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R. S. Larsen
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A PHOTOMULTIPLIER PHASE-SENSITIVE DETECTOR FOR THE OPTICAL ALIGNMENT SYSTEM

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FOR THE OPTICAL ALIGNMENT SYSTEM

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1. INTRODUCTION

The technique of phase-sensitive detection has found application in many areas of electronics. Generally speaking, phase coherent receivers achieve the ultimate in sensitivity by virtue of the fact that the bandwidth of the system can be made almost arbitrarily small. This is of course due to the fact that a locally-generated reference signal having phase coherence has a true average frequency deviation from the received signal of zero cps; hence, provided that the modulation frequency permits, the final detection bandwidth can be made as small as a fraction of a cycle per second.

This report describes the application of a phase-coherent system to the problem of detecting very low-intensity light signals in the SLAC experimental optical alignment system. The system is briefly as follows: The light signals to be detected form a pattern of known geometry at the end of a 2-foot diameter alignment tube. The accelerator circular waveguide is rigidly fixed to this tube, and the entire assembly supported at 40-foot intervals by a system of jacks (see Figure 1). At these same points, removable targets are located which can be remotely placed into the tube one at a time. A narrow laser beam, directed into the tube through an optical system, passes through the target as a 2-foot diameter parallel beam to produce

The required pattern at the receiving end. The pattern is of such geometry that any lateral or rotational mis-alignment of the target point from a straight line between the light source and the receiver can be readily determined by scanning the receiving end of the tube with a narrow-aperture detector. A simple pattern which has been used in the first experiments is the cross shown in Figure 1. Here the coordinates of four points, obtained by scanning in vertical and horizontal directions, suffice to determine the total lateral and rotational displacements.

As each alighment error is determined, then, it can be systematically corrected by appropriate actuation of the support jacks. A total of 240 such measurements are necessary in the alignment of the 10,000 foot accelerator.

A prototype photomultiplier detection system was designed and installed at Brisbane early in 1963. Since that time, the need for an improved system - that is, higher luminous sensitivity and better drift characteristics - became apparent, and a re-design was undertaken. The general improvements and simplifications which have been made will now be described.

The complete unit has recently been tested at Brisbane, and appears to be a significant improvement over the prototype system.

2. GENERAL DESCRIPTION OF DETECTION SYSTEM

The light signals to be detected have a roughly Gaussian shape of intensity versus position (x or y coordinate) as shown in Figure 2. It is desired to locate accurately the position of the maxima with respect to the center of the alignment tube. The principle is as follows: A photomultiplier is aimed into the alignment tube. A lens focuses the parallel light on the photocathode. A small aperture is placed between the lens and the light source. Now, if the aperture is moved horizontally a short distance, it is as if the phototube were moved to view a different portion of the incoming signal, and hence it sees a different intensity. If the aperture is oscillated sinusoidally, as illustrated in Figure 2, then the following situation results: When the position of the tube and aperture is to the left of the intensity maximum, a signal is detected, the phase of which is (say) zero degrees with respect to the aperture driver excitation. When the position of tube and aperture is to the right, so as to be on the other side of the maximum, s gignal of opposite phase is produced. Clearly, then, detection of the fundamental frequency of modulation in the phase-sensitive receiver results in an output signal which undergoes a sharp reversal at the exact peak of intensity. This particular form of signal is most suitable for the intended application; because to read the coordinate of the peak, one simply scales from a graph the distance from the vertical axis to the horizontal zero-crossover point.

The requirements for high sensitivity and freedom from systematic error demand (a) that the aperture modulation drive system be free from distortion; (b) that the phototube have as high a sensitivity as possible; and (c), that the phase detection system exhibit a high degree of rejection of all frequency components other than the fundamental.

The general design criterion has been that the system dynamic range should be in the order of 60 db with the lower end limited equally by narrow band photomultiplier and preamplifier noise. Total distortion components should be held to less than 0.5% through the amplifier system*. Since the latter are in general a function of signal amplitude, the maximum distortion signal amplitudes will be small compared with the fundamental and hence should not limit the accuracy. Rather, accuracy should be limited ultimately by phototube noise or mechanical tolerances, which is the ideal situation from the point of view of the electronics.

3. SYSTEM BLOCK DESCRIPTION

A block diagram of the electronic system is shown in Figure 3. The circuit operation is as follows:

A sinusoidal voltage from a 15 cps oscillator is amplified and applied to the aperture transducer. This transducer consists of the coil and cone of a large high fidelity loudspeaker, to which is attached a metal plate with a circular hole. This hole provides the path for the light reaching the photomultiplier cathode.

The light signal is detected as a voltage at the anode of the phototube. This signal is preamplified before being transported through a 15-foot long cable to the post amplifier.

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* Memo K. Trigger to R. Sandkuhle, October 18, 1963. states that accumulated distortion due to electronic equipment should be less than 0.5% to assure an error of $<$ .002 inch for the broadest line (light signal).

The post amplifier has a passband of approximately 1.5 cps centered about 15 cps. Also in cascade with this unit is a line-frequency rejection filter. The output of the tuned amplifier is fed to the primary of a balanced-secondary matching transformer.

In parallel with the signal path, a portion of the 15 cps oscillator output is passed through a variable phase shifter which then drives a Schmitt trigger. The output of the Schmitt is passed through a phase splitter which provides a train of positive and a train of negative pulses, displaced in phase by 180 degrees.

The two pulse trains trigger two separate 0.5 msec one-shots to provide the drive pulses for two transistor gates. These gates close alternately coincident with the occurrence of the input signal amplitude peaks; thus together with the balanced transformer signal path they comprise a phase detector. The final elements in the system are a high impedance buffer, a single-range meter, and a pen recorder.

A detailed explanation of the various circuits will now be undertaken. Emphasis will be placed on those circuits or features which are somewhat novel or particularly suited to the system.

4. CIRCUIT DESIGN

4.1 Oscillator, Audio Amplifier, Recorder and Transducer

The 15 cps oscillator, audio amplifier and pen recorder are commercial equipment and hence will be given only a cursory description.

The oscillator is a Hewlett-Packard 200CD which was factory calibrated to obtain a total distortion at 15 cps of 0.25%.

The audio amplifier is a 75 watt MacIntosh Model MC75, which drives the 16 ohm speaker coil. The speaker coil assembly was specially ordered to have a natural resonance at slightly greater than 15 cps.

A measurement was made using a linear position transducer to determine the harmonic distortion of the mechanical system. It was found that although some variation of the center of oscillation occurred, the deviation of the speaker's cone position from a nominal 0.25% 15 cps sine wave input could not be discerned.

The pen recorder is a standard Moseley Model 136, dual channel (xyy') unit. Its maximum sensitivity is 5 mv per inch vertical deflection, and its minimum input resistance is 100 K.

The horizontal position transducer is a linear differential transformer, Sanborn Model 7DCDT-250, which has a 1/2 inch stroke. It has a self contained oscillator and detector and hence can be run from a 6 volt storage battery or power supply.

4.2 Phase Shifter and Schmitt Trigger

The two-section phase shifter is shown in Figure 4. One section of the shifter consists of a phase splitter feeding a series R and C. The time constant of average R and C is chosen to correspond to the period of the 15 cps signal. The output is a constant amplitude signal which varies in phase from 0 to 180 degrees as R goes from 0 to 00 (R total, in this case). Two such stages provide about 240 degrees phase shift in the present design.

The Schmitt trigger and its phase splitter are conventional (Figure 5). Because of the hysteresis effect in the Schmitt, it is necessary to provide an input bias adjustment so that the output square wave can be made exactly symmetrical. The output signal is differentiated and split to provide the two opposite polarity pulse trains.

4.3 One-Shot Driver and Transmission Gate

One channel of the 0.5 msec one-shot driver and the transmission gate is shown in Figure 6. The one-shot is a conventional non-saturating design.

The one-shot output pulse couples through the step-down transformer to the transmission gate. The dual transistor gate is equivalent in operation to the circuit shown in Figure 7. The transistors are forward biased through their base-collector junctions, which causes saturation and breakdown of the emitter junctions also. Thus, between emitter leads, the unit acts as a current switch, the signal current being limited to less than half the total drive current. In this particular drive arrangement, the total drive current is 10 mA.

The advantages of this form of transistor gate are manifold. With no gate pulse applied, the switch resistance, for input signals up to ± 18 volts, is many megohms. During conduction, the resistance is about 10 ohms for a 10 mA drive. The saturation voltage drops (Vce sat) through the two units cancel, so that in the 3N76 the total offset voltage is only 200 μV with a 1 mA drive, and is stable over very wide temperature ranges. Units similar to the 3N76 are available which have offset voltages much lower than 200 μV.

4.4 Photomultiplier Head and Preamplifier

Figure 8 shows the photomultiplier bias circuit and transistor preamplifier.

The phototube is an EMI 9558B, which has a spectral response well suited to measurement of the laser light (~6300Å). Typical characteristics of the tube are:

Spectral response	S20
Peak Quantum Efficiency	20% at 4400 Å
Quantum Efficiency:	7% at 6300 Å
Number of dynodes:	11
Gain:	1.4×10^6 at 1450 volts
Anode Sensitivity:	200 amps/L
Anode dark current:	.001 μA
Cathode diameter:	2 inches

Operation at approximately 1350 - 1450 volts offers the best ratio of anode sensitivity to dark current.

The photomultiplier, together with the preamplifier, is housed in an aluminum tube. Connections are made at the rear end, and the cathode faces out the opposite end. The cathode is essentially masked except for the aforementioned aperture, which has a diameter of between 20 mils and 1 mil. The assembly is mounted on a motor-driven carriage which allows it to scan the entire end of the experimental 12" alignment tube.

The preamplifier utilizes the high input impedance of a field effect transistor (FET) to buffer the phototube signal. A current modulation of .001 μA (the dark current level) will provide a signal of roughly 1 millivolt. At the output of the gain of 100 preamplifier, then, the corresponding signal is about 100 mV.

The preamplifier FET and differential stages are direct coupled to avoid the need for very large coupling capacitors. The differential stage uses a compound transistor configuration which provides excellent temperature stability and isolation of the input circuit. An emitter-follower buffers the final output for transmission through a 15-foot shielded cable to the main amplifier and detector chassis. Parallel cables carry the phototube high voltage and the preamplifier ±12 volt lines.

4.5 Twin-Tee Bandpass Amplifier and 60 cps Filter

The twin-tee feedback amplifier and 60 cps filter are shown in Figure 9.

The 60 cps rejection filter has been included primarily because of the probability of the presence of ripple and pickup from the high-voltage power supply. In addition, it helps to attenuate higher harmonics of the 15 cps signal. The rejection at 60 cps through the filter and its field-effect buffer was measured to be

54 db. The FET buffer is necessary to present a high impedance to the filter.

The main amplifier has a gain of approximately 40X, set by the dc feedback path. A parallel feedback path contains the 15 cps twin-tee rejection filter. The over-all response function of this active filter has a Q of 10 centered at 15 cps. This value of Q results in an effective time constant for a step change in 15 cps signal amplitude of about 0.3 seconds.

The total frequency response of the amplifier and filter is shown in Figure 10. The response to a step change of input signal and the total distortion of a nominal 0.5% distortion input, are shown in Figures 11a and 11b respectively. It can be seen that the total distortion at the output (transformer secondary) is also about 0.5%; hence the amplifier contribution is indiscernible.

4.6 Phase Detector and Buffer

The modulation frequency of 15 cps was originally chosen because of the fact that in a 15 cps coherent detector, 60 cps is rejected as an even harmonic.

The present 15 cps oscillator is not phase-locked to the 60 cps line, hence the rejection will not be perfect. However, with the 60 cps rejection filter also in the system, this is not important. All even harmonics of the modulating frequency will still be rejected.

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The modulation frequency of 15 cps makes it difficult to obtain reasonable fast response with the conventional form of coherent detector. In the usual detector, the signal is gated into an RC filter for the full half-cycle of the signal; hence to maintain a 1 second response time with a 15 cps modulation results in an intolerable output ripple of about 1/15th the input amplitude.

To circumvent this problem, a modified form of phase detector was developed. In this design, the input sinusoidal signal is sampled at its crests, rather than averaged for the whole half-cycle, and the sampled value stored on a capacitor. The circuit is shown in Figure 12. The capacitor voltage is buffered to a low impedance dc level using the same FET - bipolar transistor combination as in the other circuits. The only ripple present in this system is due to decay of the capacitor voltage through the FET and back-biased transmission gates. This total leakage is very small for a 250 mV final output, the ripple was measured to be 1 mV.

We now have a phase detector which responds very quickly to changes in input amplitude because of the low source impedance and small storage capacitor. In fact, a step can be completely registered upon passage of a single sampling pulse, or 1/30 seconds. The final bandwidth of the system now can be chosen independently of the response time of the detector. In the present circuit the time constant of the final filter is 0.1 seconds. This is somewhat faster than the response of the tuned amplifier previously discussed, so that here the tuned amplifier limits the speed of response.

The action of the detector just described is different in one main respect from the conventional full-wave circuit. In the usual circuit, the input signal and noise components are integrated, in which case the detector rejects even harmonics and responds to odd harmonics of the fundamental. But the response to odd harmonics decreases inversely with the harmonic number. In the sampling type detector, the circuit responds equally to all higher odd harmonics. Therefore, we must rely on the preceding circuitry to limit the response of the system to higher odd harmonics. As can be seen from the over-all system response in Figure 10, this has been accomplished rather effectively by the combination of twin-tee filters and R-C section.

A multiturn potentiometer is provided to zero the output of the dc buffer. The buffer drifts are normally smaller than the system noise fluctuations, so that readjustment of the zero is seldom required.

4.7 Packaging of Components

Photographs of the phototube head and of the main cabinet containing the instrument are shown in Figure 13.

The phototube and preamplifier are housed in an aluminim tube which mates with the carriage at the end of the alignment.

tube. The phototube itself has both an electrostatic shield of conduction paint (Tubekoat), and a thin mu-metal magnetic shield.

The main cabinet contains the high-voltage power supply, the phase detector chassis, and an output meter with a fixed 1 volt full-scale movement. Front panel controls include a phase adjustment, a phase reversing switch, and a meter-read push-button. The entire electronics is packaged on two standard 7" plug-in circuit boards. The dc power is supplied by two EECo modular transistor supplies, rated at $\pm$ 12 volts, 1 ampere. Ripple and regulation are .05 and .01% respectively.

5. SYSTEM PERFORMANCE

The performance of various components of the electronic system has already been discussed. Some additional laboratory tests were made to determine the over-all performance, particularly with respect to noise and pickup rejection. Total system noise was measured with and without the 9558B phototube. The tube of course was darkened for this purpose.

5.1 System Dynamic Range

The first important performance aspect is dynamic range. Without the preamplifier connected into the system, noise fluctuations at the final detector output, as read on a HP 412A voltmeter, are small compared with 1 mV. This means that systematic errors due to pickup of 60 cps and 15 cps are insignificant compared with 1 mV. When the preamplifier (but not the phototube) is connected, preamplifier noise can be seen at the final output as a random, ± 2 mV rms fluctuation. The over-all gain from preamp to final detector is 2000; hence this represents an equivalent input noise, in a 1 cps bandwidth, of 1 μV.

The maximum linear range of the tuned amplifier is in excess of 4 volts peak-to-peak. Therefore the output meter range, being limited to ± 1 volt dc, operates well within the 0.5% total distortion requirement. This establishes an over-all dynamic range of 60 db, and a S/N of 60 db at the upper end. The signal, then, will normally be adjusted to this range by adjusting either the phototube gain (high voltage supply) or the laser intensity.

5.2 Photomultiplier Noise and Pickup

The system noise was measured with the 9558B operated at recommended voltages with the photocathode masked.

With the tube operated at 1250 volts (Sensitivity = 200 A/L) the following measurements were made:

Dark Current	=	2 nA
Preamp Output:		
random noise	=	100 mv p-p
60 cps pickup	=	400 mv p-p
Detector Output:		
Total noise	=	20 mv p-p

The total output noise of 20 mv is about 10× greater than the preamplifier noise above. Hence for optimum dynamic range the tube gain should be decreased by decreasing the voltage. It was found that at a HV of 900 volts, the total noise output dropped to 2 mv p-p, the same as the preamplifier alone. Hence, operation at 900 volts will assure a S/N of 60 db with a 1 volt maximum output signal.

5.3 Long-Term Stability

In the present design, small temperature drifts can occur in the final FET buffer. For a laboratory environment, these drifts are insignificant compared with the system random noise levels. In actual operation, even if drifts do occur, they can easily be compensated by readjustment of the recorder zero. Random drifts in the coherent detector itself are completely negligible for the system described.

5.4 Field Operation

An example of a typical recording made while the system scanned an intensity peak is shown in Figure 14. The two curves repres nt successive recordings with the target shifted horizontally by 4 mils. The recording was repeated for each setting of target. The horizontal scale is 6 mils per minor division.

As nearly as can be seen, the repeatability seems to be within 1 or 2 mils for this particular measurement. The systematic errors, of course, have not been resolved. The recording represents an output signal of about 0.5 volt maximum, or half the capability of the detector. At this point, the system noise should be about 60 db down.

6. SUMMARY AND RECOMMENDATIONS

The prototype system appears to meet the immediate design goals - that is, to have a sensitivity limited essentially by the photomultiplier noise characteristikcs; and to have total distortion and noise less than 0.5% of the normal operating signal level. It seems that for a practical instrument, we are approaching the limits of sensitivity.

The immediate use of the instrument is, of course, to aid in continuing experiments directed toward better defining the design requirements for the Two-mile Accelerator. As this is done, the system will be enlarged or re-designed to accommodate the particular alignment procedure adopted.

The present instrument may be adapted to an array of phototubes, rather than a single tube, rather simply. The present driver circuits could be easily modified to drive additional phase detectors; and about three complete phase detectors could be housed in a single 5" rack chassis. The present unit has sufficient power at both high and low voltages to supply the additional load.

It might be desirable to provide some additional features in the final system. Specifically, if it turns out that light signals are very strong, so that system sensitivity is not a problem, then it would certainly be useful to be able to increase the system bandwidth and speed up the scanning rate. This would result in a significant speed-up of the alignment procedure. This flexibility can be built into the system by providing variable bandwidth in the tuned amplifier and final detector filters.

Additional recommendations must necessarily await further clarification of the over-all alignment system concept. We simply note here that the electronic system is flexible and will be modified to best suit the finalized system.

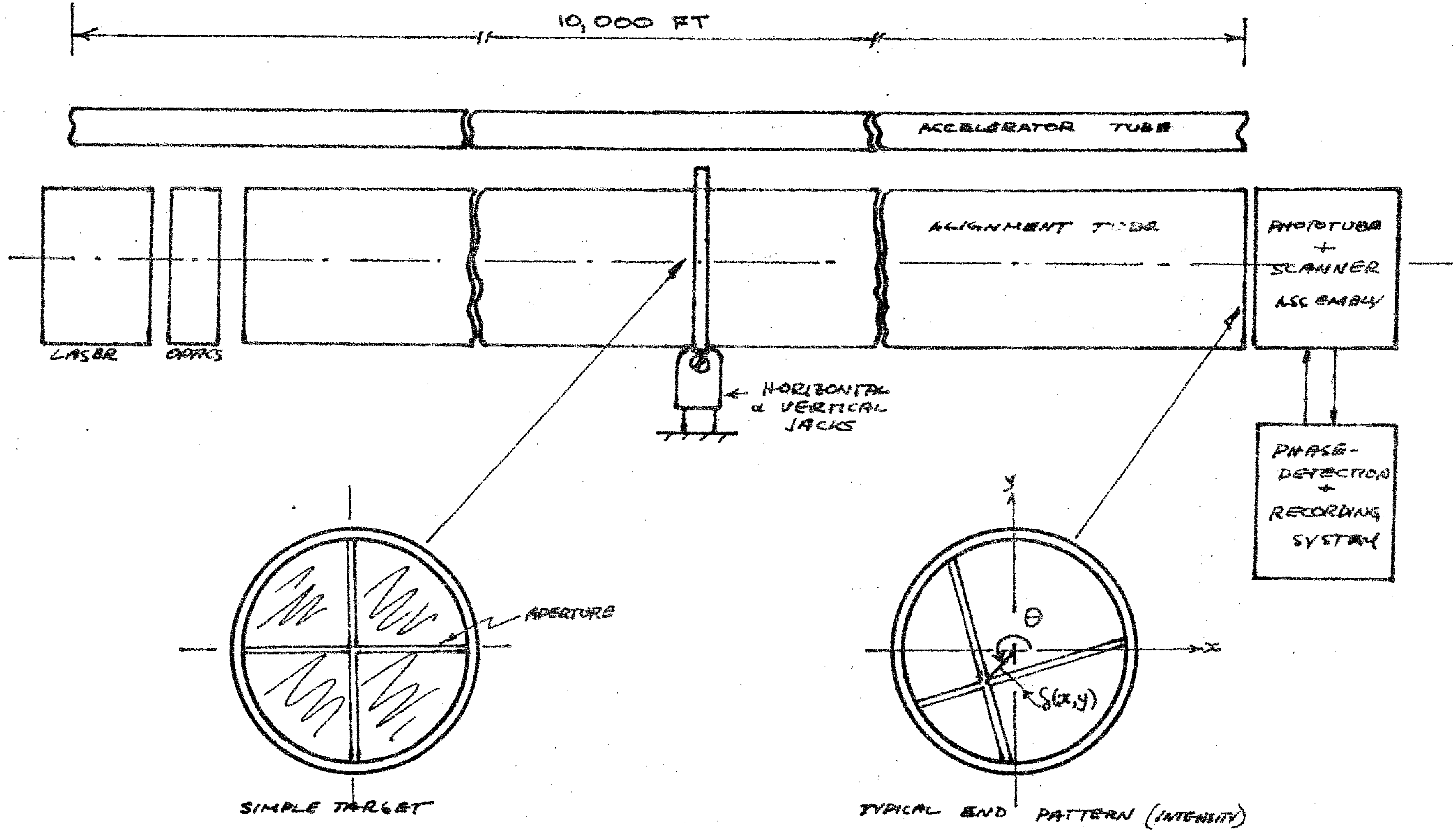


FIGURE 1 - BASIC ALIGNMENT SYSTEM

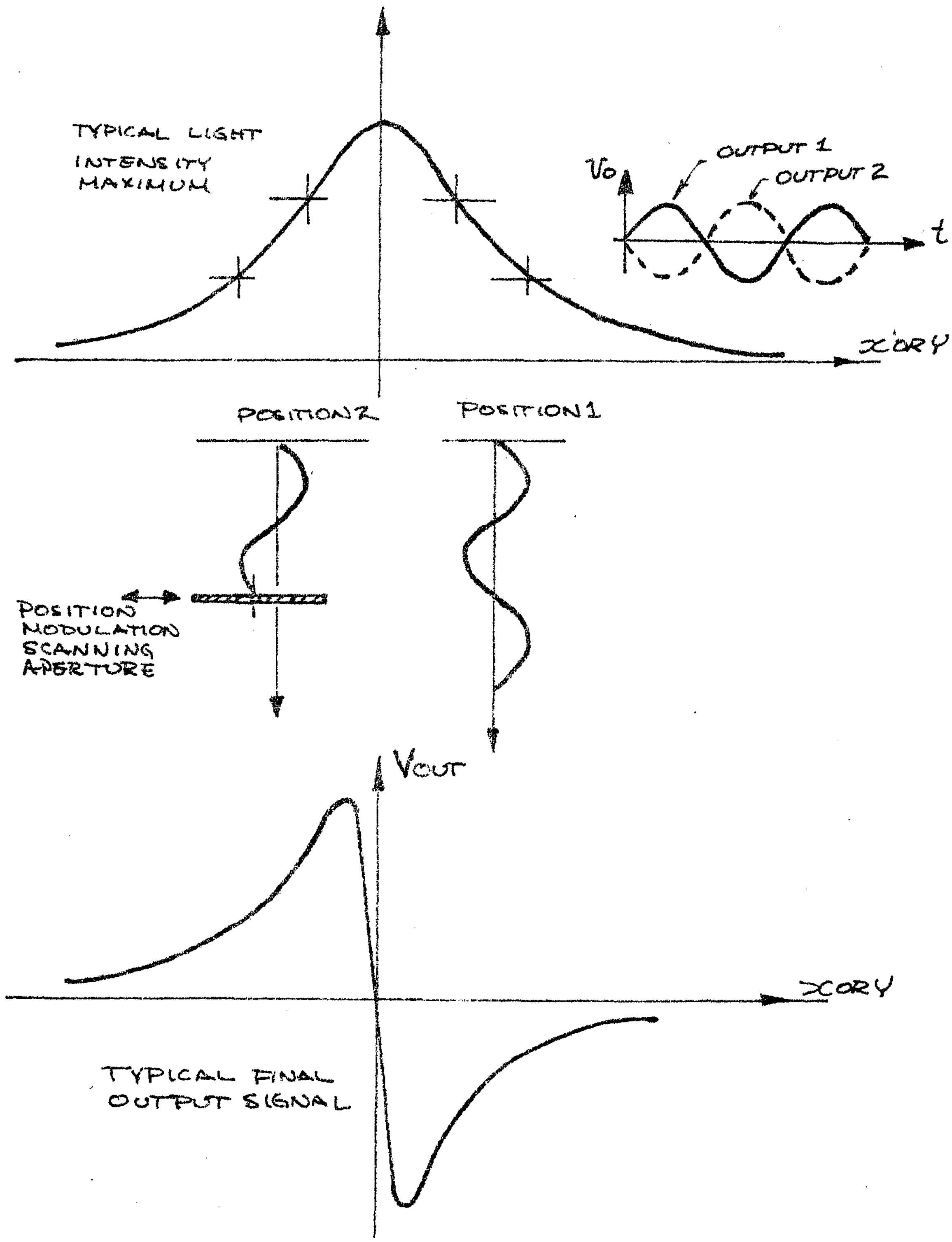


FIGURE 2 - MODULATION WAVEFORMS

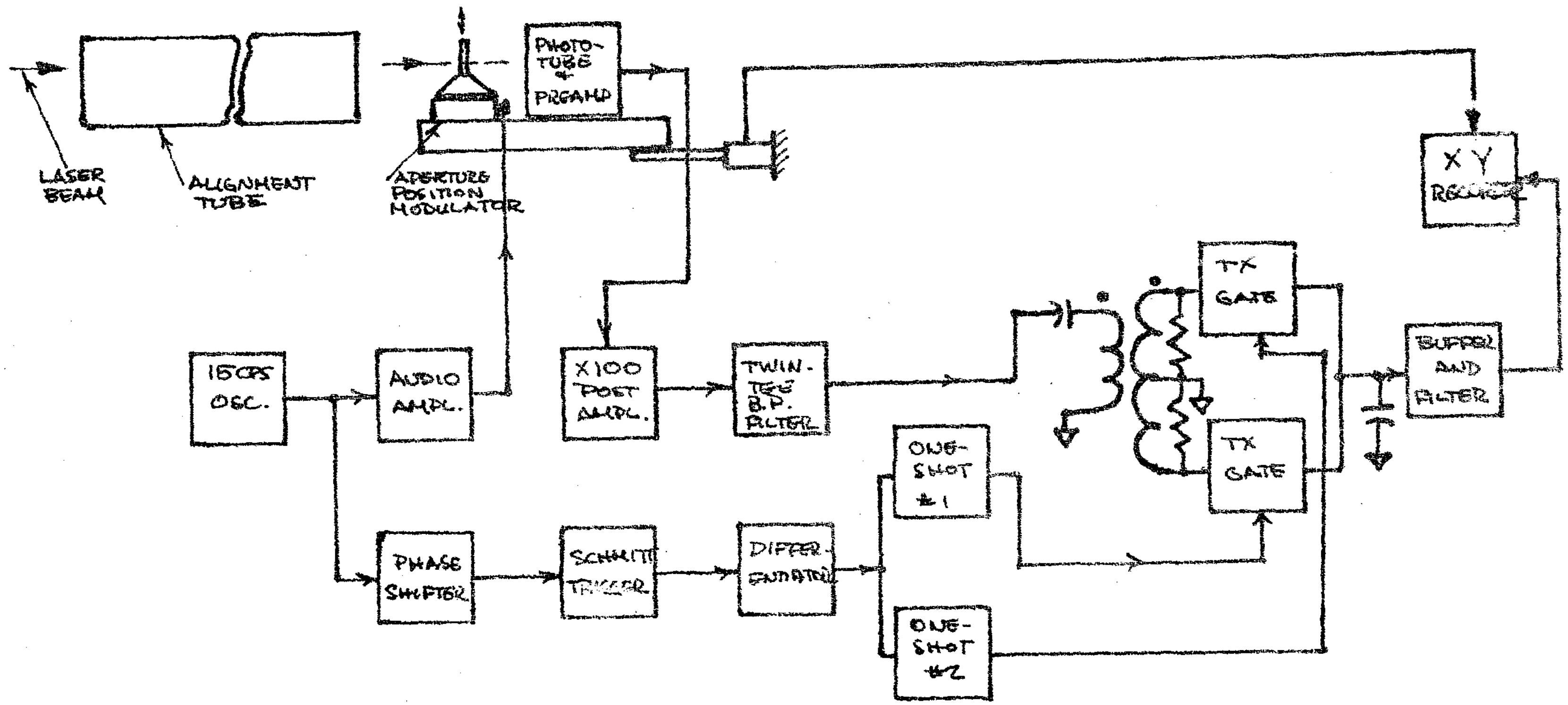


FIGURE 3 – BLOCK DIAGRAM OF PHOTOMULTIPLIER PHASE DETECTION SYSTEM

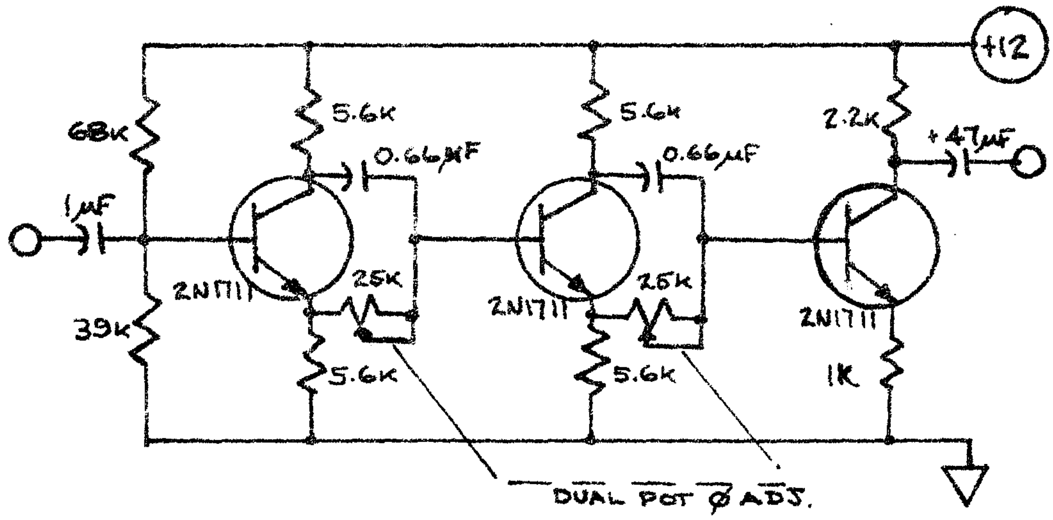


FIGURE 4- 15CPS PHASE SHIFTER

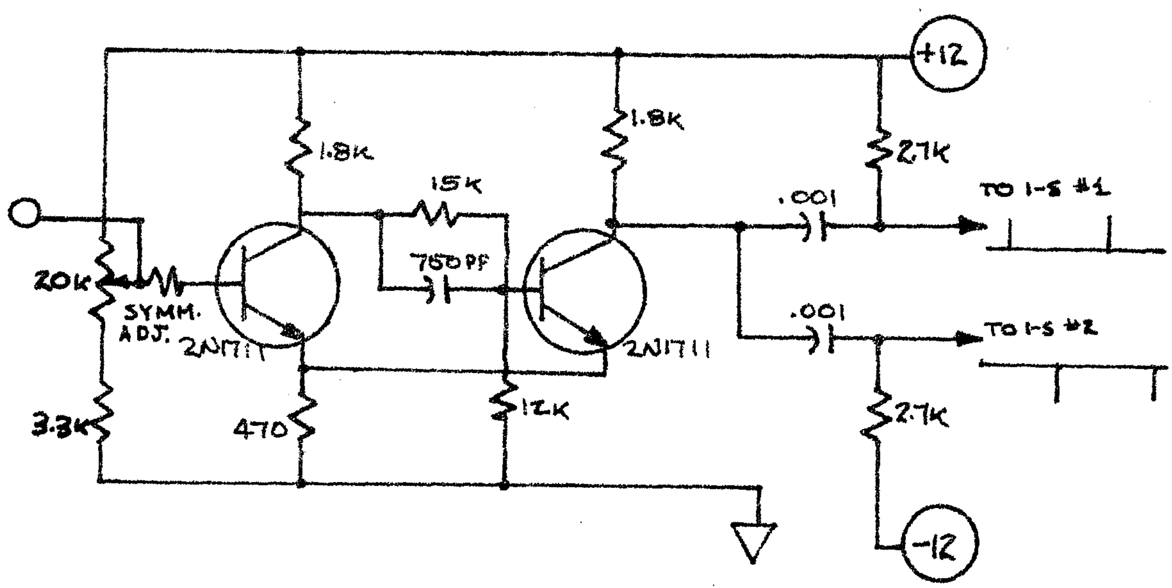


FIGURE 5 - SCHMITT TRIGGER

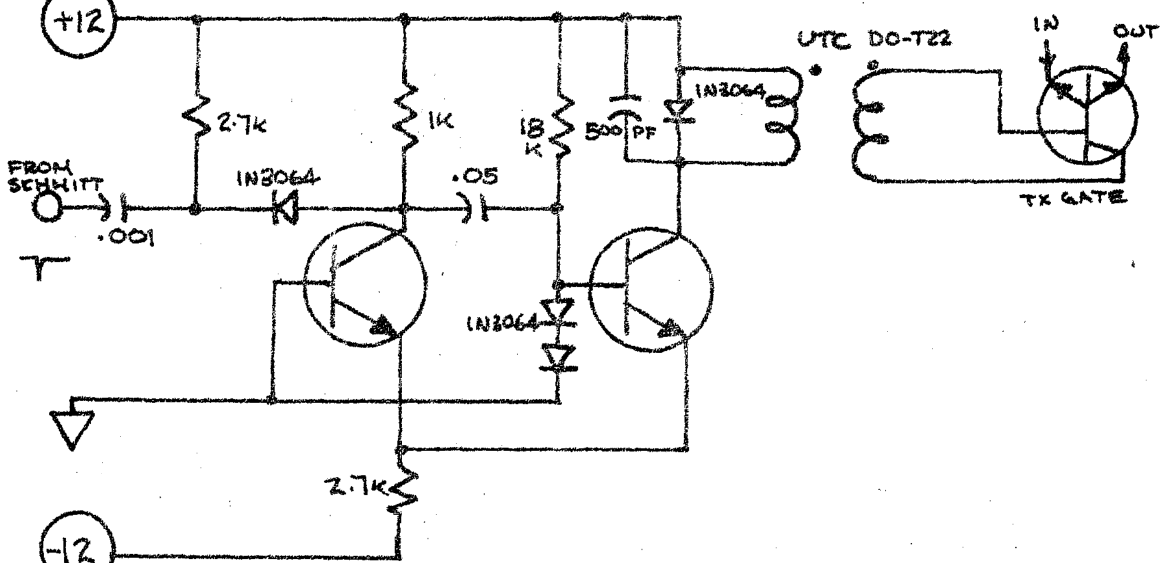


FIGURE 6 - ONE-SHOT #2 AND GATE

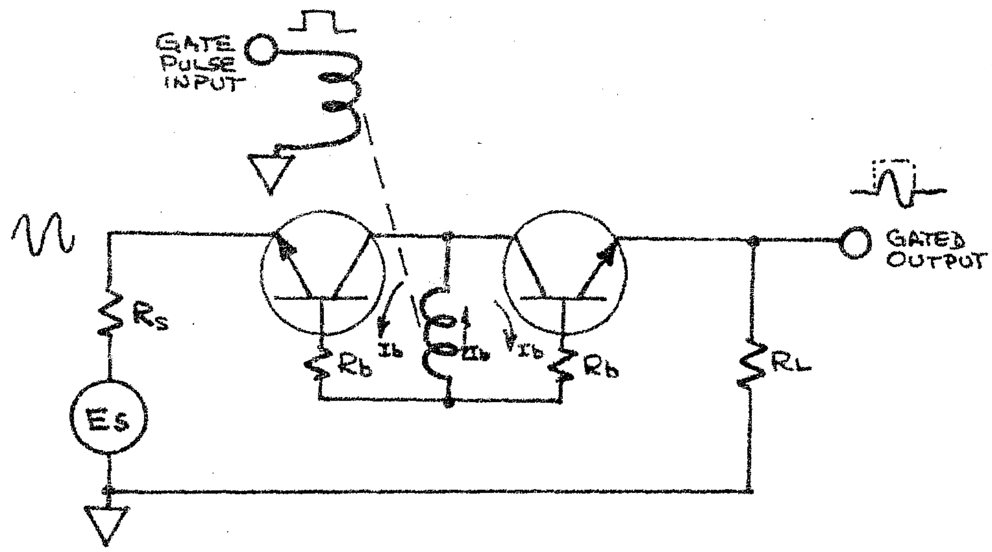


FIGURE 7 - CHOPPER TRANSISTOR TRANSMISSION GATE

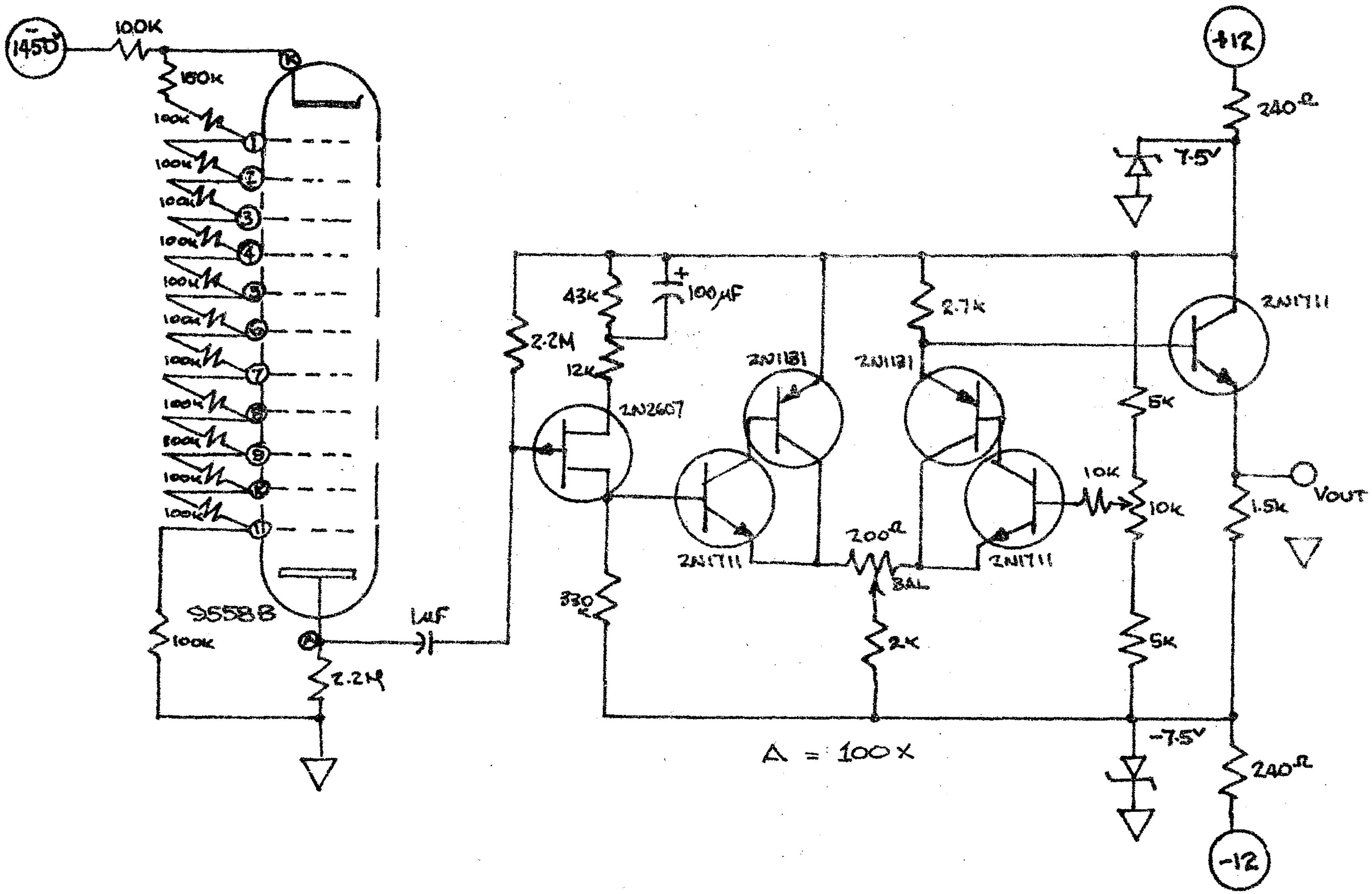


FIGURE 8 - PHOTOMULTIPLIER AND PREAMPLIFIER

$R_1 = 48.9K$
$C_1 = .054\,\mu F$

$R_2 = 203K$
$C_2 = .0521\,\mu F$

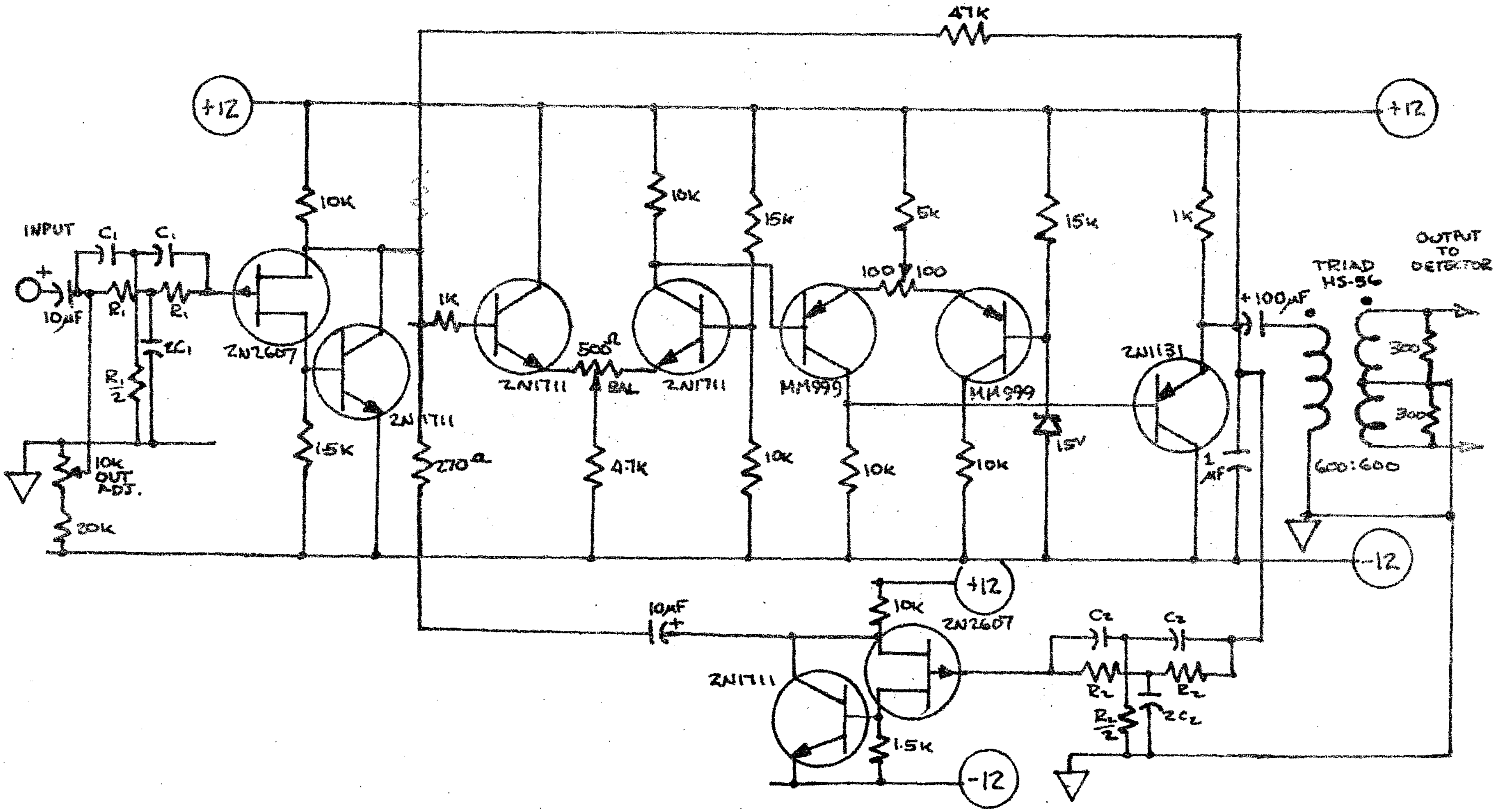


FIGURE 9 — BANDPASS AMPLIFIER AND 60 CPS FILTER

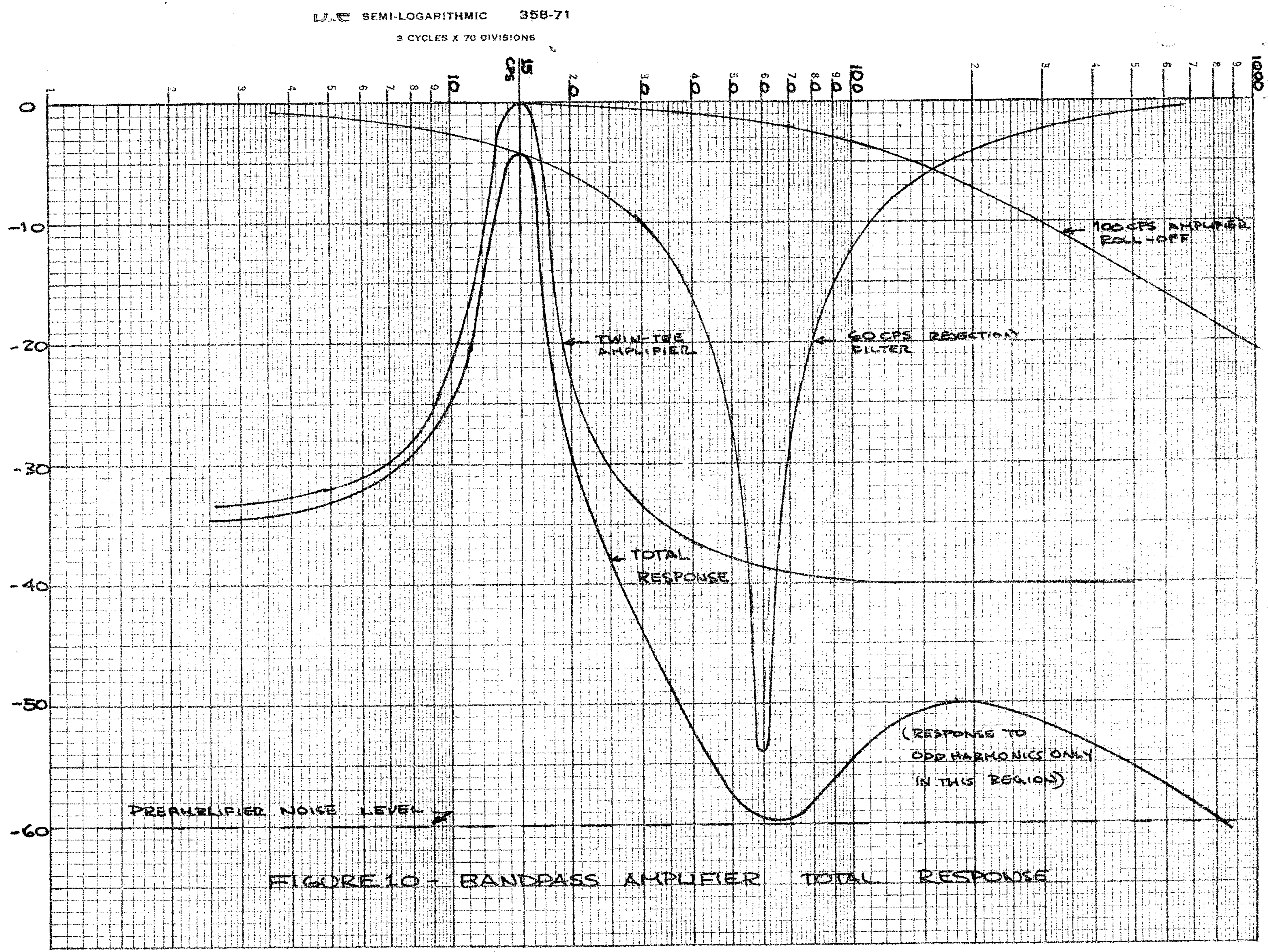
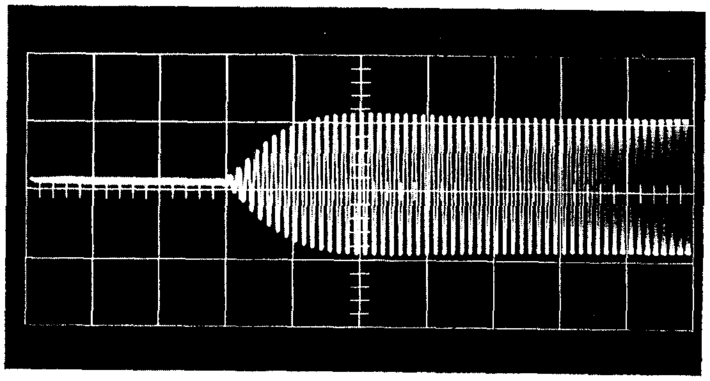
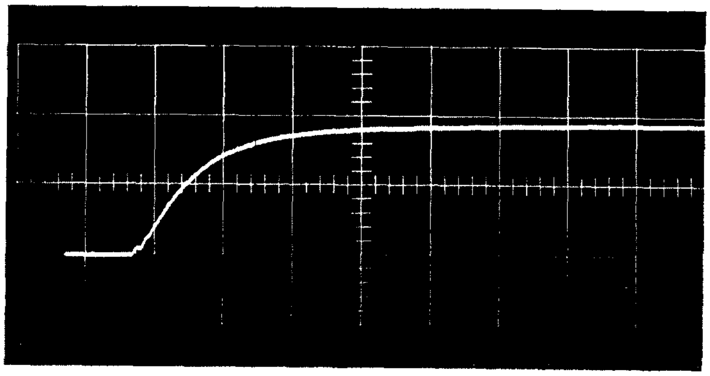


FIGURE 10 - BANDPASS AMPLIFIER TOTAL RESPONSE

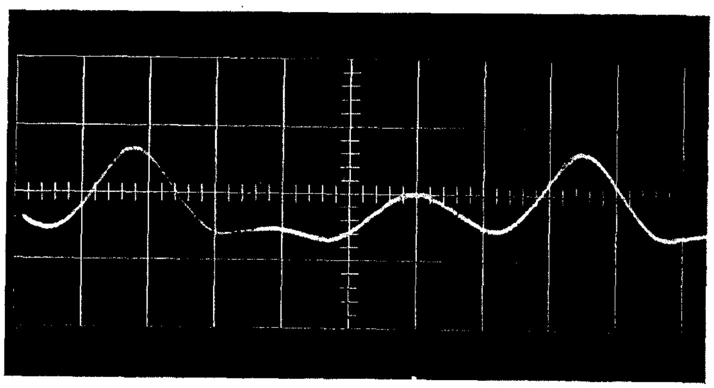


VERT - 2V/CM
HORIZ - 0.5 SEC/CM



VERT - 0.5V/CM
HORIZ - 0.5 SEC/CM

(a) TOP - TUNED AMPLIFIER OUTPUT
BOTTOM - PHASE DETECTOR FINAL OUTPUT



VERT - 0.25% OF INPUT AMPLITUDE PER CM.

HORIZ - 10 ms/CM

(b) TOTAL % DISTORTION

FIGURE 11 - SPEED OF RESPONSE AND TOTAL DISTORTION

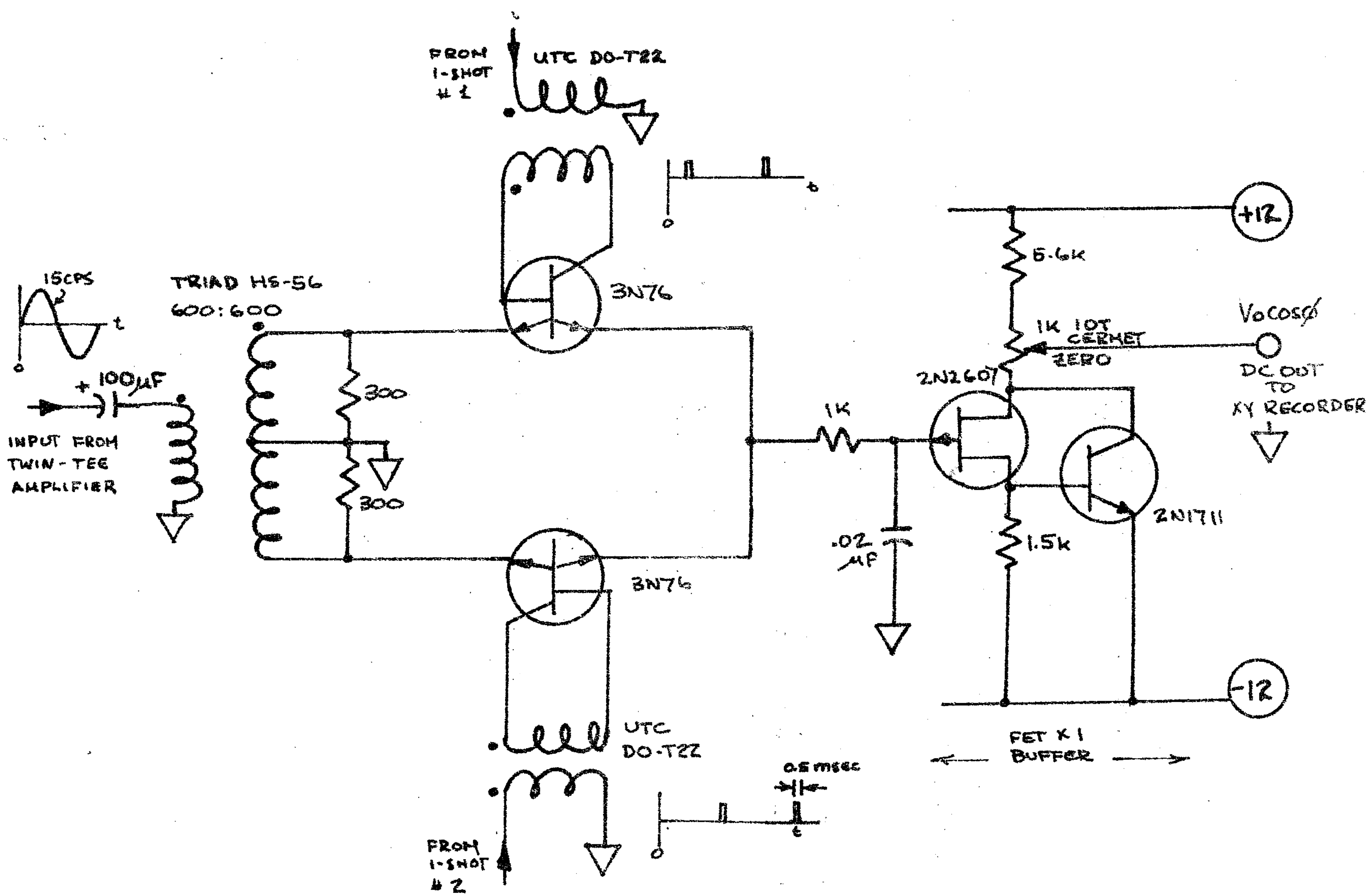
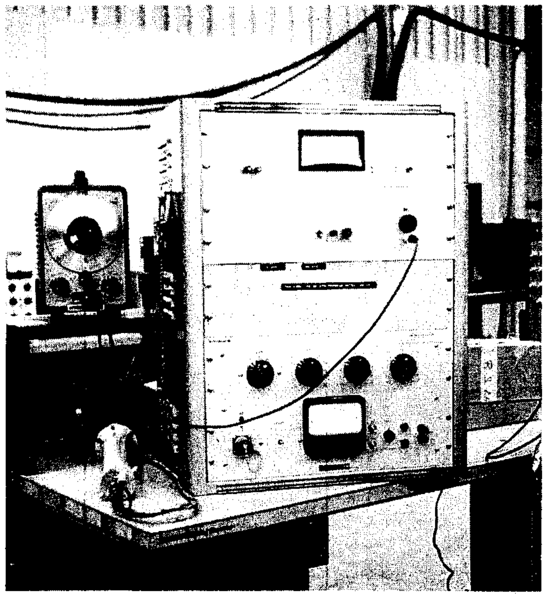
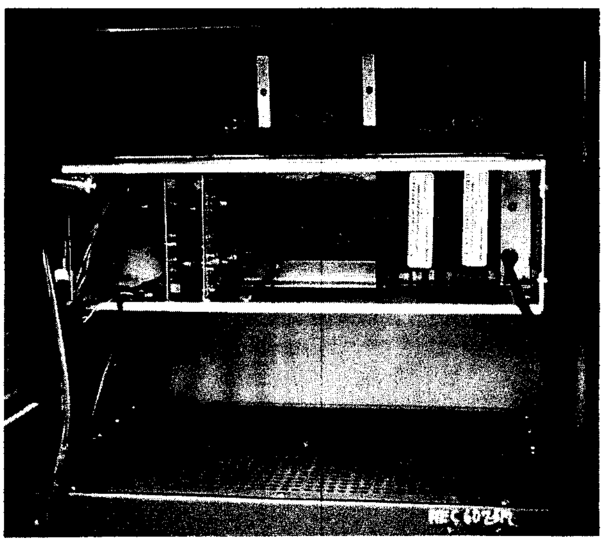


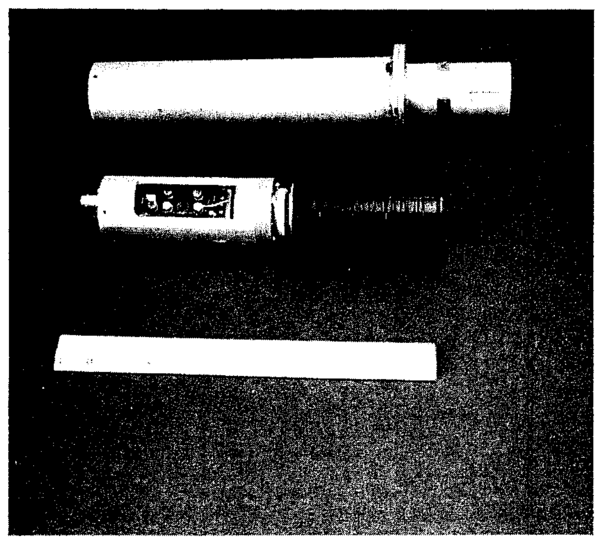
FIGURE 12 - PHASE DETECTOR AND BUFFER



EQUIPMENT CABINET AND REFERENCE OSCILLATOR



CABINET REAR VIEW



PHOTOMULTIPLIER ASSEMBLY

FIGURE 13 — EQUIPMENT CABINET AND PHOTOMULTIPLIER ASSEMBLY

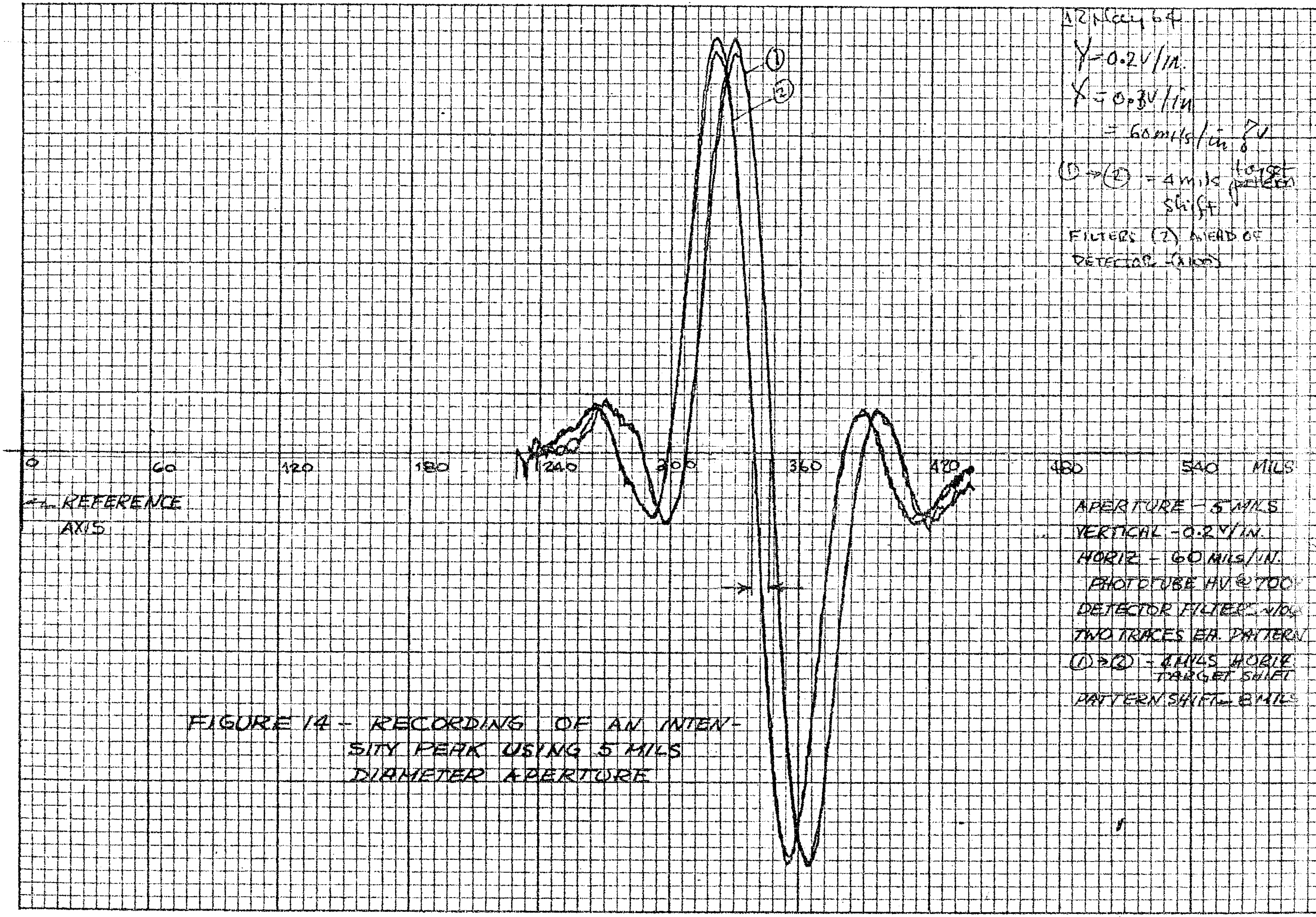


FIGURE 14 - RECORDING OF AN INTENSITY PEAK USING 5 MILS DIAMETER APERTURE