to modulate the echo delay. A more rapid delay variation could have been used.

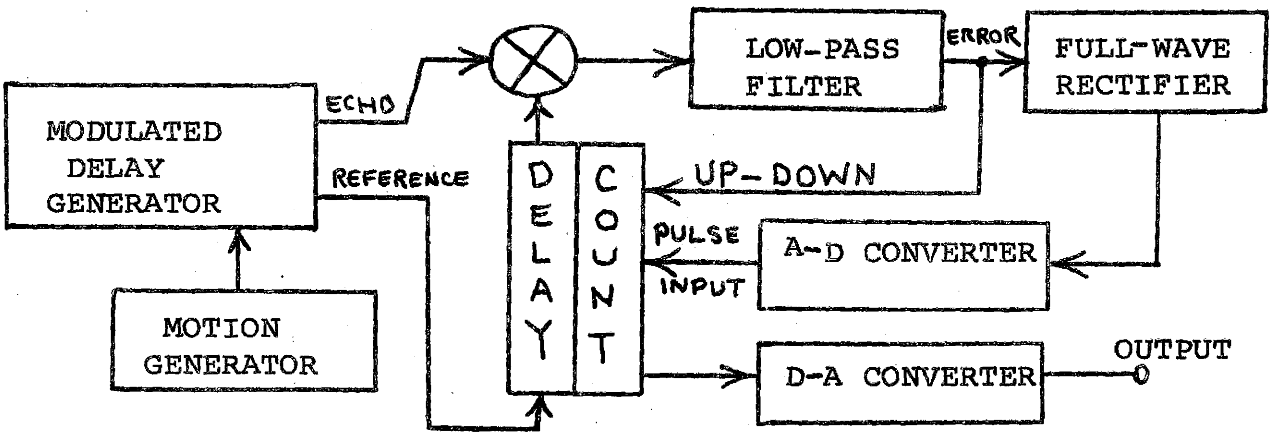
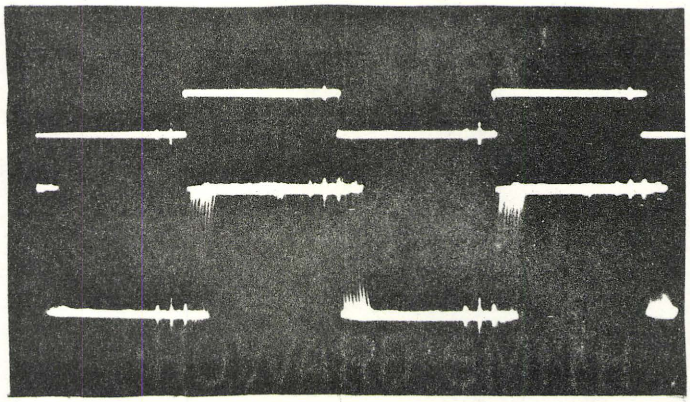


fig.37 Dynamic Motion Tracking Tests (A-D Converter Shown)

Details of the delayed forms of the references are shown in fig.38 and expanded in fig.39. In fig.39 the falling edge of the square wave is shown to illustrate the even spacing in delay of sixteen of the references.

3-6 (a) The A-D Converter Feedback

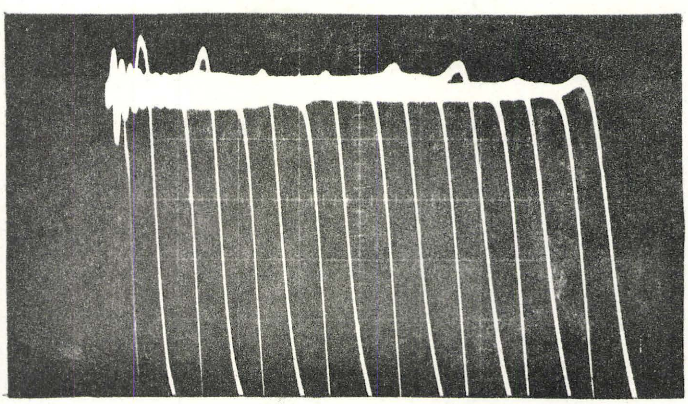
In fig.40 the input delay as represented by the electri--cal input to the linear delay generator and the output esti--mate as represented by the output of the D-A converter, are shown simultaneously. Approximately 24 of the available 32



HORIZONTAL SCALE:
10 μS. / cm.

VERTICAL SCALE:
1 volt / cm.

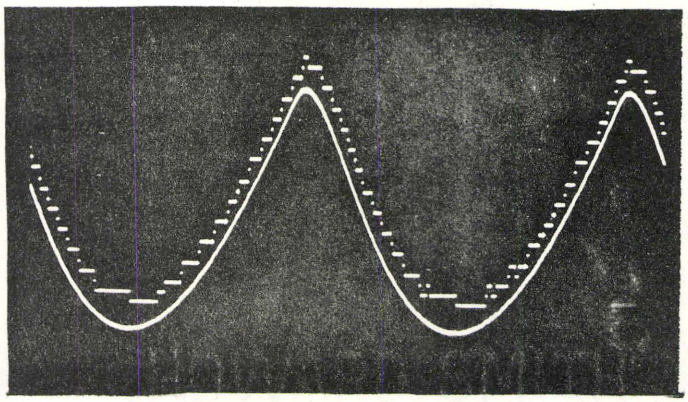
fig.38 Eight of The Delayed References



HORIZONTAL SCALE:
0.5 μS. / cm.

VERTICAL SCALE:
0.05 volt / cm.

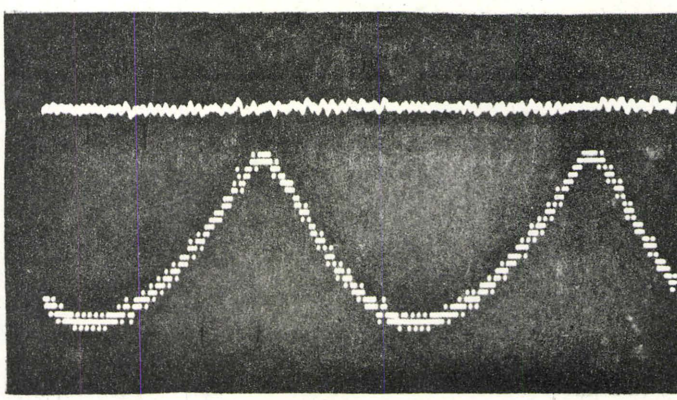
fig. 39 The Even Spacing of 16 References



HORIZONTAL SCALE:
0.5 seconds per period

VERTICAL SCALE:
6 μS. peak-to-peak

fig.40 Input, Output of The Quantized Delay-Lock Discriminator



HORIZONTAL SCALE:
0.5 seconds per period

VERTICAL SCALE:
0.5 volts / cm.
6 μS. peak-to-peak

fig.41 The Relay Feedback Tracker

delay steps were used, the input having a 6 μS. delay variation, of period 0.5 second. The action of the A-D converter allows the output to rest on one delay step if the input is not fluctuating rapidly.

3-6 (b) The Relay Tracker

Another type of operation was also studied. This was the relay method of tracking, which is similar to the static method, utilizing full increment and full decrement rate with no stop at any time. For this test the A-D converter was replaced by a continuous constant frequency pulse generator of pulse rate 200 Hz. In this case the only feedback around the loop was through the counter reversal control, a Schmitt Trigger circuit. The error voltage at the filter output is simultane--ously exhibited in fig.41. The input was identical to fig.40.

3-6 (c) A Comparison of The Relay Delay Tracker With A Relay Motor Position Control

The action of the relay tracker to time varying delay can be compared with a simple non-linear position control servomechanism. The output shaft may either increase or decrease the angular position, but at a fixed rate controlled by the RPM of the motor. The subtraction junction in fig.42 takes the place of the correlator and the motor direction relay takes the place of the binary counter Schmitt Trigger circuit. The motor represents the constant rate pulse generator which " revolves " the binary counter and hence the delay.

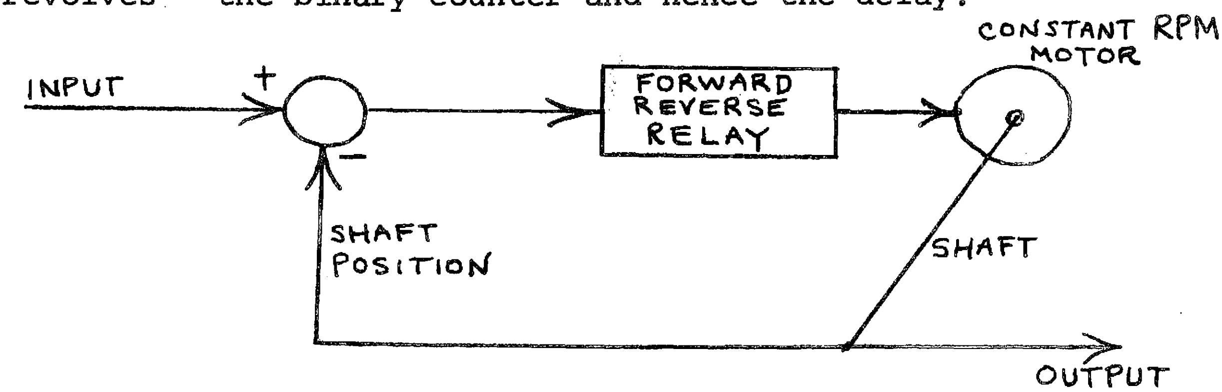


fig.42 The Relay Control Servomechanism

The comparison breaks down in that the motor angular position is continuous whereas the positions of the delay line are quantized; however this model has useful intuitive value where the motions are large compared to the quantization.

3-7 Discussion of The Results of The Tracking Tests

The greatest single difference between fig.40, the A-D feedback, and fig.41, the relay feedback,was in the number of steps or estimates which the output of each system produced. Notice the A-D system generally exhibited a monotonic increase of the output without the back-tracking see-saw motion evident in the relay system. The more linear response of the A-D system showed up as a fast rate of printing estimates where the delay was varying rapidly, and a slow estimate rate where the delay derivative was small.

Recalling that a transient was produced each time the quantized delay line was switched, the correlation process of the relay system would be the more contaminated by spurious waveforms. Therefore the A-D system would be preferable for below noise tracking.

Detailed examination of the sequence of estimates in fig.41, the relay system, reveals a curious backward and forward motion centered about the correct delay. This motion often extends for three or four quantization steps whereas the ideal motion would be an alternation between those two delay steps directly straddling the correct delay. At the present time this phenomenon is attributed to the high counting rate, 200 Hz., which was a sizeable fraction of the low-pass filter bandwidth of 800 Hz. Indeed an increase in the counting rate to 1000 Hz. with the same low-pass filter was observed to cause an increase in the amplitude of output oscillation to 5 steps, and a de--crease in counting rate to 100 Hz. produced the two step alternation expected.

Where the quantized nature of the output is undesireable a first-order hold could be connected to the output of the D-A converter and the quantization error could be smoothed.

CHAPTER FOUR

A GENERAL DISCUSSION WITH FUTURE RESEARCH INDICATED

The purpose of this thesis has been to implement a quantized delay-lock discriminator and to prove the practi--cality of the use of quantized delay in lieu of continuous delay. The success of this project was evident in Chapter Three but much further reseach remains to be done on problems encountered. In the following sections fruitful areas of research are suggested.

4-1 Logarithmic Delay Steps

The systems developed have utilized even spacing of the discrete delays of the reference. If no interpolation between steps is considered then a constant uncertainty equal to one-half delay step exists in the distance measurements. This uncertainty or error will be percentage-wise quite large for very short distances and small for long distances. A new method of spacing the delays has been suggested by which the error is a fixed percentage of the distance measured, irrespect--ive of the magnitude of that distance. This reduction in error at short distances is obtained by a fine delay spacing of the references for small delays and a corresponding coarser spac--ing at long distances. A logarithmic spacing of the taps on the delay line suggests itself.

A similarity exists between this delay quantization and the amplitude quantization in PCM. For small amplitudes in PCM the quantization error is intolerably large and the output signal-to-noise ratio therefore falls. By utilizing finer level spacing in the low levels in the signal quantizer the signal-to-noise ratio can be improved for small amplitude signals.

The manner in which this logarithmic tapping could be implemented is not yet clear but the advantages in lower error and improved signal-to-noise ratio for small delays indicate the merit of further research in this area.

4-2 The Advantages of Wideband Transmission for Pull-In Effect

The analog signal delay line has the ability to delay waveforms having complicated amplitude structures. The auto--correlation function which is most desireable for use in the delay-lock discriminator has only one lock-on region and no ambiguities. It has a long skirt which allows the system to pull into synchronism those signals which are initially unlocked. A white low-pass noise waveform exhibits a differentiated autocorrelation function similar to fig.43.

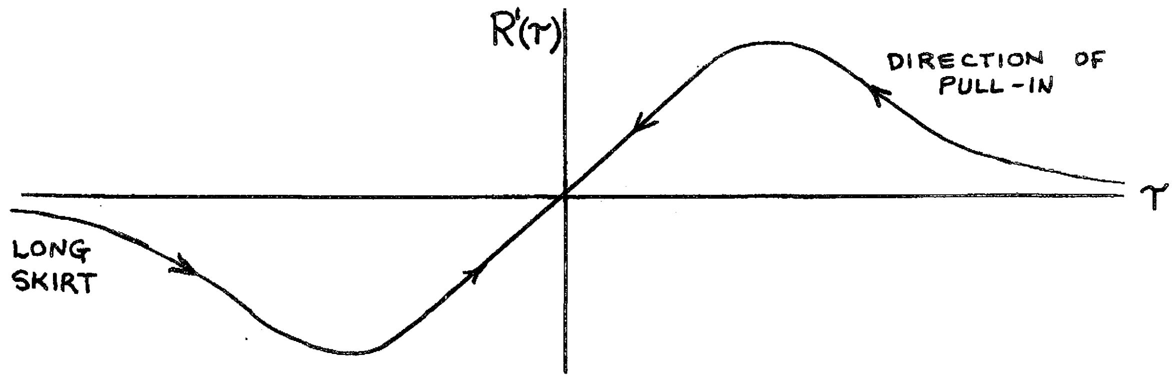


fig.43 A Desireable Differentiated Autocorrelation Function

The voltage $R'(\tau)$ is always positive in the first quadrant and a positive voltage from the correlator will pull the system to the left toward decreasing values of delay diff--erence τ. Similarly in the third quadrant of fig.43 the pull-in direction is toward the right. Therefore a signal which is initially unsynchronized with the reference will pull the reference into synchronism, given enough time and sufficient loop gain to do so.

Narrow bandpass transmissions such as sine waves, square waves, or narrow band noises have differentiated auto--correlation functions which exhibit both ambiguities and a limited pull-in range. A typical function is shown in fig.44.

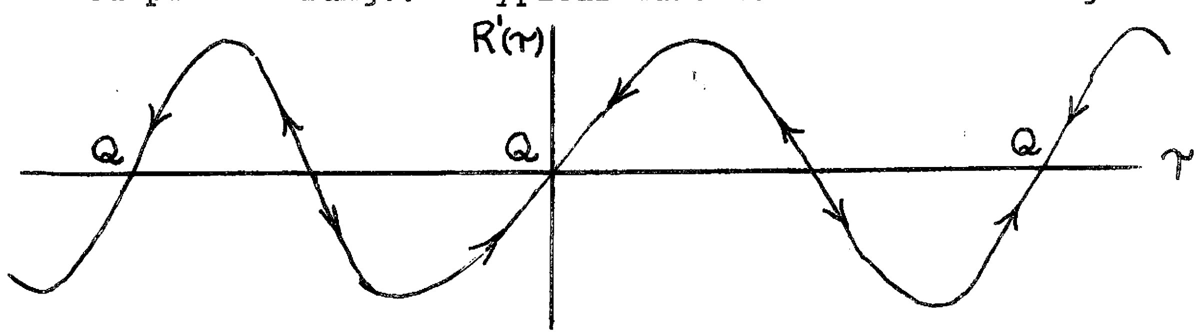


fig.44 A Typical Bandpass Differentiated Autocorrelation

In general the unambiguous pull-in range will be of the order of the period of the transmitted waveform. The low--pass spectrum of fig.43 has components of infinite period and therefore has infinite pull-in range, all other considera--tions being ideal.

The use of wideband random signals such as might be derived from a noise generator gives the added advantage of a secret reference for below noise undetectable and unjammable tracking. The transmitter and the receiver being in close proximity in this radar system allows the following scheme.

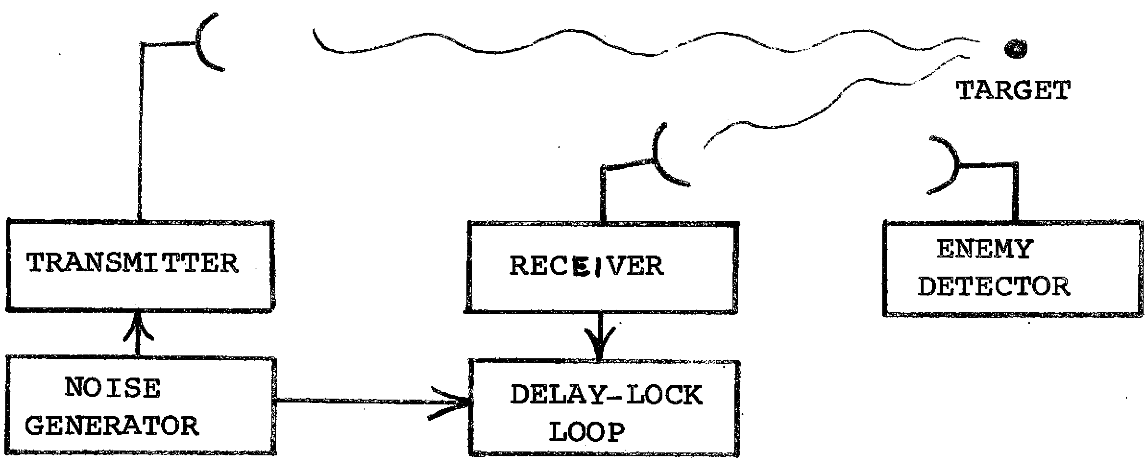


fig.45 Secret Wideband Noise Waveform Tracking

The enemy detector not having the reference available for correlation detection will presumably be unable to receive the transmission.

4-3 Narrow Bandwidth Below Noise Tracking and Loop Filter Optimization in the Continuous Model

Let us consider an ideal quantized delay-lock discrim--inator with very fine delay quantization approaching a cont--inuous field.

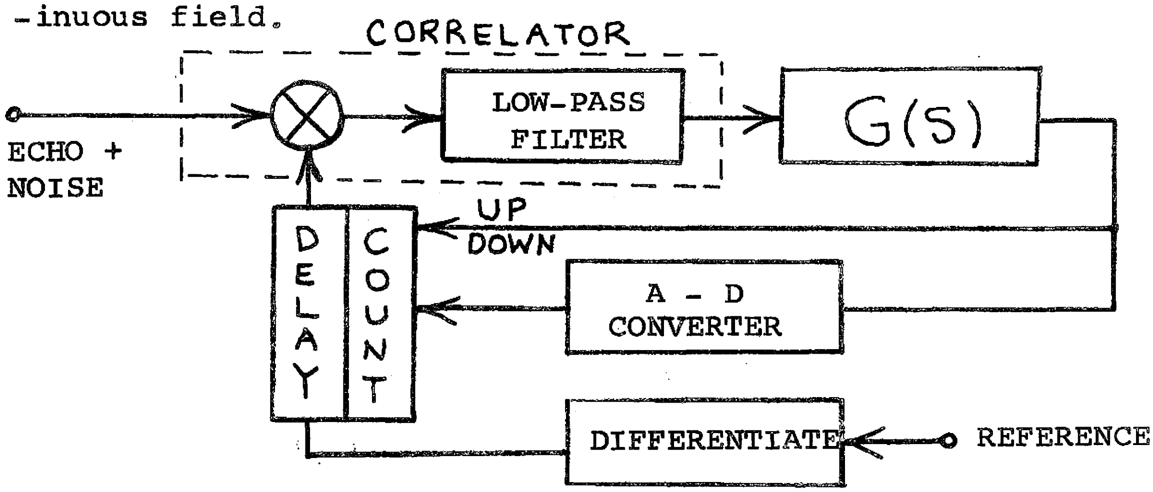


fig.46 Delay-Lock Discriminator with Optimization Filter G(S)

The input echo is of fixed amplitude. Let the correla--tor output produce a voltage proportional to the delay diff--erence. Let the analog-to-digital converter produce a pulse rate which is directly proportional to the correlator output. The correlator contains a low-pass filter of necessity to remove those high frequency components attributable to the power spectral density of the signal and to set a minimum to the time of integration. The parts within the correlator, the differentiator, and the delay system including the A-D converter are assumed ideal and of fixed gain. The optimization filter will contain the integrators and compensation networks necessary to best reject random noise while retaining good dynamic tracking ability. It is assumed that excursions of the delay of the input signal are never so large as to knock the correlator output off of the linear region of its character--istic and so unlock the system. Similarly the noise jitter of the delayed reference is assumed to remain within this bound. Keeping these assumptions in mind an ideal linearized model with simplified inputs can be drawn.

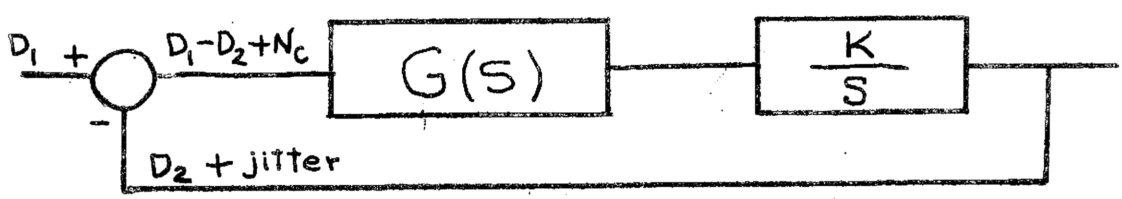


fig.47 Ideal Linearized Delay-Lock Model

d_1 and d_2 are slowly varying numbers representing only the delay of the input and reference signals. The correla--tor is replaced by the difference junction and the various gains around the loop have been absorbed into the constant K. N_c is the noise voltage produced at the correlator output by noises within the passband of the correlator. The power spect--ral density of N_c will be assumed flat and baseband.

The problem is now recognized to be that of optimizing the output D_2 of the noisy control system of fig.47 by varying the transfer function G(S) of the optimizing loop filter.

The most commonly used criterion, the solution of which may involve the calculus of variations, minimizes the weighted sum of the delay jitter and the transient error. By contracting the bandwidth of the system to zero the jitter in D_2 is eliminated but the system response becomes exceedingly sluggish and the transient error is intolerable. The Lagrangian multiplier λ is used to find a compromise.

For calculations of optimum filters G(S) previously derived by other authors for use with the phase-lock loop see Chapter One of this thesis. The optimum filters shown there, for the phase-lock loop model, apply to this delay-lock loop model without further modification.

It is well to note that those optimum filters which were derived hold only for the set level of input signal strength. In situations where the signal strength varies, the input to the correlator must be preceded by an AGC amplifier. Failure to present a constant input strength to the correlator results in a fluctuating loop gain in the feedback system.

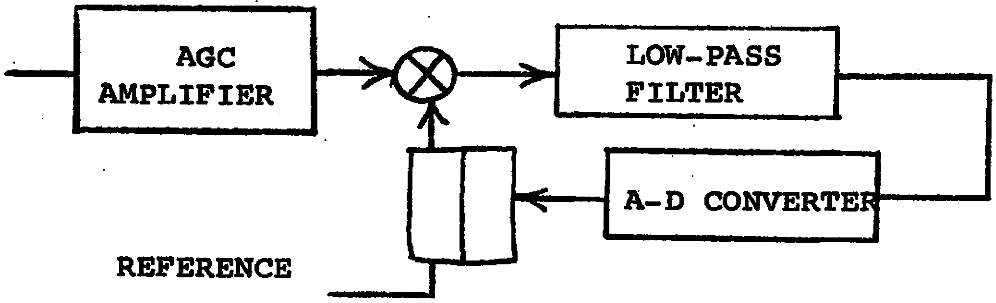


fig.48 Application of Automatic Gain Control to Tracker

4-4 The Acquisition Problem With Signal Below Noise

The previous dissertation on optimum filtering seems merely academic until the problem of acquiring a locked-on condition in systems having good noise rejecting properties arises.

The third order ideal delay-lock tracker follows a parabola of delay with zero steady state error. Examination of fig.6, Chapter One, reveals several integrators into which initial conditions must be placed. The initial conditions are all zero only if the parabola conveniently places itself about the origin; that is the signal as it appears has zero delay difference from the reference and has zero doppler shift.

Consider a satellite rising over the horizon as tracked from a ground based radar station and passing overhead to disappear at the other horizon. An approximate graph of delay versus time would be as shown in fig.49.

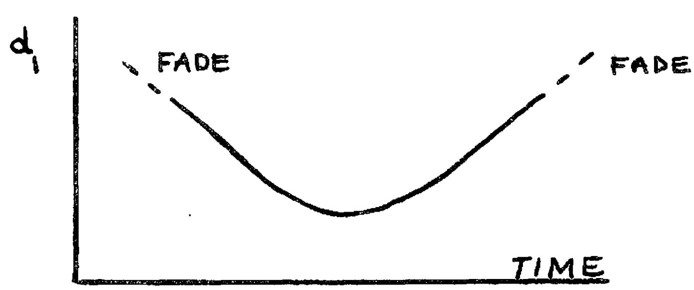


fig.49 Hypothetical Satellite Range Versus Time

The initial searching track in the delay doppler plane must be set up to acquire the signal as it fades in.

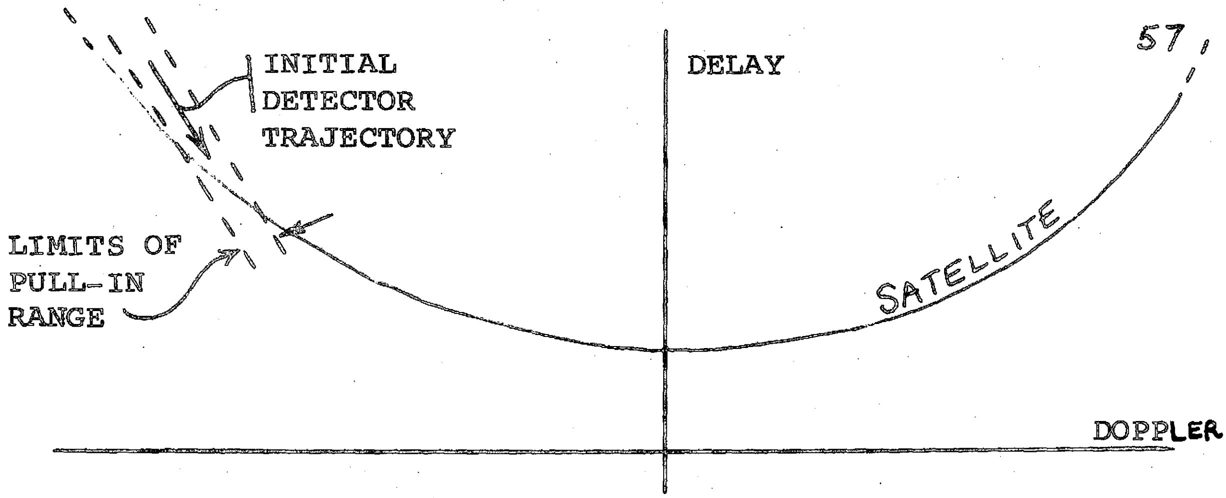


fig.50 The Initial Trajectory in The Delay Doppler Plane

The delay-lock discriminator exhibits a pull-in range which is a function of the width of the autocorrelation function on the delay axis. This means that signals which present themselves within a certain range of delay near to that of the delayed reference with which the correlator is operating, will pull the reference into co-incidence with the received echo and lock-on the system.

The third order tracking system must not only exhibit a similar delay to the signal but must also have a similar doppeler shift, to be pulled into synchronism. Those filters resulting in a very narrow system bandwidth B_n are best suit--ed to high noise levels but are slow to react to signals pass--ing through the pull-in range. Thus locking-in on a signal which passes through the pull-in range is not assured if the bandwidth of the system is narrower than the inverse of the time in which the signal traverses the pull-in region.

4-5 Quantitative Analysis Suggested

In this project two delay-lock loop systems have been demonstrated, the relay feedback tracker and the A-D converter feedback tracker. Many exact calculations remain to be performed. For example, the relation of the amplitude of the output oscil--lation of the relay tracker to the low-pass filter cutoff frequency and the counting rate, remains to be discovered. There is ample scope for optimization in other areas. Before calculations can be made preliminary assumptions fixing the non-adjustable and adjustable parameters (bandwidth, gain, transient response and noise rejection) of the system must be formulated. Perhaps the most pertinent research lies in the area of signal seeking and acquisition of lock-on conditions. As mentioned previously the pull-in range and the time to lock-up are functions of the transmitted spectrum, the detector filter and loop gain. After suitable spectra have been est--ablished, the exact calculations of these system properties can be performed for the two types of loop feedback. The A-D converter system is the more versatile of the two, having at its disposal such adjustable factors as error sampling rate and analog-to-digital gain characteristic.

The transfer function of the delay-lock loop is singul--arly dependent on the properties of the low-pass loop filter which follows the signal correlator. After a suitable criterion for good response has been developed, and the expected motion of the target has been defined, an optimization procedure will yield the best possible filter characteristics. The criterion for good response must weigh by importance many compromises between conflicting requirements. For example, the best noise rejection requires a low cutoff frequency in the feedback loop whereas good transient response requires fast action from the feedback system and a corresponding wider bandwidth within the loop. Again, the secure and undisturbable tracking of a single target while other targets pass through the line of sight of the radar, is traded off with quick pull-in and acquisition of new desired targets.

Optimum filters which are designed under assumptions of certain signal strengths, noise statistics, and target motions are found to be sub-optimum for other than design signal para- -meters.

4-6 Adaptive Filtering

The most suitable means of overcoming the necessity of compromise in the areas previously mentioned is through the use of adaptive filtering. Adaptive filtering requires that some variable parameters of the signal be measured and on the basis of these measurements a decision be made to alter the characteristics of the loop filter to make the response opti--mum for the pertinent situation. In particular the modes of tracking or acquisition are two very separate cases each of which might be handled by an entirely different filter switch--ed in as the situation requires.

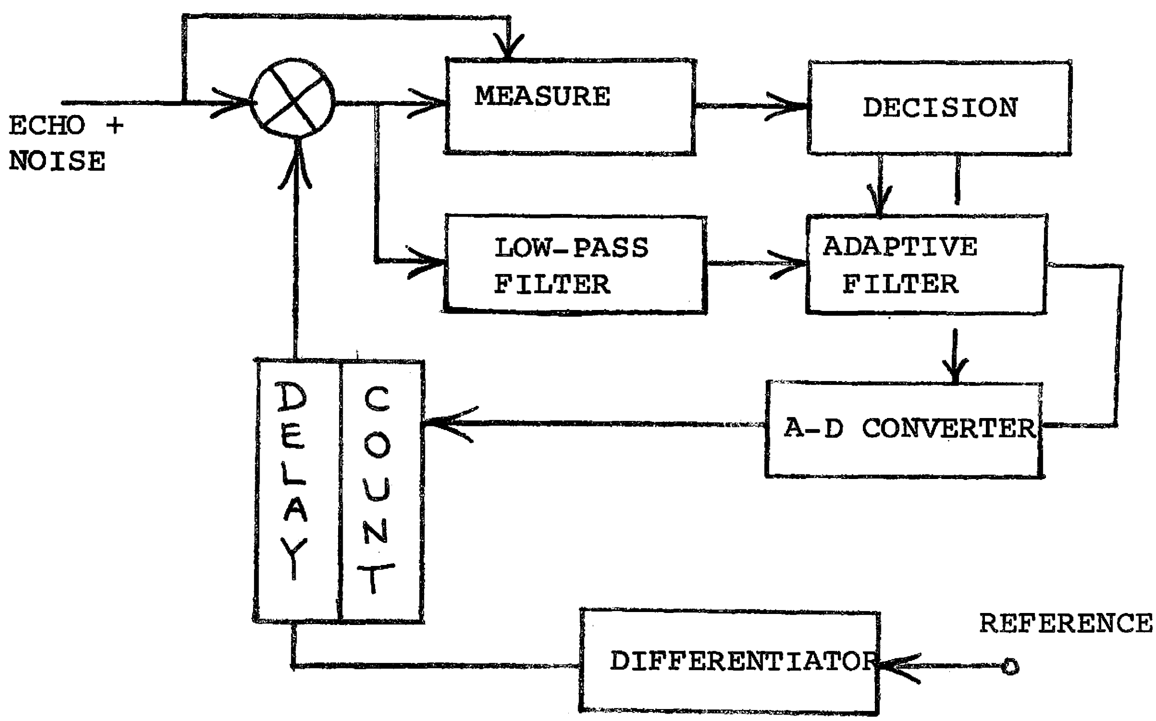


fig 51 An Adaptive Filtering Delay-Lock Loop

CONCLUSIONS

The use of fixed delay lines switched in and out to replace a continuously adjustable delay line has proved successful.[16] Many continuously adjustable delay lines have been built by other authors, but these lines have suffered from a restriction in bandwidth and a nonlinearity between control voltage and resultant delay.[8,14] A quantized delay line can be more easily built and therefore can have wider band--width. Very fast changes of delay are possible. The only disadvantage is the quantization of delay which means that a fixed error exists in the delay setting equal to one-half the smallest delay increment.

This quantized delay line has been included in a correlation detector which tracks the delay of the incoming signal. Experimental evidence for two systems of controlling the delay line was presented; the binary counter of the delay line was actuated by a constant frequency clock, resulting in relay control, and by an A-D converter giving a linear control.

16 S.S.Haykim and C. Thorsteinson," A Quantized Delay-Lock Discriminator," Letter to the Proceedings of the IEEE, (to be published). (see Appendix this thesis for copy)

In the A-D feedback system the setting of the delay line was proportional to the integral of the analog error voltage obtained from the correlator. Good agreement between input delay and output delay estimate for tracking time-varying delay has been demonstrated. The switching transient which contaminates the analog delayed reference at each change of the delay was not found to be objectionable even for very high rates of delay change. The use of transistors for the switches enables the length of the switching transient to be reduced to the order of 100 nanoseconds. The lack of correlation between the transient waveform and the incoming signal allows the filter to reduce the effect of the disturbance still further.

The quantized delay-lock discriminator removes many of the weaknesses of previous continuously variable analog delay-lock loops and allows the analog waveform discriminator to take its rightful place among other correlation detectors notably the phase-lock loop and the binary delay-lock loop. The unique contribution of this discriminator is the tracking of the delay of complex analog waveforms at microsecond delays.

THE APPENDIX

This appendix contains: A Theorem
Circuit Diagrams
A Summary Letter

DEFINE:
$$R(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)\, f(t-\tau)\, dt$$

THEOREM:
$$-\frac{d}{d\tau} R(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)\left[\frac{d}{dt} f(t-\tau)\right] dt$$

LET US RETURN TO THE DEFINITION OF DERIVATIVE;

$$\frac{d}{d\tau} R(\tau) = \lim_{\Delta\tau\to 0} \frac{R(\tau+\Delta\tau) - R(\tau)}{\Delta\tau}$$

$$\frac{d}{d\tau} R(\tau) = \lim_{\Delta\tau\to 0} \frac{1}{\Delta\tau}\left\{ \lim_{T\to\infty} \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)\, f(t-\tau-\Delta\tau)\, dt - \lim_{T\to\infty} \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)\, f(t-\tau)\, dt \right\}$$

$$= \lim_{\Delta\tau\to 0} \frac{1}{\Delta\tau}\left\{ \lim_{T\to\infty} \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)\left[f(t-\tau-\Delta\tau) - f(t-\tau)\right] dt \right\}$$

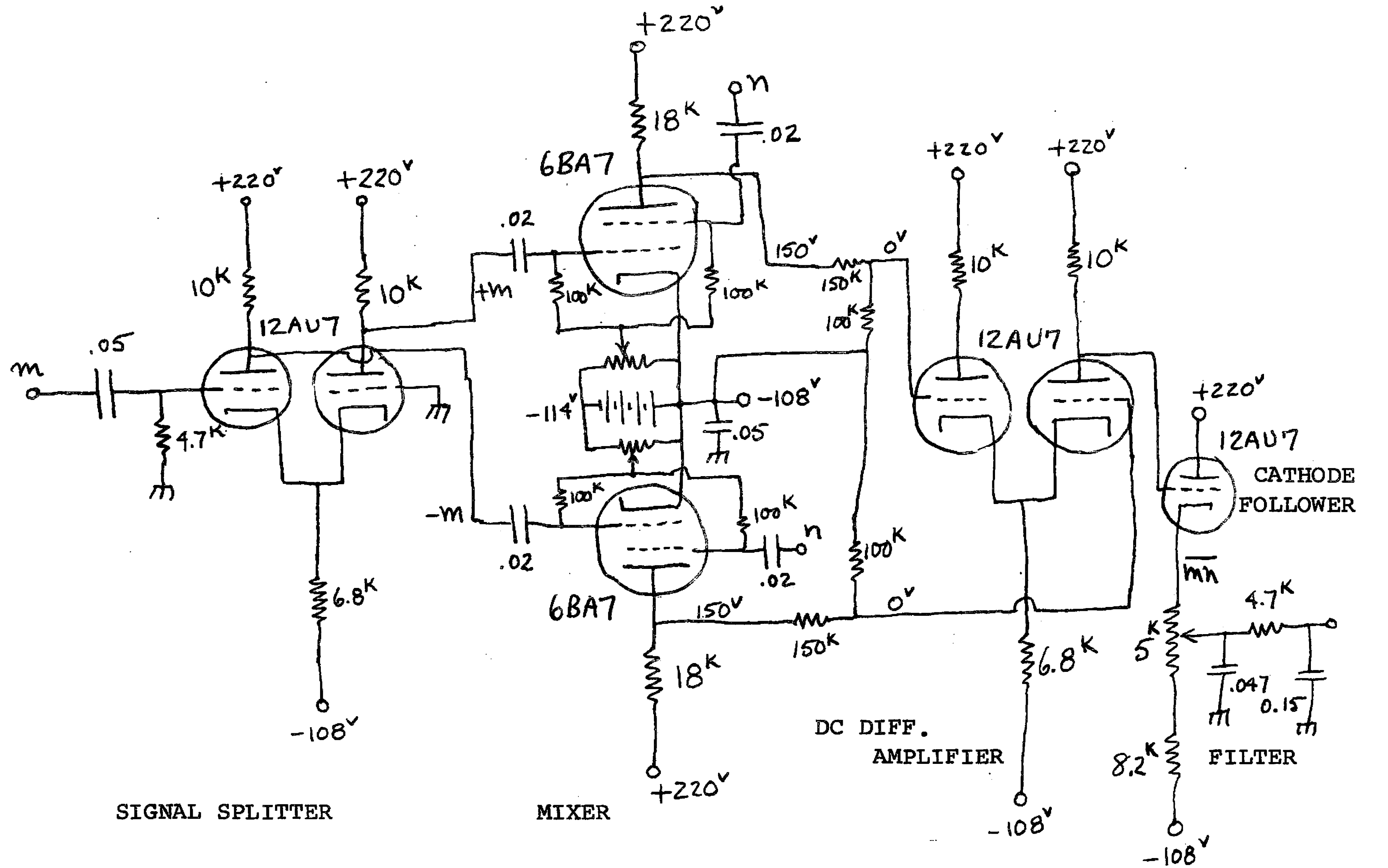
INTERCHANGE THE TWO LIMIT PROCESSES AND CARRY OUT UNDER INTEGRATION SIGN †

$$= \lim_{T\to\infty} \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)\left[\lim_{\substack{\Delta\tau\to 0 \\ \tau \text{ CONSTANT}}} \frac{f(t-\tau-\Delta\tau) - f(t-\tau)}{\Delta\tau}\right] dt$$

$$= \lim_{T\to\infty} \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)\left[-\frac{d}{dt} f(t-\tau)\right] dt$$

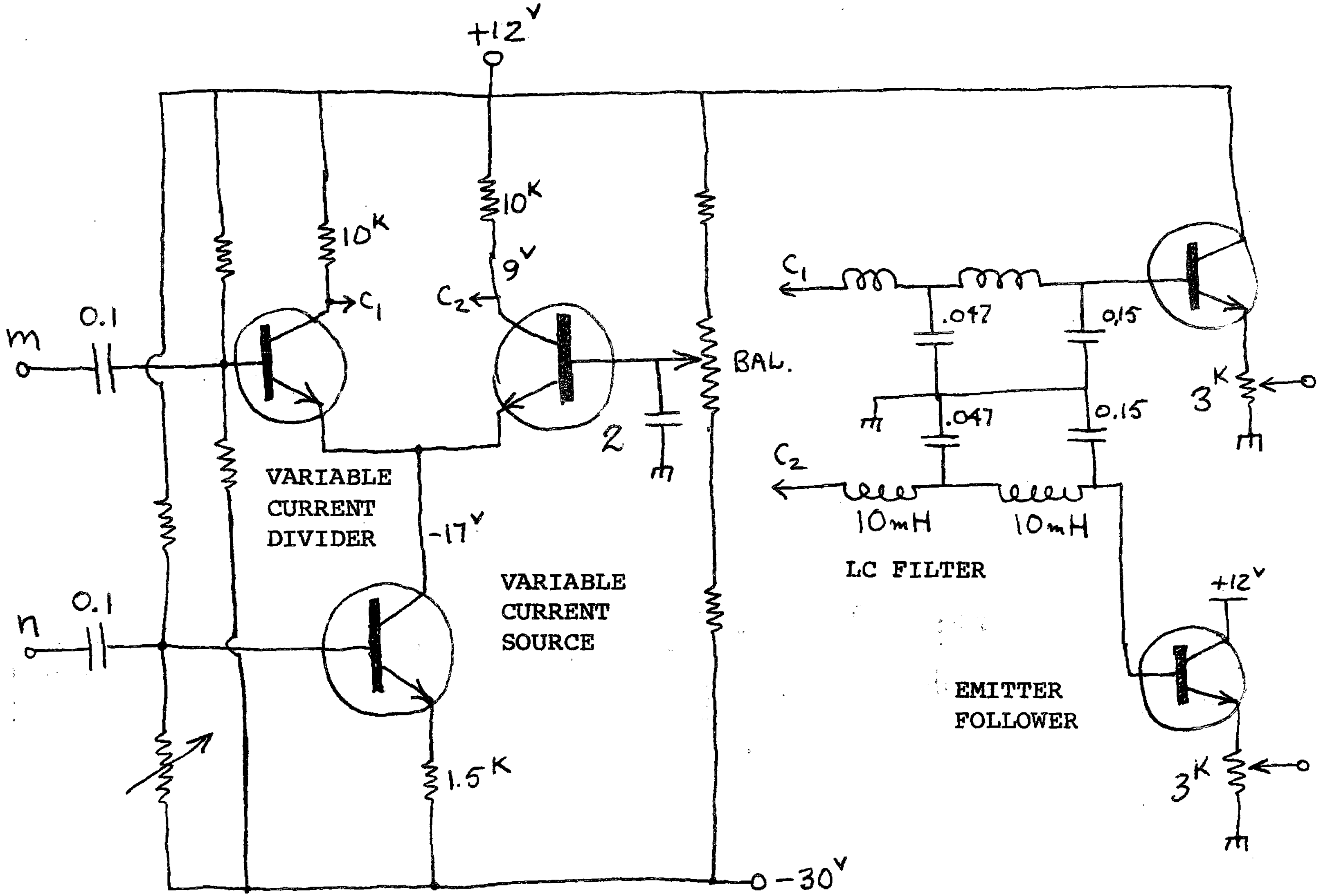
AS REQUIRED!

† see conditions, A. Papoulis, "Probability, random Variables and Stochastic Processes," McGraw-Hill, 1965.



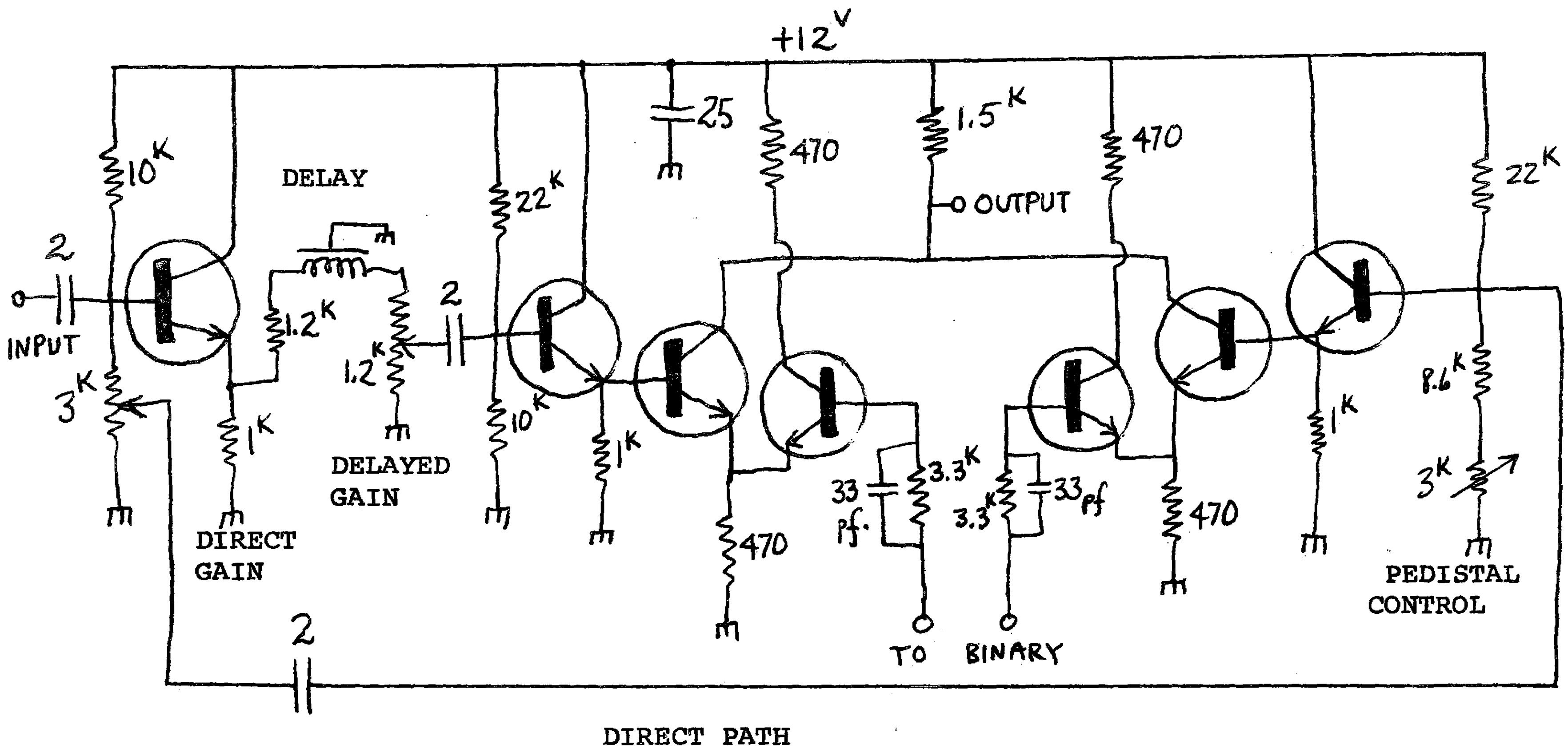
THE VACUUM TUBE ELECTRONIC MULTIPLIER AND RC FILTER

NOTE: henceforth all resistors in ohms and all capacitors in microfarads unless otherwise indicated

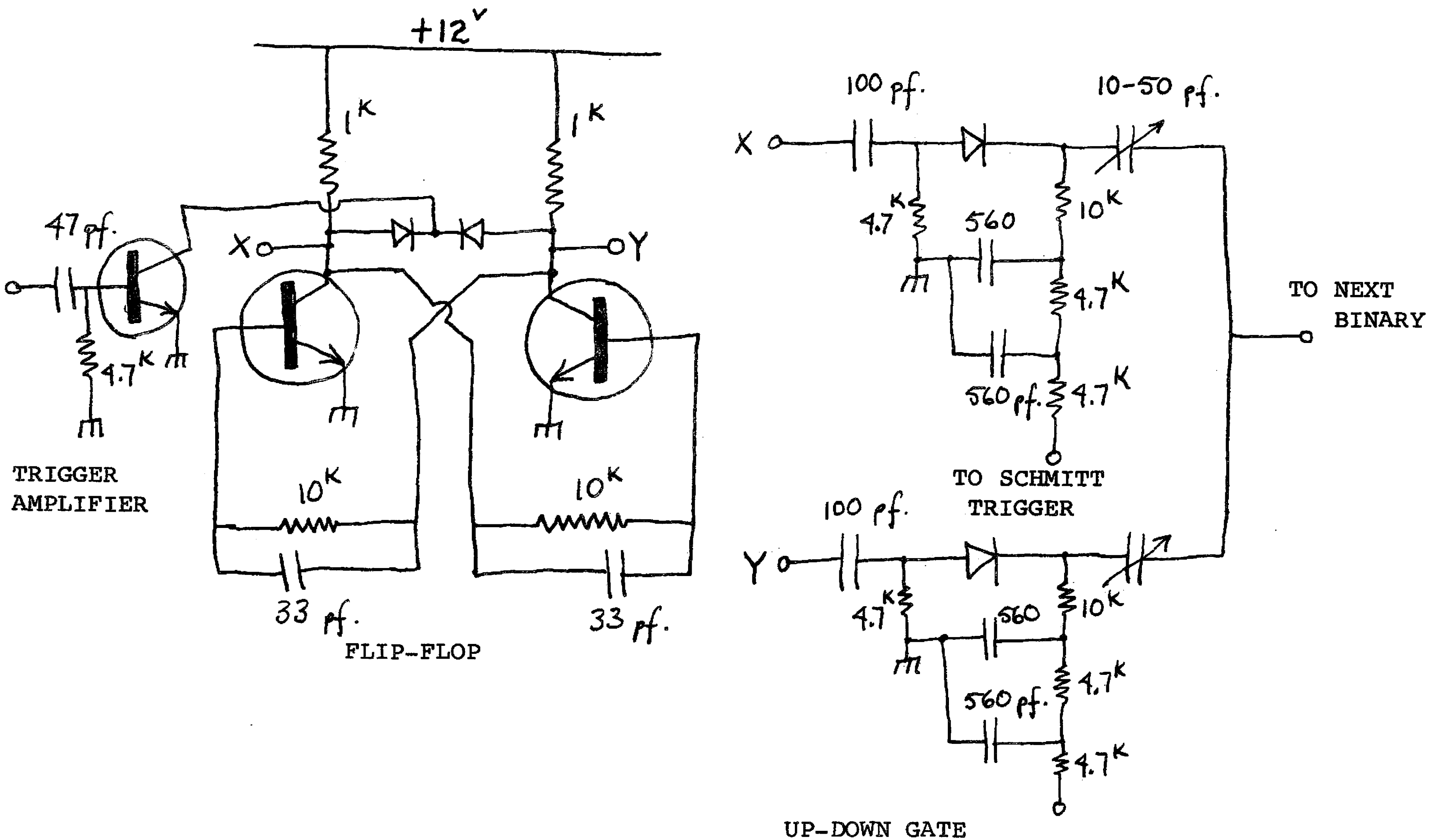


TRANSISTOR MULTIPLIER AND FILTER

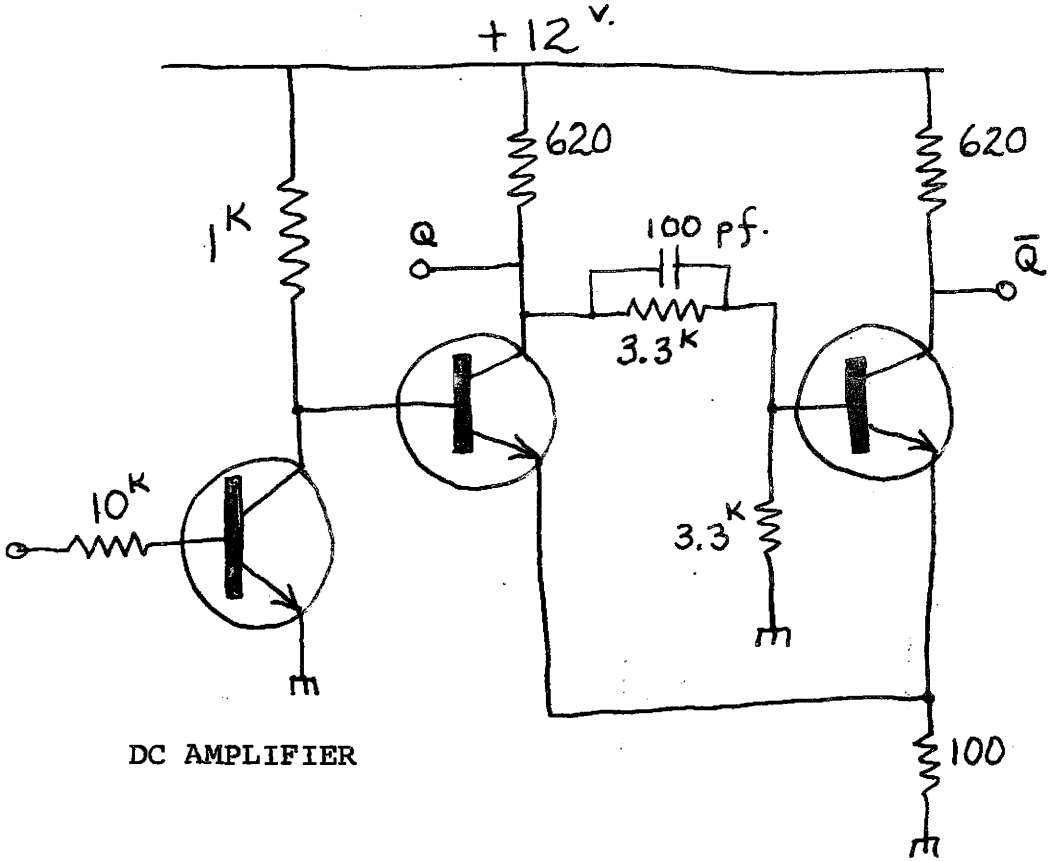
NOTE: all NPN transistors are G.E. silicon types 2N2924, 2N3414, 2N3391, and similar



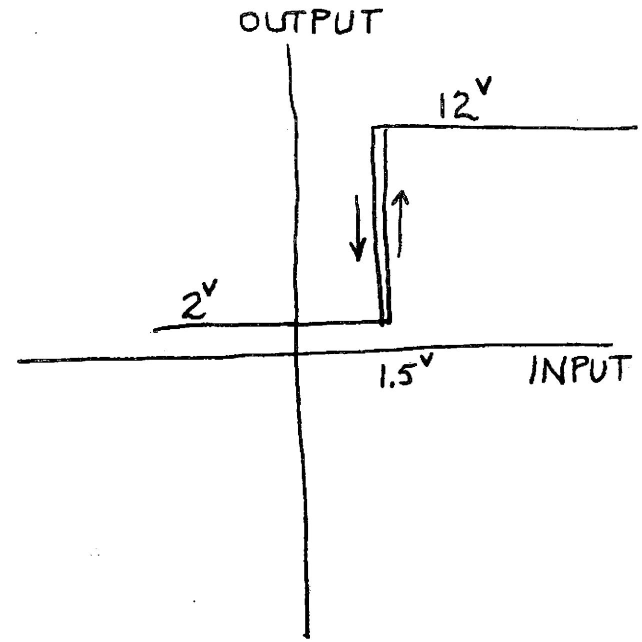
<u>ONE SECTION OF SWITCHED ANALOG-WAVEFORM DELAY</u>



BINARY FLIP-FLOP STAGE AND UP-DOWN GATES

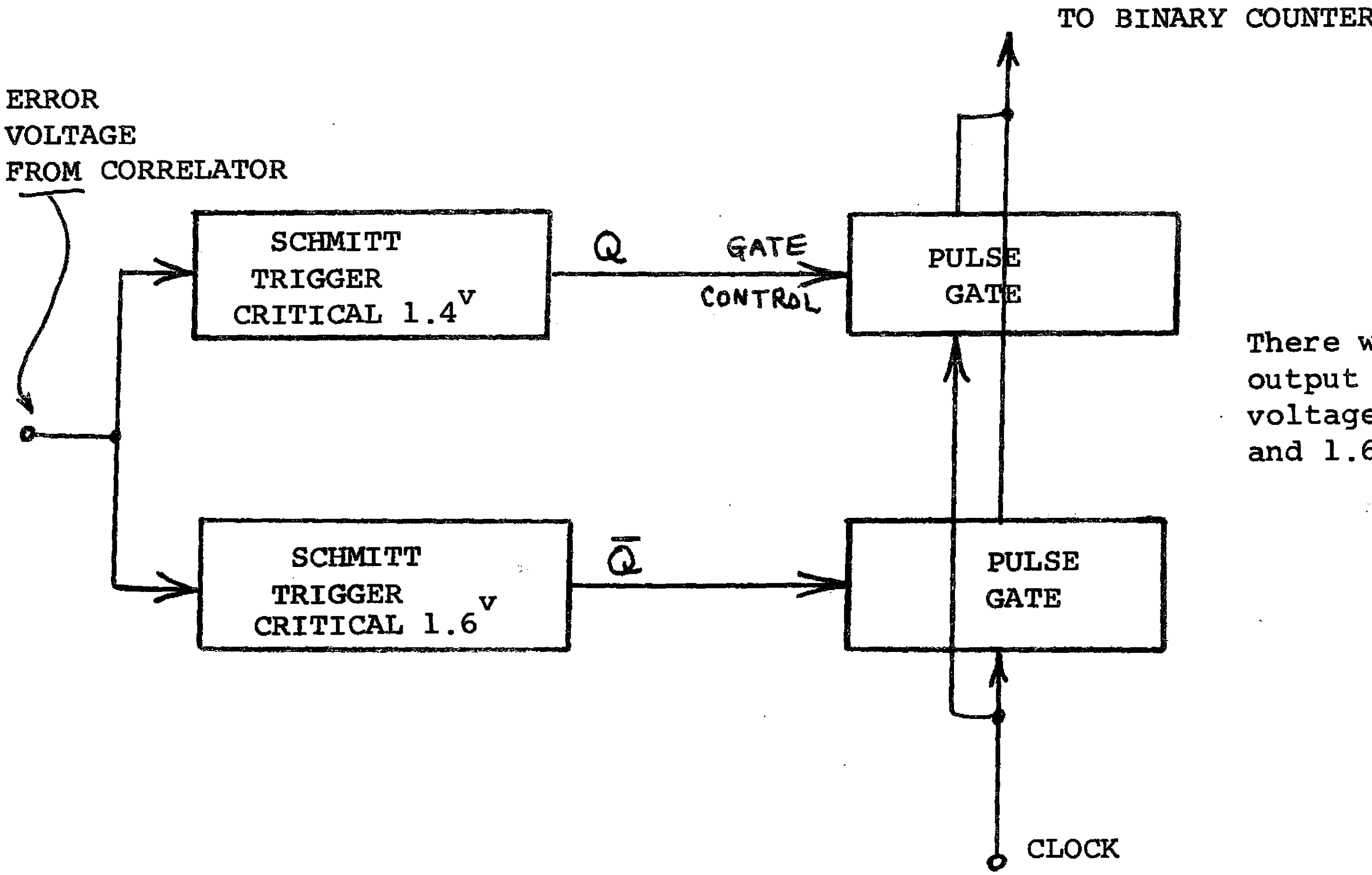


DC AMPLIFIER



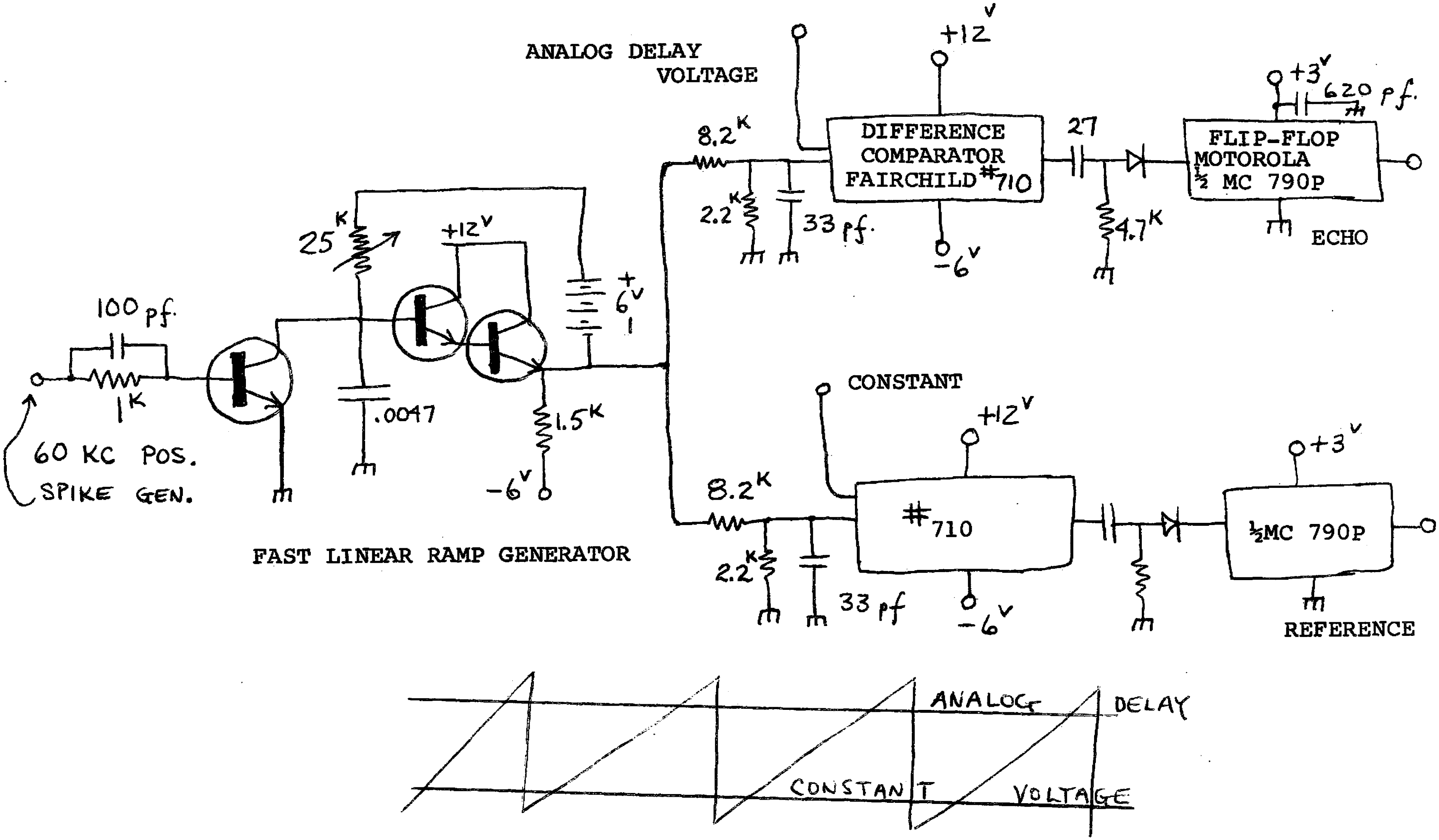
CHARACTERISTIC SHOWING
HYSTERYSIS

THE UP-DOWN SCHMITT TRIGGER CIRCUIT

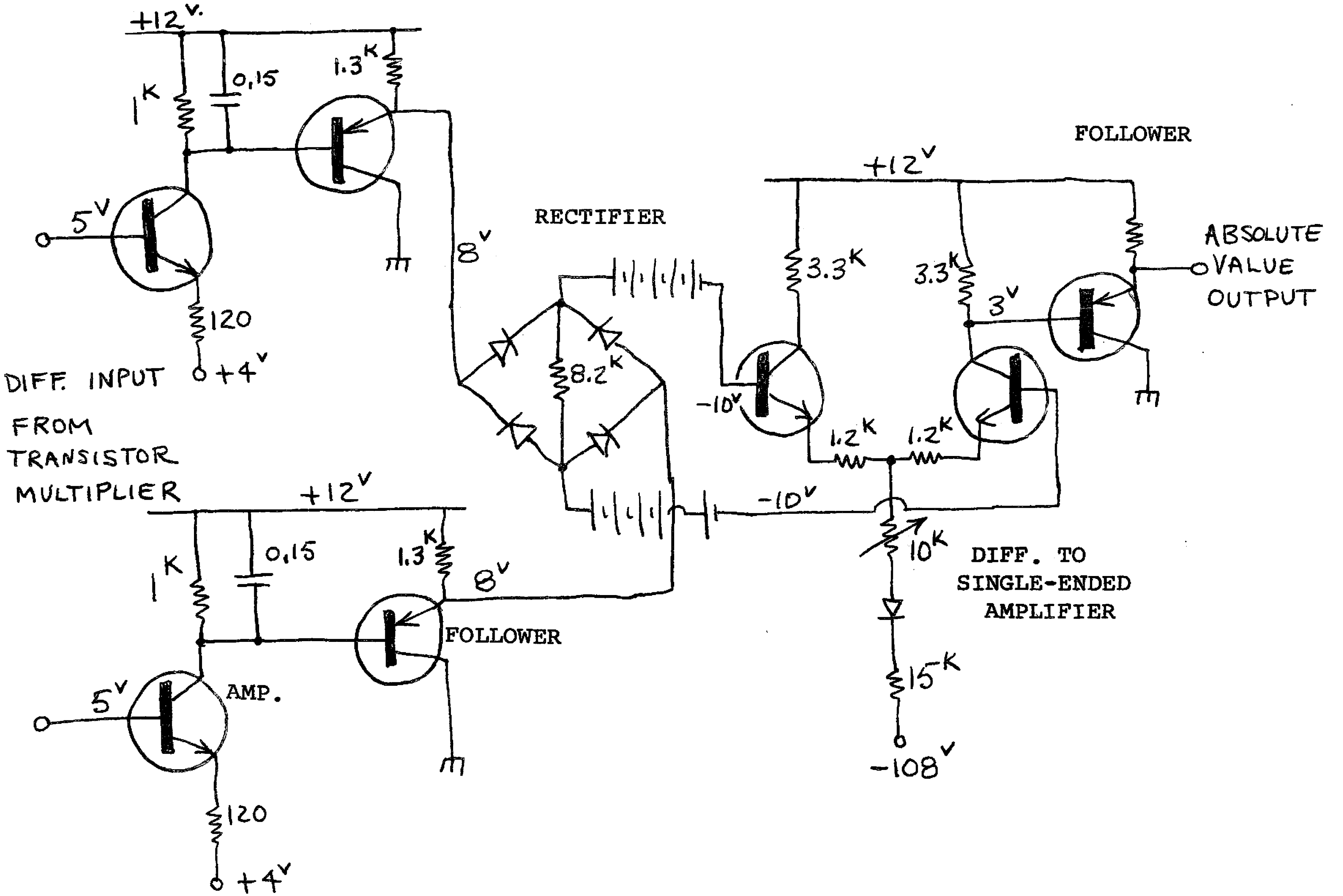


There will be no pulse output when the error voltage is between 1.4 and 1.6 volts.

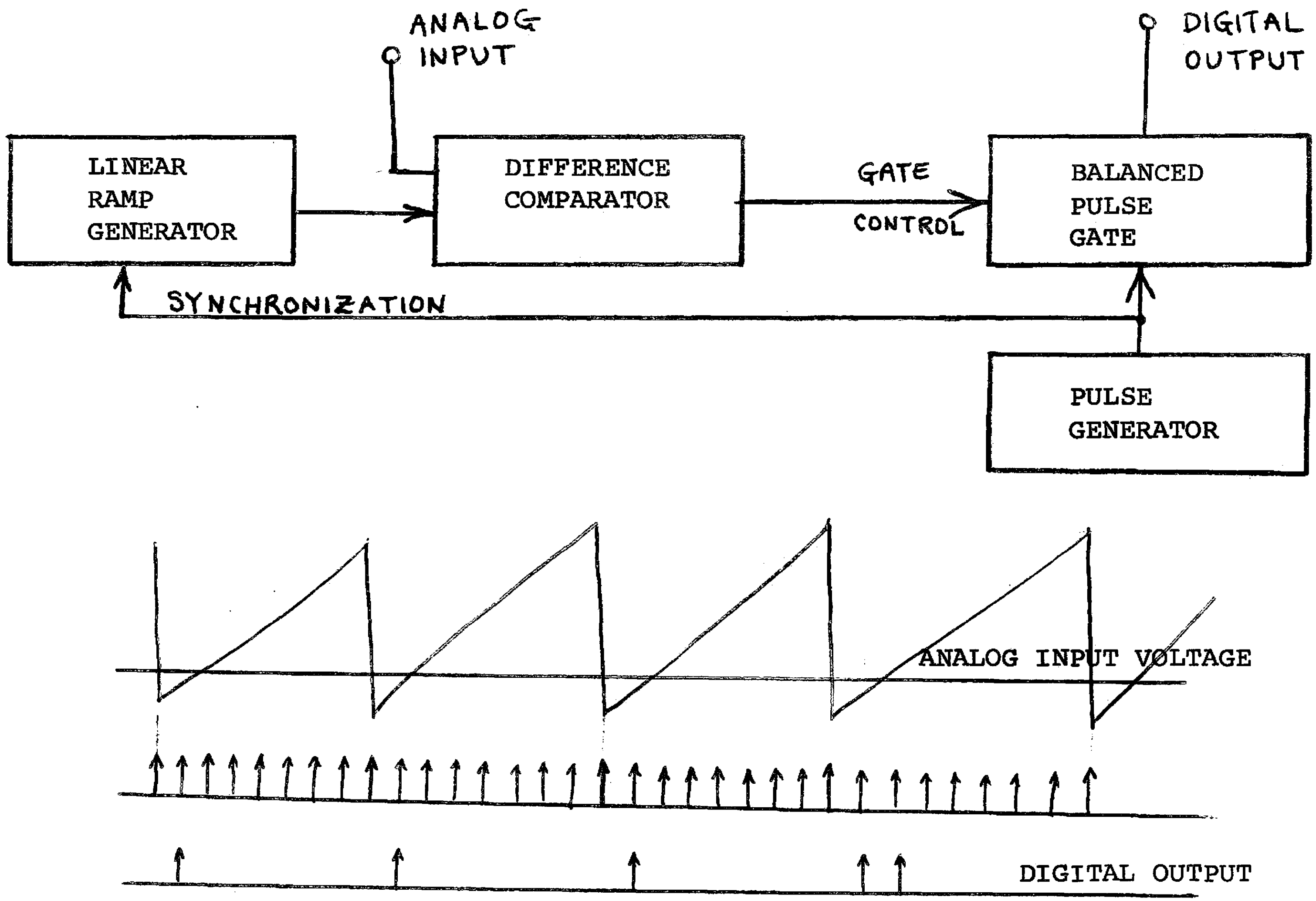
THE DEADBAND STOP DEVICE



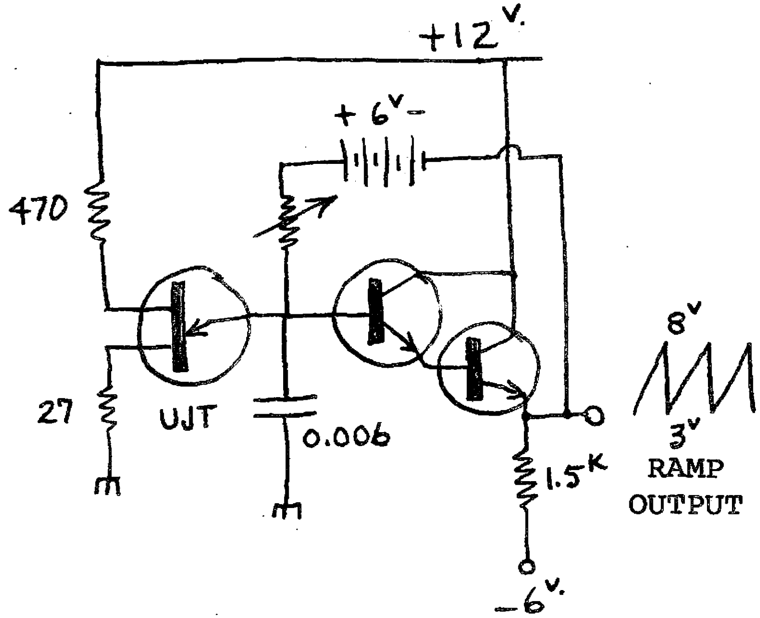
THE ELECTRONICALLY VARIABLE DELAY GENERATOR USING INTEGRATED CIRCUITS



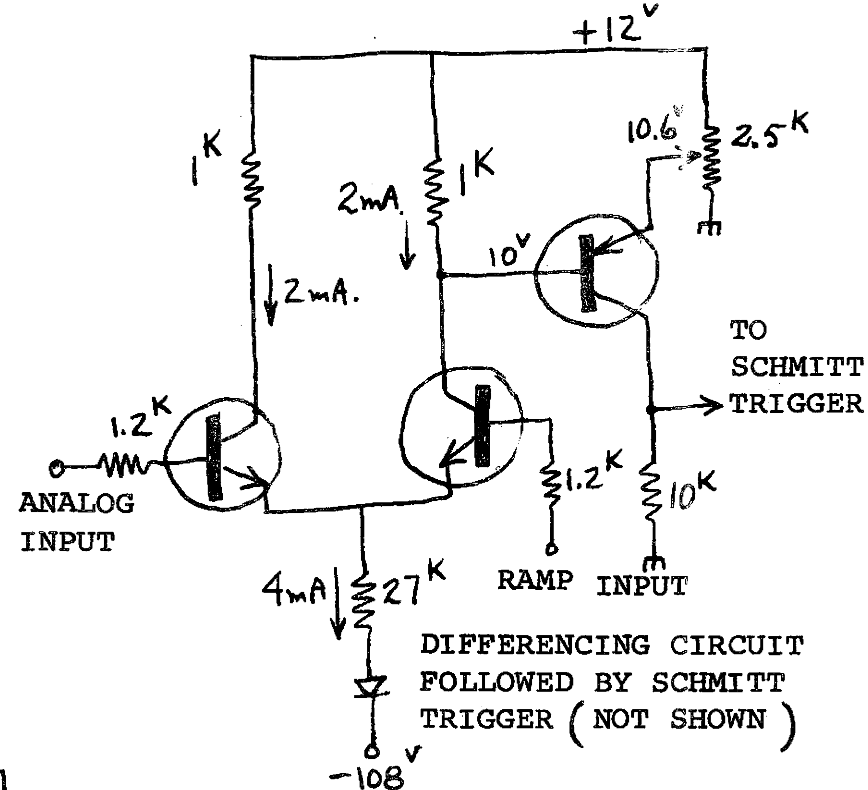
AMPLIFIER AND FULL-WAVE RECTIFIER



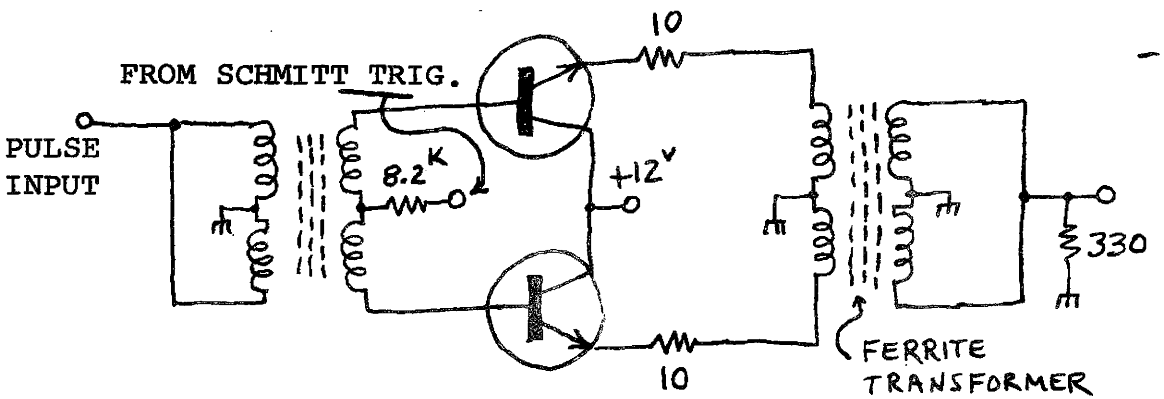
THE ANALOG-TO-DIGITAL CONVERTER



LINEAR RAMP GENERATOR (200 Hz.)



DIFFERENCING CIRCUIT
FOLLOWED BY SCHMITT
TRIGGER (NOT SHOWN)



BALANCED PULSE GATE

CIRCUIT DETAILS OF ANALOG-TO-DIGITAL CONVERTER

REFERENCES

1 D.O.North,"Analysis of the Factors which Determine Signal / Noise Discrimination in Radar," Report PTR-6C,RCA Laboratory, June 1943.

2 J.Van Vleck and D.Middleton,"A Theoretical Comparison of Visual, Aural, and Meter Reception of Pulsed Signals in the Presence of Noise," Journal Applied Physics Vol.17, pp.940-970, November 1946

3 Transactions PGIT-IRE, MATCHED FILTER ISSUE, Vol.IT-6, No.3 June 1960

4 Y.W.Lee, T.P.Cheatham and J.B.Wiesner,"Application of Correlation Analysis to the Detection of Periodic Signals in Noise," PROC. IRE, Vol.38,pp.1165-1172, October 1950.

5 A.J.Talamini and E.C.Farnett,"New Target for Radar: Sharper Vision with Optics," ELECTRONICS, December 27, 1965.

6 R.Jaffe and E.Rechtin,"Design and Performance of Phase-Lock Circuits Capable of Near-Optimum Performance," IRE TRANS. INFORMATION THEORY Vol.IT-1,pp.66-76, March 1955.

7 S.C.Gupta and R.J.Solem,"Optimum Filters for Second- and Third-Order Phase-Locked Loops," IEEE TRANS. SPACE ELECTRONICS and TELEMETRY, pp.54-62, June 1965.

8 J.J.Spilker and D.T.Magill,"The Delay-Lock Discriminator An Optimum Tracking Device," PROC. IRE., pp. 1403-1416, September 1961

9 M.R.O'Sullivan,"Tracking Systems Employing the Delay-Lock Discriminator," IRE TRANS. SPACE ELECTRONICS and TELEMETRY Vol.SET-8, pp.1-7, March 1962.

10 J.J.Spilker," Delay-Lock Tracking of Binary Signals," IRE TRANS. SPACE ELECTRONICS and TELEMETRY, Vol.SET-9, pp. 1-8 March 1963.

11 R.B.Ward," Application of Delay-Lock Tracking Techniques to Deep Space Tasks," IEEE TRANS, SPACE ELECTRONICS and TELEMETRY, Vol.SET-10, pp. 49-65, June 1964.

12 P.A.Wintz," A Strategy for Obtaining Explicit Estimators of Signal Delay," IEEE TRANS. SPACE ELECTRONICS and TELEM. pp.23-28, March 1965.

13 W.J.GILL," A Comparison of Binary Delay-Lock Tracking Loop Implementations," IEEE. TRANS. AEROSPACE and ELECTRONIC SYSTEMS, Vol.AES-2, No.4, July 1966.

14 W.J.Hannan, J.F.Schanne, and D.J.Woywood," Automatic Correction of Timing Errors in Magnetic Tape Recorders," IEEE TRANS. MIL. ELECTRONICS, pp.246-254, July-Oct, 1965.

15 J.B.Payne," Wide Bandwidth Electronically Controlled Digital Delay Line," Correspondence IEEE TRANS. AEROSPACE and ELECTRONIC SYSTEMS, Vol.AES-2, No.5, September 1966.

16 S.S.Haykim and C.Thorsteinson," A Quantized Delay-Lock Discriminator," Letter to the Proceedings of the IEEE, (to be published). (see Appendix for copy)

A QUANTIZED DELAY-LOCK DISCRIMINATOR †

by

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Department of Electrical Engineering
McMaster University
Hamilton, Canada

ABSTRACT

A new quantized delay-lock discriminator is described using fixed delay lines that are switched in and out, depending upon the output of a correlator. Two versions of the system, with analog to digital feedback and relay feedback, are discussed. Some experimental results are also included.

The Delay-Lock Discriminator is an optimum tracking radar detector. The transmitted signal is taken in noise free form and delayed an amount similar to the expected echo. A correlator provides an error feedback voltage which synchronizes the delay of the discriminator with that of the echo. Like the Phase-Lock Loop, the echo can be tracked at low signal-to-noise ratios. Spilker and Magill described an analog form of the system employing a controlled permeability LC delay cable for the electrically variable delay line, abbreviated EVDL[1].

Most EVDL's have poor linearity of delay vs. control. Other authors have tried varactor diodes in the LC line but also obtain non-linearity[2]. Limitations in LC delay have prompted the binary delay-lock detector using shift registers to store the binary transmission[3]. Many of the objections to the analog Delay-Lock are eliminated by the use of fixed delays switched in and out. A delay line having four different delays in the nanosecond region and 450 MHz band width has been described[4]. This letter concerns the use of quantized delay for the analog Delay-Lock Loop and shows results of a system built. By switching a set of "n" delay lines of binarily weighted lengths in different series combinations 2^n evenly spaced delays are obtained. A binary up-down serial counter conveniently controls the switching sequence.

In practice the switching is accomplished by transistors and therefore very fast delay changes are possible. Each delay line is matched and isolated by transistor buffer amplifiers. In operation, the counter is fed by pulses and the

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† TO BE PUBLISHED IN THE "LETTERS" OF THE "PROCEEDINGS" OF THE INSTITUTE OF ELECTRICAL AND ELECTRONIC ENGINEERS.

delay is incremented by the smallest unit of delay at each pulse. The counter can be reversed and delay decremented if the state of the gates between flip-flops is changed. A comparator or Schmitt trigger controls the up-down state line. The apparatus tested used five delay lines of 1/4, 1/2, 1, 2, and 4 μS. delay; 32 delays from 0 to 7 3/4 μS. by 1/4 μS. steps are thus available. The finished quantized EVDL had 2 MHz band width and the principal limitation was the frequency response of the transistors used.

Two methods of actuating the counter, in order to synchronize the delay of the reference and the echo, have been tried. In fig. 3 the serial A-D converter feedback is shown, producing a pulse rate proportional to the absolute value of the delay error. By cutting the loop on the dotted line and tripping the counter at a constant rate by a clock, relay feedback is produced, the sole feedback being the bang-bang action of the counter reversal comparator. In order to test the stability and linearity a testing apparatus was constructed. The transmitter waveform was a 30 KHz square wave in order to be able to electrically vary the delay of the simulated echo by the use of a linear ramp generator and a differential comparator. The delay of the simulated echo was modulated by a pseudo-sine squared wave with a 1/2 second period. The amplitude of the delay variation exercized 23 of the delay steps, or about 6 μS. Results taken from the input delay waveform and a D-A converter connected to the counter are simultaneously shown in fig. 4(a) and (b), for the A-D and relay feedback respectively.

The system employing an A-D converter is a quantized but linear feedback control system, whereas the system with relay feedback must operate by a backward and forward motion centered at the correct delay. The switching transient which leaves the delay line at each count and contaminates the analog reference was found to be less troublesome than expected. Indeed, the counter could be operated at 1000 counts per second with good correlation.

The results shown are for a noise free echo, but substantially the same results could be obtained at low signal-to-noise ratios. Disregarding the quantization error, good linearity of input delay vs. output delay estimate has been demonstrated. Future research will involve a more sophisticated analog transmission waveform such as wide band random noise. Optimization of the transfer function of the low pass filter and the sampling rate for the A-D converter remains to be solved. The advantages of the analog quantized Delay-Lock are fast delay changes, easy EVDL construction and therefore wider bandwidth than continuous EVDL's. While the binary Delay-Lock will remain superior for long delays the analog system can process complex waveforms at μS. delays with good results.

REFERENCES

1. J. J. Spilker, Jr. and D. T. Magill, "The Delay-Lock Discriminator -- an Optimum Tracking Device", Proc. IRE, vol. 49, pp. 1403 - 1416; September, 1961.

2. W. J. Hannan, J. F. Schanne and D. J. Woywood, "Automatic Correction of Timing Errors in Magnetic Tape Recorders", IEEE Trans. Military Electronics, vol. MIL-9, pp. 246 - 254; July - October, 1965.

3. J. J. Spilker, Jr., "Delay-Lock Tracking of Binary Signals", IRE Trans. Space Electronics and Telemetry, vol. SET-9, pp. 1 - 8; March, 1963.

4. John B. Payne III, "Wide Band Width, Electronically Controlled Digital Delay Line", Correspondence IEEE, Trans. Aerospace and Electronic Systems, vol. AES-2, pp. 612-614; September, 1966.

SUGGESTED FIGURE CAPTIONS

1. The Analog Delay-lock Discriminator
2. A Quantized EVDL With Binary Counter
3. A Quantized Delay-lock Discriminator
4. Tracking Linearity Tests
   - (a) A-D Feedback
   - (b) Bang-Bang Feedback

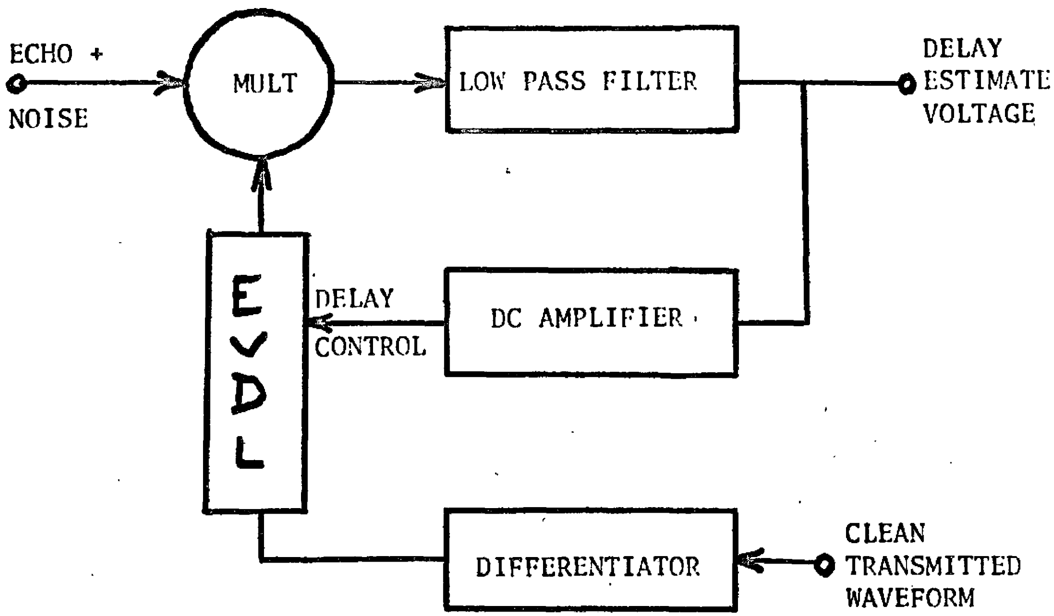


fig. 1

CMT
Jan 19'68

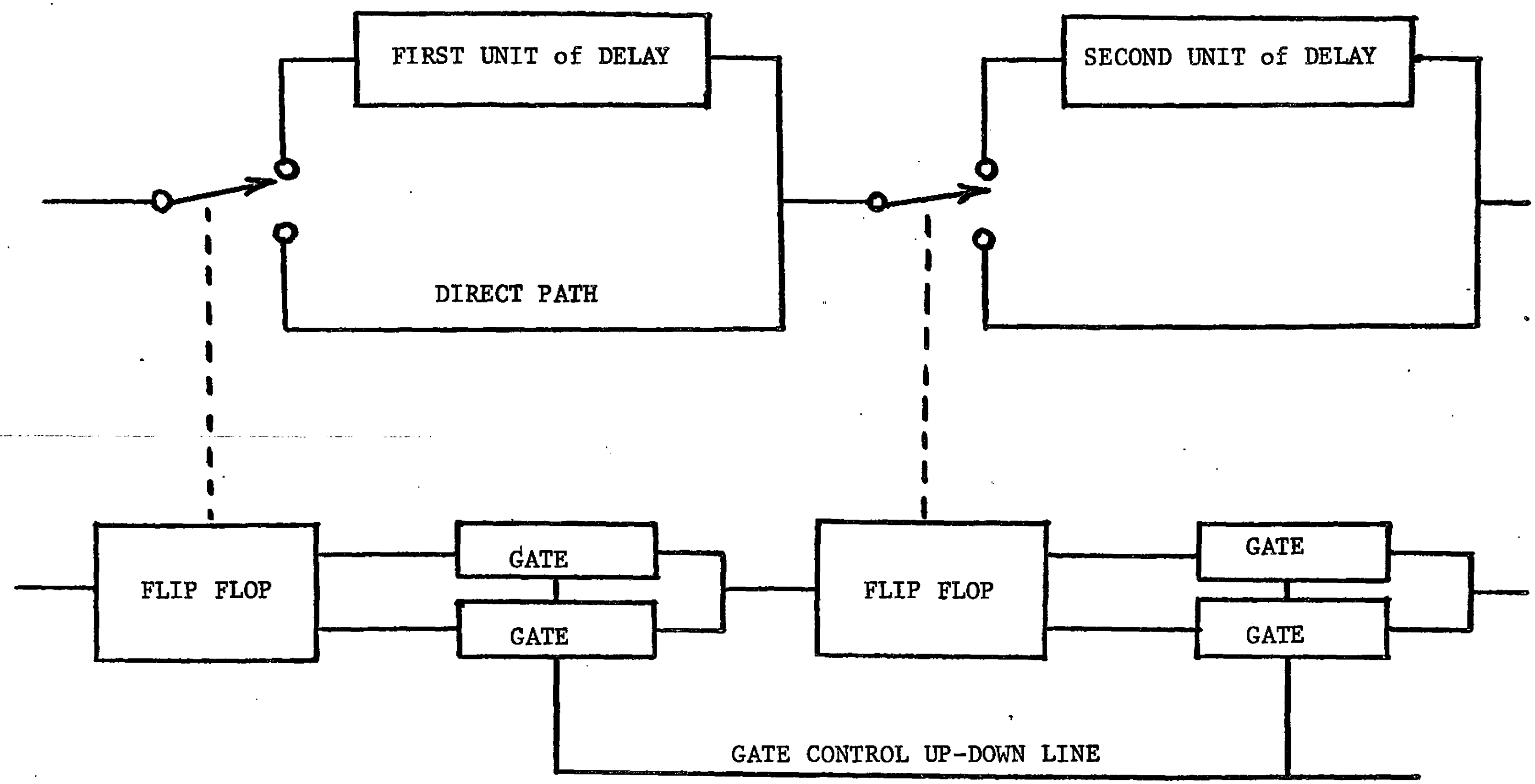
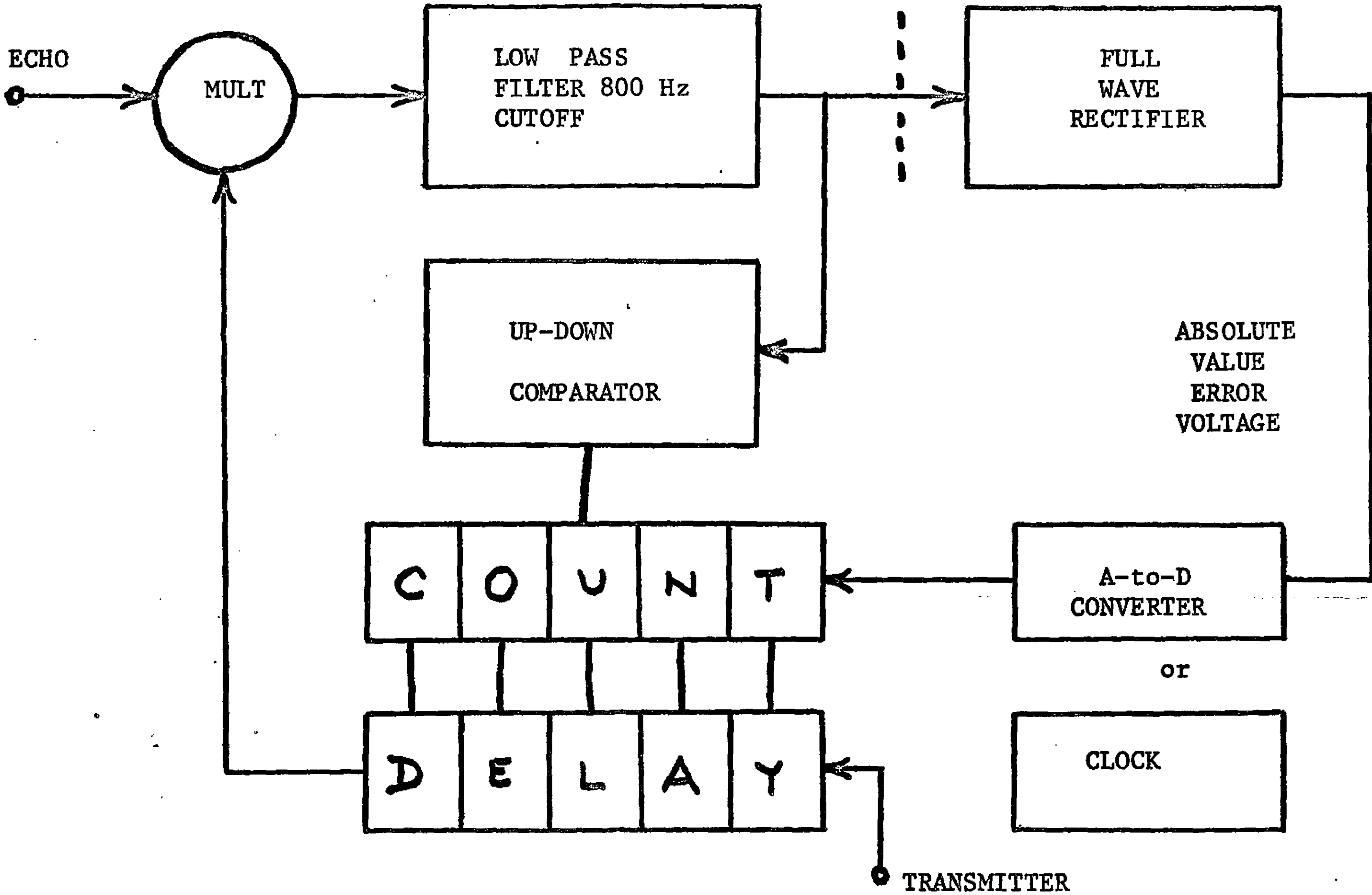

FIRST UNIT of DELAY
SECOND UNIT of DELAY
DIRECT PATH
FLIP FLOP
GATE
GATE
FLIP FLOP
GATE
GATE
GATE CONTROL UP-DOWN LINE

fig.2


ECHO
MULT
LOW PASS
FILTER 800 Hz
CUTOFF
FULL
WAVE
RECTIFIER
UP-DOWN
COMPARATOR
ABSOLUTE
VALUE
ERROR
VOLTAGE
COUNT
DELAY
A-to-D
CONVERTER
or
CLOCK
TRANSMITTER

CMT, Jan 15 '68

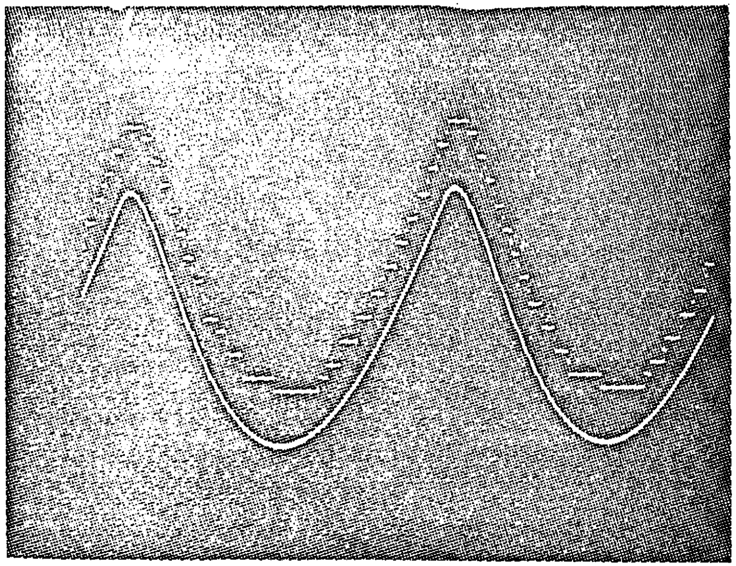


fig. 4 (a)

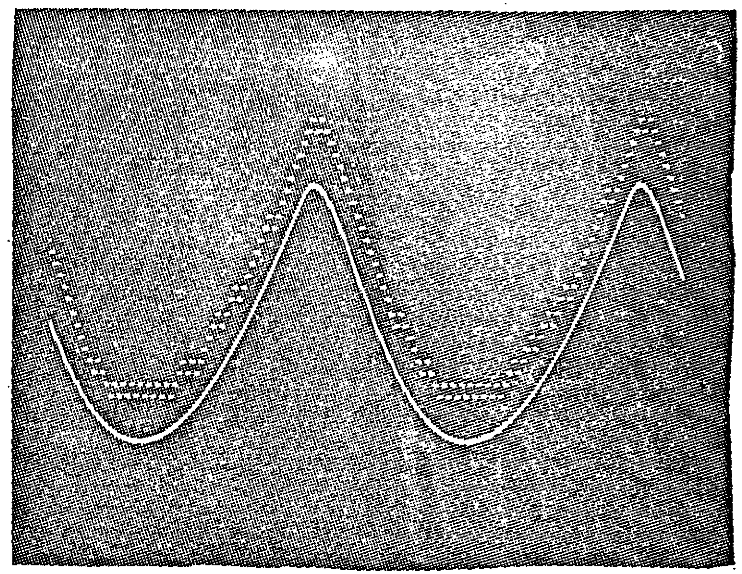


fig. 4 (b)