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Final Project Report

for

DUAL RETICLE STAR TRACKER

Contract No. NAS 5-10354

Goddard Space Flight Center

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INTRODUCTION

This report describes the design and construction of a dual reticle startracker performed under GSFC contract NAS 5-10354 to Washington Technological Associates, Inc.

The startracker is intended for use in the Fine Attitude Control System (FACS) of an Aerobee sounding rocket.

The performance characteristics are described in GSFC Specification 72-79. Briefly, the desired performance characteristics are:

1. Tracking sensitivity down to a +3.5 visual magnitude, class A0 star. At this target magnitude, the peak-to-peak noise from either channel shall be less than 25 seconds of arc equivalent at null.
2. The frequency response of both channels shall be 5Hz, with a phase shift of no more than 22° at 1 Hz.
3. The startracker shall be equipped with a star magnitude detector with four externally commanded gain settings.
4. The field of view shall be $\pm 1.8^\circ$ with an externally commanded field stop to limit the field of view to $\pm 1/2^\circ$.
5. The proportional region shall be ± 12 minutes of arc, with the error signal saturating beyond this limit. In the proportional region, the magnitude and polarity of the error signal shall be proportional to the angular deviation between the tracker center line and the null line. The proportionality constant shall be about 5 mv per sec of arc.
6. The tracker shall have two channels: an X or pitch, and a Y or yaw. These channels will correspond to the Cartesian coordinate system.
7. The tracker shall use the dual reticle principle, with one photomultiplier tube.
8. The tracker shall have a dynamic range from +3.5 to -4.0 magnitude.

The dual reticle system was chosen because of the inherent ability of this type of system to encode the angular deviation in a frequency modulation (FM) signal. There are several advantages to this arrangement. First of all, an FM system performs better than an amplitude modulation (AM) system under most conditions of noise, resulting in a more sensitive startracker. Secondly, an FM system tends to select the brightest target within the field of view, to almost complete exclusion of all other, dimmer targets. Finally, an FM system can be made more tolerant of temperature changes since the circuitry is largely

AC coupled until the very final stages of the processing circuitry. These features are not found in AM systems.

GENERAL DESCRIPTION

Theory of Operation

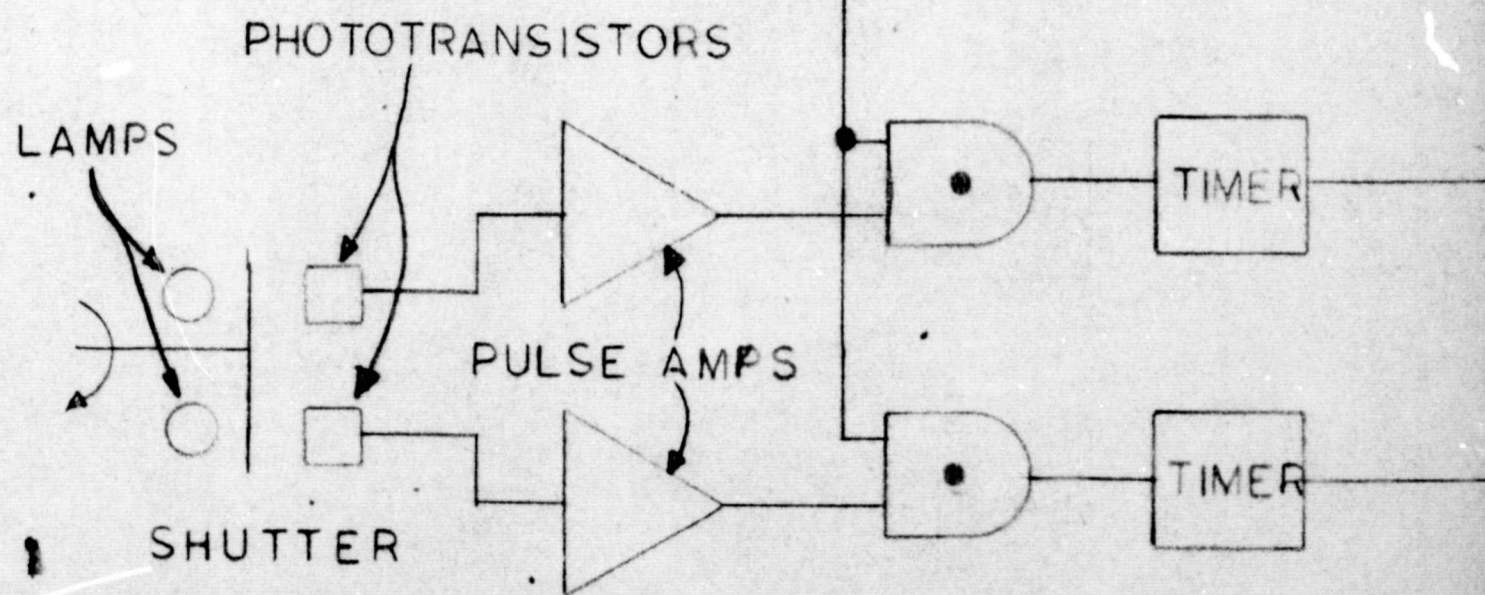
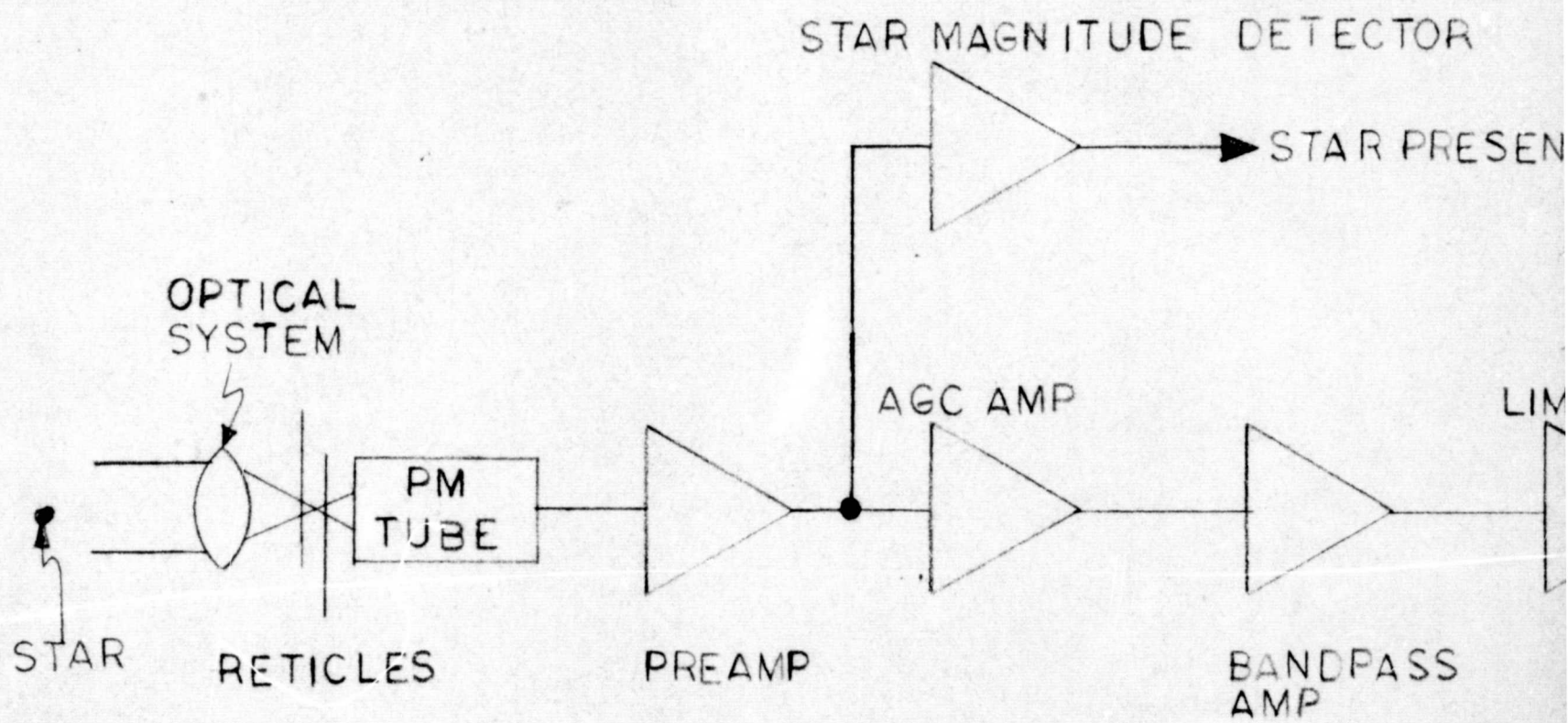
This section describes the operation of the startracker, excluding the very detailed electronic and mechanical components, which are described in later sections. The information in this section is suitable for understanding the operation of the startracker while the later sections give a detailed explanation adequate to repair or adjust the startracker. A functional diagram of the startracker system is shown in Figure 1.

Reticle System. - The light from a target star, assumed to be at infinity, is collected by the optical system and focused at a point between the overlapping reticles. As long as the center line of the startracker is pointed directly at the target star, the angular deviation is zero, and the tracker is at null. Under these conditions, the light beam passes through the null line of both reticles. If this angular relationship is altered by rotating the tracker, the light beam passes through the reticles at a point other than through the reticle null line.

A reticle is shown in Figure 2. The geometry of the reticle is arranged in the following manner:

The reticles are divided into two 90° patterned segments alternated with two 90° clear segments. This arrangement allows the reticles to be overlapped, requires only one photomultiplier (PM) tube, a single optical system, and helps reduce the package diameter.

Note that if a reticle is rotating at a constant frequency and the light beam from the target star passes through any part of the reticle outboard of the null line, the frequency of the chopped light beam is always increasing. If the light beam passes through the reticle inboard of the null line, the frequency is always decreasing. The magnitude of the frequency shift is proportional to the angular deviation of the tracker center line from the null line, out to or in to the edge of the saturated region. The frequency shift remains the same throughout either saturated region. The inherent directional indication is an additional advantage of the segmented reticle system.



FOLDOUT FRAME 1

SENT

LIMITER

ONESHOT

LOWPASS FILTER

X ERROR

X DISCRIMINATOR

LOWPASS FILTER

Y ERROR

Y DISCRIMINATOR

FLIP
FLOP

FLIP
FLOP

EOLDOUT FRAME 2

FIGURE 1.
FUNCTIONAL BLOCK
DIAGRAM

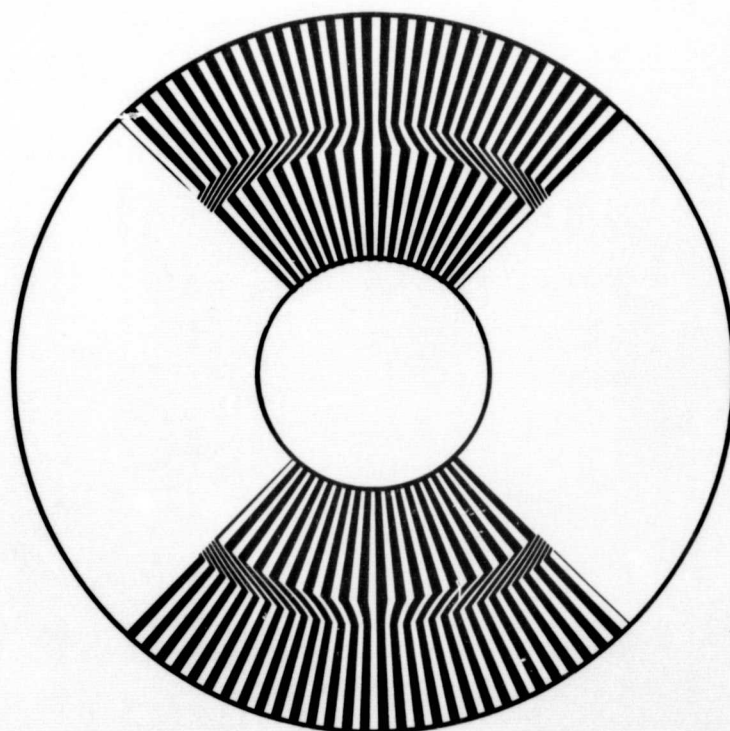


FIGURE 2.
STAR TRACKER RETICLE

Signal Amplifier System. - The chopped light beam falls on the photocathode of the PM tube. The current output of the PM tube generates a signal voltage across the load resistor. This voltage is amplified by about 40 by the preamplifier which also lowers the impedance of the signal line to about 100 ohms. The preamplifier is a differential input type amplifier, used mainly to reject the ripple from the high voltage (HV) power supply.

The output of the preamplifier drives the AGC (Automatic Gain Control) amplifier and the star magnitude detector circuit. The AGC amplifier accepts the widely varying signal from the preamplifier and holds it to a .25 to .5 volt level at its output.

The next stage is the bandpass amplifier which limits the bandwidth of the signal to 3830 ± 150 Hz and amplifies it to about 4 to 8 volts.

Limiter and One-Shot Stage. - The band-limited signal is now applied to the limiter stage which is simply a very high gain amplifier driven to saturation in both the positive and negative directions. This stage has enough gain to eliminate all amplitude variations from the signal. At this point, the signal is a square wave of varying frequency.

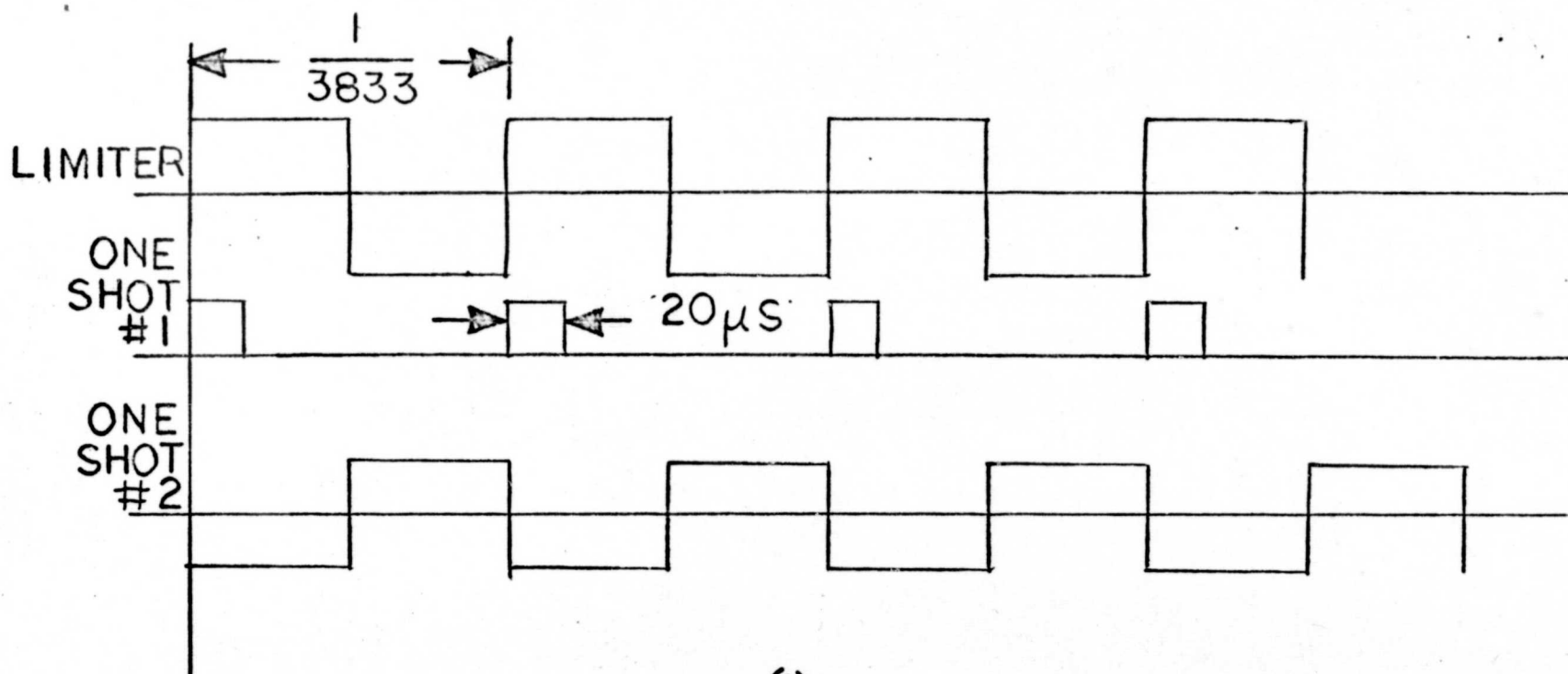
Following the limiter are two one-shot multivibrators, the first being driven by the limiter, the second being driven by the first one-shot.

The first one-shot, the trigger one-shot, is used only to trigger the second one-shot, the information one-shot. The 3 microsecond pulse from the trigger one-shot is short enough so that it does not interfere with the period of the information one-shot. The information one-shot is designed to have a very stable on-time and to produce a polar output. If the limiter drives this one-shot directly, the next transition of the limiter stage following the triggering edge tends to lead this one-shot slightly, causing hysteresis in the output signal around null.

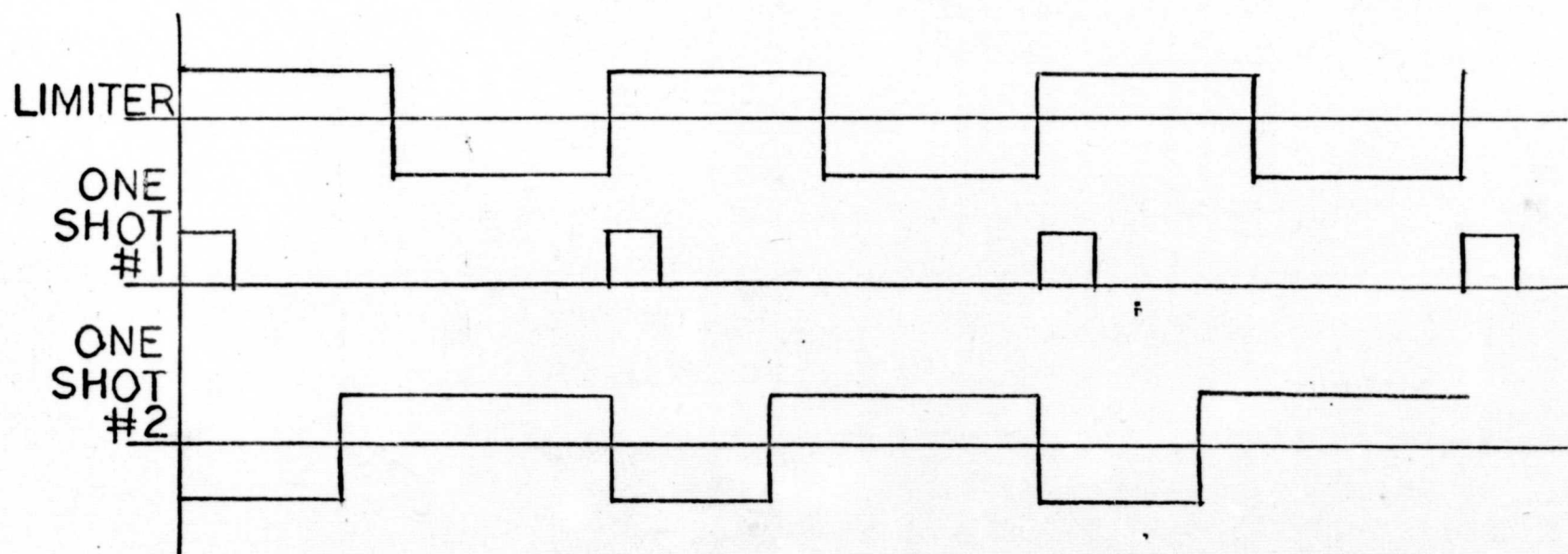
Three conditions of the output of the information one-shot for three different input conditions are shown in Figure 3. In (A), the input to the limiter is a 3833 Hz sine wave; the limiter output is a 3833 Hz square wave as is the output of the information one-shot. In (B), however, the limiter output is something less than a 3833 Hz square wave. Note that the output from the one-shot is no longer a symmetrical square wave as in case (A) but has an average DC value somewhat greater than 0 volts. In case (C), the frequency is greater than 3833 Hz and the pulse train from the information one-shot has an average DC value somewhat less than 0 volts.

It should be realized that cases (B) and (C) never occur; the frequency is either decreasing or increasing. The larger the angular deviation, the larger the frequency excursion, this excursion occurring at a 38.3 Hz rate. Also, the frequency increases or decreases every one-half revolution.

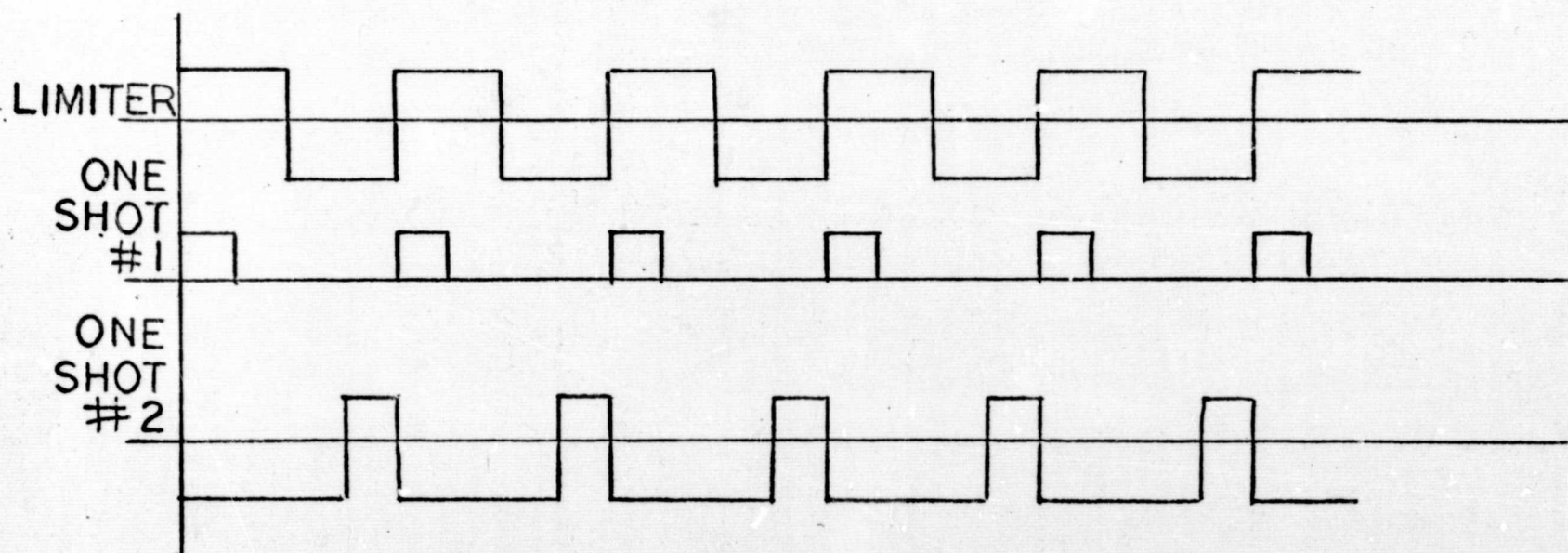
Signal Separation System. - At this point, it is helpful to examine the output of the information one-shot over a period of time, say 180° of reticle rotation. Referring to Figure 4, it can be seen that the X- and Y- channel information is interlaced. In this



(A)



(B)



(C)

FIGURE 3. LIMITER AND ONE-SHOT WAVEFORMS

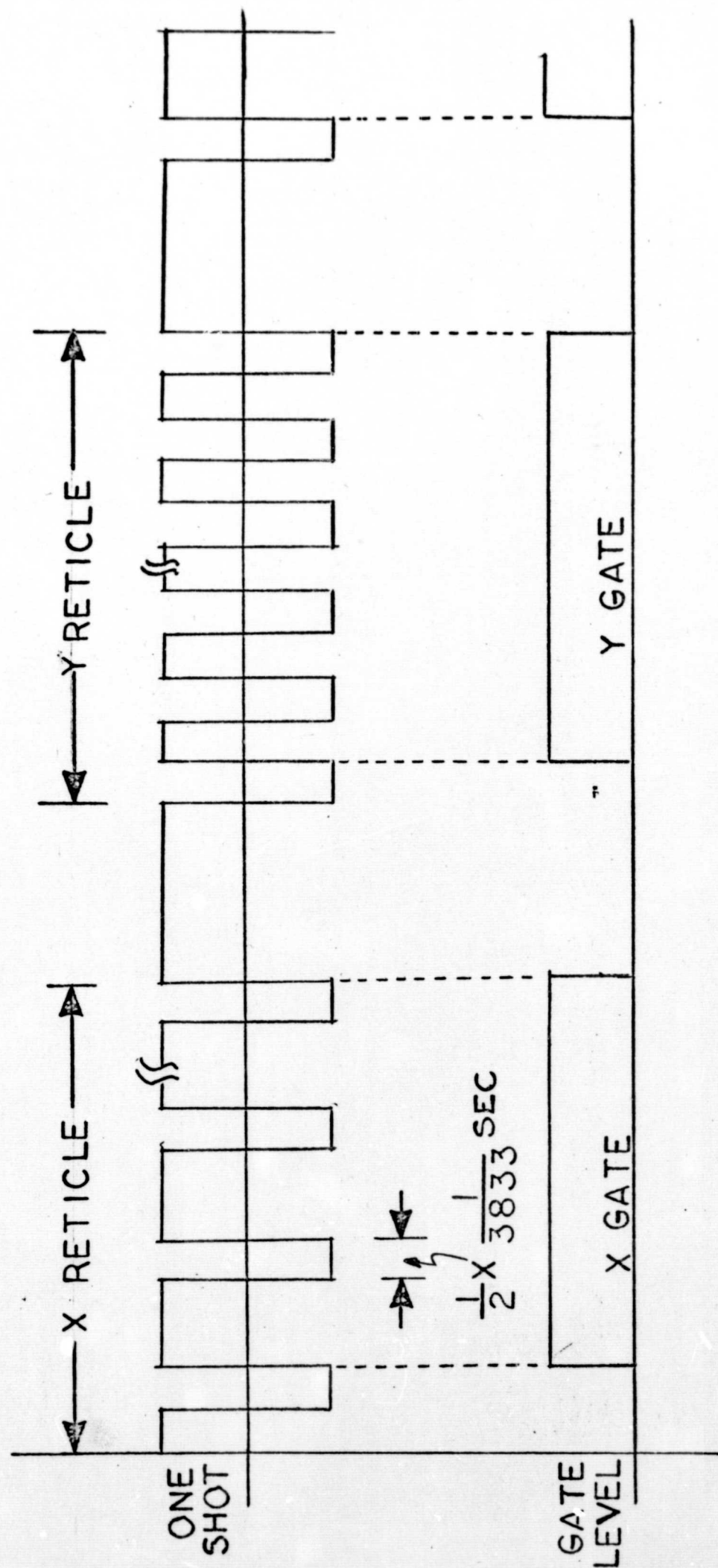


FIGURE 4. ONE-SHOT PULSE TRAIN

example, the X channel is near one extreme of the proportional region while the Y channel is near the other.

The information separation is accomplished by selective gating, which is controlled by a rotating shutter and phototransistor assembly. The shutter, connected to the Y-reticle shaft, has two light gates spaced 180° apart. The two phototransistors and the two light sources are spaced 90° apart. The net result of this arrangement is that an X gate is generated every 180° and a Y gate is generated every 180° , 90° behind the X gate.

The gate pulses and their relation to the data stream are shown in Figure 5. Note that the leading and trailing edge of the gate pulses are timed with a positive transition of the data stream, gating only integral numbers of full cycles into the discriminators. This arrangement was found to minimize the effect of reticle jitter which causes small frequency changes not associated with angular displacement. The frequency changes would cause slightly varying amounts of energy to enter the discriminators, resulting in a noise in the output signal.

The exact gating scheme for each channel employs a timing one-shot, a flip-flop, and two and-gates. The output of the phototransistor is one input to one of the and-gates and a differentiated pulse train, from the information one-shot, is the other. At the first coincidence of these two inputs, the timing one-shot is fired; this in turn sets the gate flip-flop. After the timing one-shot completes its cycle, the next positive-going pulse from the pulse train anded with the expired one-shot output resets the gate flip-flop. The set side of the gate flip-flop is used as the channel gate pulse; the timing of this circuit is shown in Figure 5.

The period of the timing one-shot is adjustable -- varying the period causes a greater or lesser number of integral pulse cycles to enter the discriminators. This variation causes a change in the output voltage of the discriminator and is used for the channel-gain adjustment; note that this adjustment is not continuous but is in small, discrete steps.

Discriminator and Low Pass Filter. - The various waveforms for the discriminator and filters are shown in Figure 6. Each discriminator extracts the DC average from the polar pulse train at its inputs. Due to the gated nature of the pulse train, however, the output of the discriminators is not a continuous level but a time-varying one. These variations are smoothed by the low pass filters, as shown. The remaining ripple from the low pass filter is very small, however, corresponding to about one or two seconds of arc, at null; away from null, however, the ripple amplitude increases.

The low pass filter has a passband from DC to 4.85 Hz, the 3 db point, and a phase shift of about 22° at 1 Hz. The output of the low pass filter is either used directly as the channel output or is inverted by the unity gain amplifier and then used as the channel output.

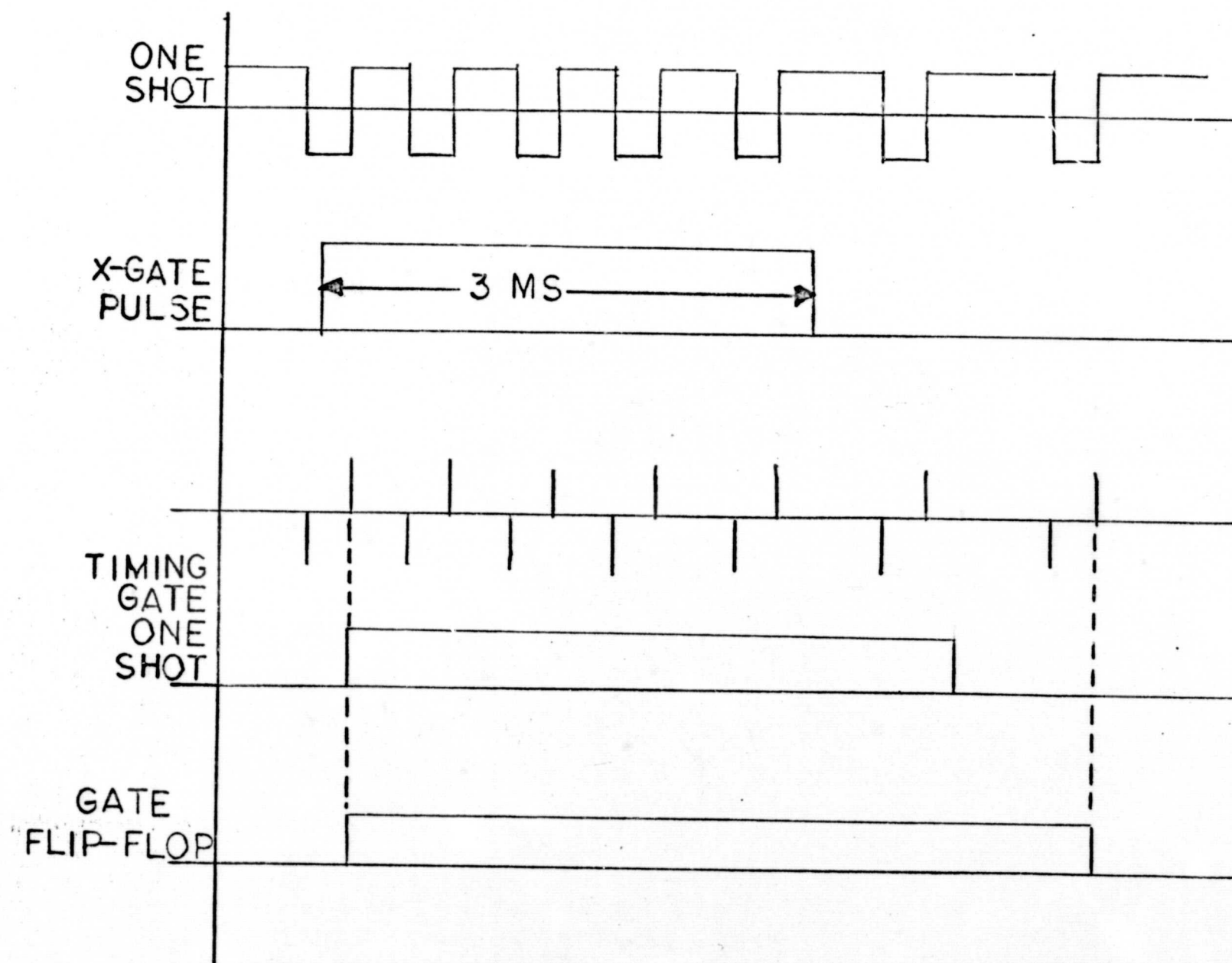


FIGURE 5. GATE CIRCUIT WAVEFORMS

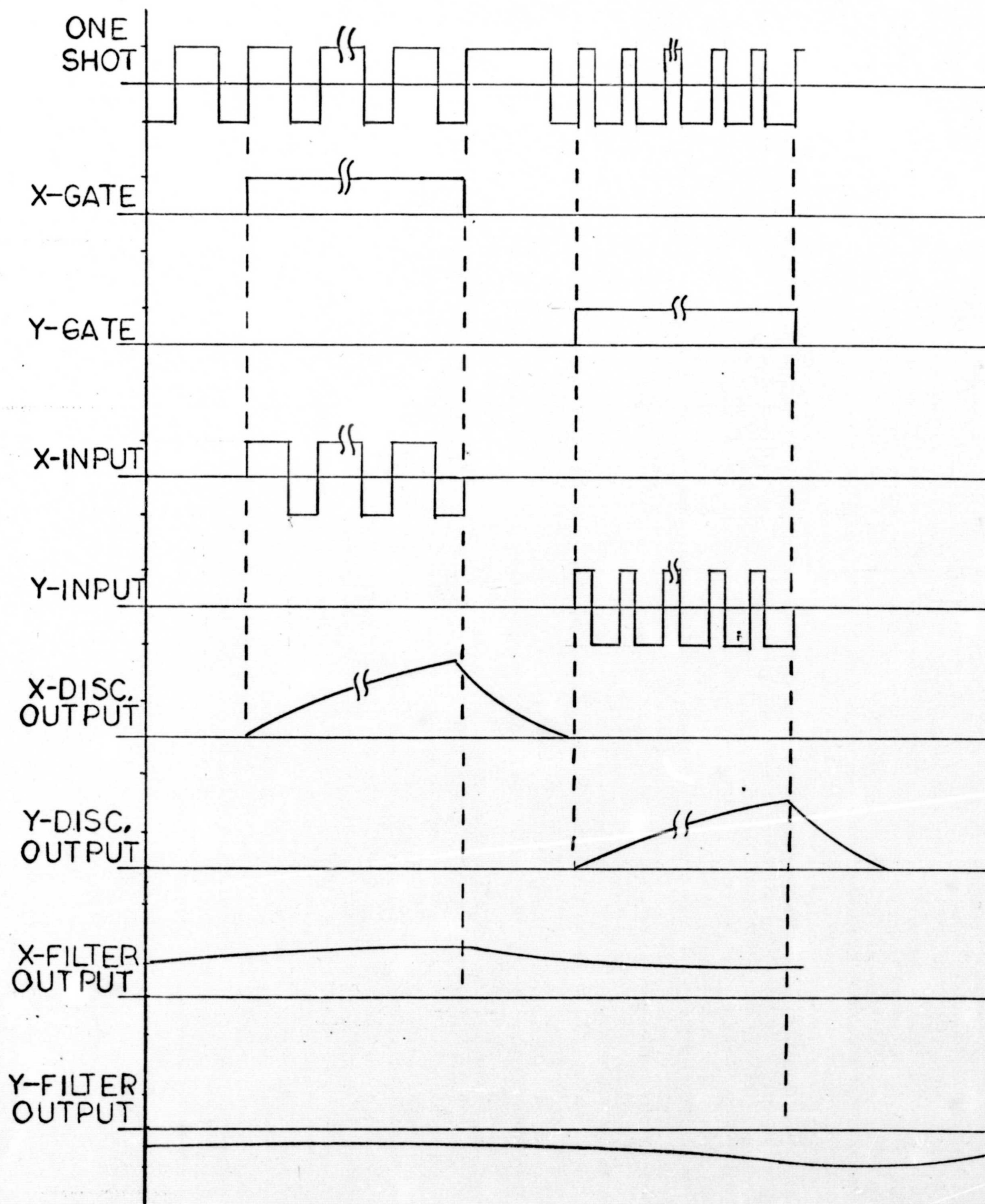


FIGURE 6. DISCRIMINATOR WAVE SHAPES

THEORETICAL BACKGROUND

Signal to Noise Ratio Calculations

The parameters that affect the startracker sensitivity are the optical system aperture diameter and its efficiency, the bandwidth of the modulating system, and the quantum efficiency and dark current noise of the PM tube. In a relatively narrow bandwidth system, such as this one, the dark current is not too significant.

The required signal to noise ratio (S/N), at the cathode of the PM tube, is assumed to be 6. Also, the dimmest expected target is assumed to be a + 4.0 visual magnitude, A0 class star. The dimmer target was chosen to provide a safety factor for unforeseen difficulties that could arise.

The S/N for a PM tube is given by the equation

$$S/N = \left[\frac{2 e \Delta f (1 + \frac{i_d}{i_s})}{i_s} \right]^{1/2}$$

where: e is the charge on an electron, 1.6×10^{-19} coulombs,
 Δf is the bandwidth of the system, 2300 Hz,
 i_d is the DC dark current, 3×10^{-16} amps,
 S/N is the signal to noise ratio, 6 in this case, and
 i_s is the DC signal, the unknown in the equation.

Solving the equation, $i_s = 2.67 \times 10^{-14}$ amps at the cathode.

Note that the effect of the DC dark current is included in this calculation. This equation for S/N is the familiar shot noise current equation divided into the signal current.

The magnitude of i_s represents the minimum signal current that will produce a useful S/N ratio. The number of lumens required to produce this current is

$$L \text{ (lumens)} = \frac{i_s}{\text{photocathode sensitivity}}$$

$$= \frac{2.67 \times 10^{-14}}{165 \times 10^{-6}}$$

$$= 1.6 \times 10^{-10} \text{ lumens.}$$

Starting with the equation,

$$m_1 - m_2 = 2.5 \log_{10} B_1 / B_2 ,$$

which defines star magnitude and

$$B_2 = 2.43 \times 10^{-10} \text{ lumens/cm}^2 ,$$

the defined illuminance of an A0 class, 0 visual magnitude star, the equation

$$2.5 \log_{10}(L) = 7.57 - 30 + 5 \log(d) - m$$

results.

Using the value of (L) for $m = 4$, we get

$$2.5 \log_{10}(1.6 \times 10^{-10}) = 7.57 - 30 + 5 \log(d) - 4.0, \text{ or}$$

$$d = 2.25 \text{ inches}$$

The required clear area of the aperture (A_o) is therefore

$$A_o = \frac{\pi d^2}{4} = 4.1 \text{ in}^2$$

Assuming a 50% transmission loss through the optical system results in a required aperture area of 8.2 square inches.

The actual aperture area of this startracker is about 10 square inches.

Bandwidth Calculations

The frequency spectrum produced by the reticles chopping the light beam can be estimated in the following manner.

The reticles rotate at 38.33 rps. There are one hundred spokes around the full reticle producing a carrier frequency of 3833 Hz. This frequency alone is actually generated if the light beam passes through the null line of the reticle. The spoke

spacing is arranged so that the maximum frequency produced is $3833 + 958 = 4791$ Hz and the minimum frequency produced is $3833 - 958 = 2875$ Hz. Since there is one complete frequency excursion around the reticle, the modulating frequency is 38.33 Hz with a frequency deviation of 958 Hz, producing a deviation ratio of

$$\delta = \frac{958}{38.3} = 25.$$

The Bessel function for $J_n(25) < .01$ can be estimated from the graph shown in Figure 14-8 of "Seely" ¹ at $n = 30$. The required bandwidth to contain this frequency spectrum is therefore $3833 + (30 \times 38.33)$ or $3833 + 1150$ Hz. This frequency band contains more than 99% of the useful energy generated by the reticle-chopping of the light beam.

Initially, the reticle speed was chosen as 20 rps rather than 38.33 rps. At this frequency, however, the reticles tended to flutter, causing the carrier frequency to drift. This carrier drift was demodulated along with the signal and caused low frequency noise in the output signal. The change to the higher rotational speed reduced the noise in the output signal by shifting it upward in frequency so that it was attenuated by the low pass filters.

Theoretical considerations argue for a lower rotational speed or for fewer spokes on the reticle to allow more photons per opening to pass through the reticle. This tends to integrate out the statistical fluctuations in the number of photons and therefore reduce signal flickering. Also, a slower modulating frequency, all other things being equal, requires less bandwidth, thereby reducing electrical noise. Lower frequencies mean lower sampling rates which means more ripple in the error signal, which reduces the theoretical gain to be achieved by a lower frequency. For example, with the present low pass filter arrangement, halving the 38.33 Hz modulating frequency would cause the ripple near null to increase to the equivalent of about 25 seconds of arc.

Photomultiplier Tube Considerations. - The PM tube selected for this startracker is the EMR 541E-05M-14. This tube has a one-inch diameter photocathode, a sapphire window and an encapsulated dynode resistor chain. The dynode structure is a 14-stage "venetian blind" type.

The spectral response is 1400 to 8000 Angstroms and this good response in the UV region was the principle reason for the selection of the tube, since A0 stars have large spectral emissions in this region.

¹ Samuel Seely, Radio Electronics, (New York: McGraw-Hill, 1956), p. 385

OPTICAL SYSTEM

Selection of the startracker optical system involved a number of trade-off situations. Major considerations were:

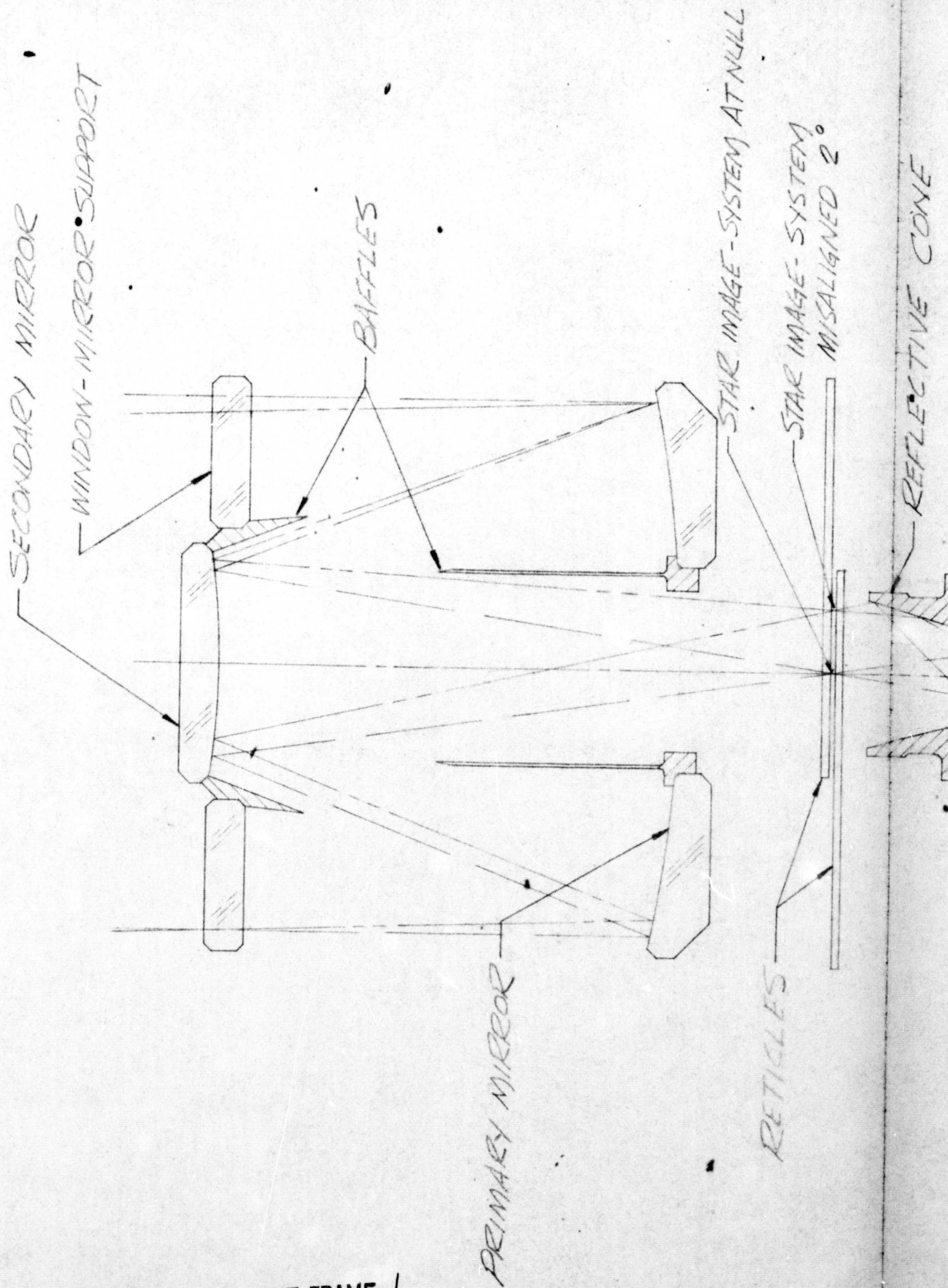
- Field of view required -- 4°
- Aperture - largest practical within the package envelope to obtain the maximum sensitivity
- Focal length - longest practical. The startracker accuracy is increased as the focal length is increased. This is due to the greater image displacement at the focal plane per unit of angular misalignment with the target star. Also, increased focal length and higher f number reduce the optical system costs since the resulting design becomes easier to fabricate. However, the focal length is limited by the mounting arrangement and physical size of the reticles, the reticle drive system, and the overall tracker envelope. The reticle size and mounting arrangement limit the area within which the 4° field of view must be imaged while the overall tracker envelope limits the size of the optical system proper.

The optimum reticle size and lateral location to obtain maximum useful imaging area while maintaining the optical system center line as near as possible to the tracker center line for the greatest aperture dimension was first established. This arrangement placed the optical center line .40 inches from the tracker center line and provided an area of 1-inch diameter in which stars within the 4° field of view must be imaged. This 1-inch diameter limits the optical system focal length to 14 inches. ($2 \times 14 \tan 2^\circ = .974$ inches)

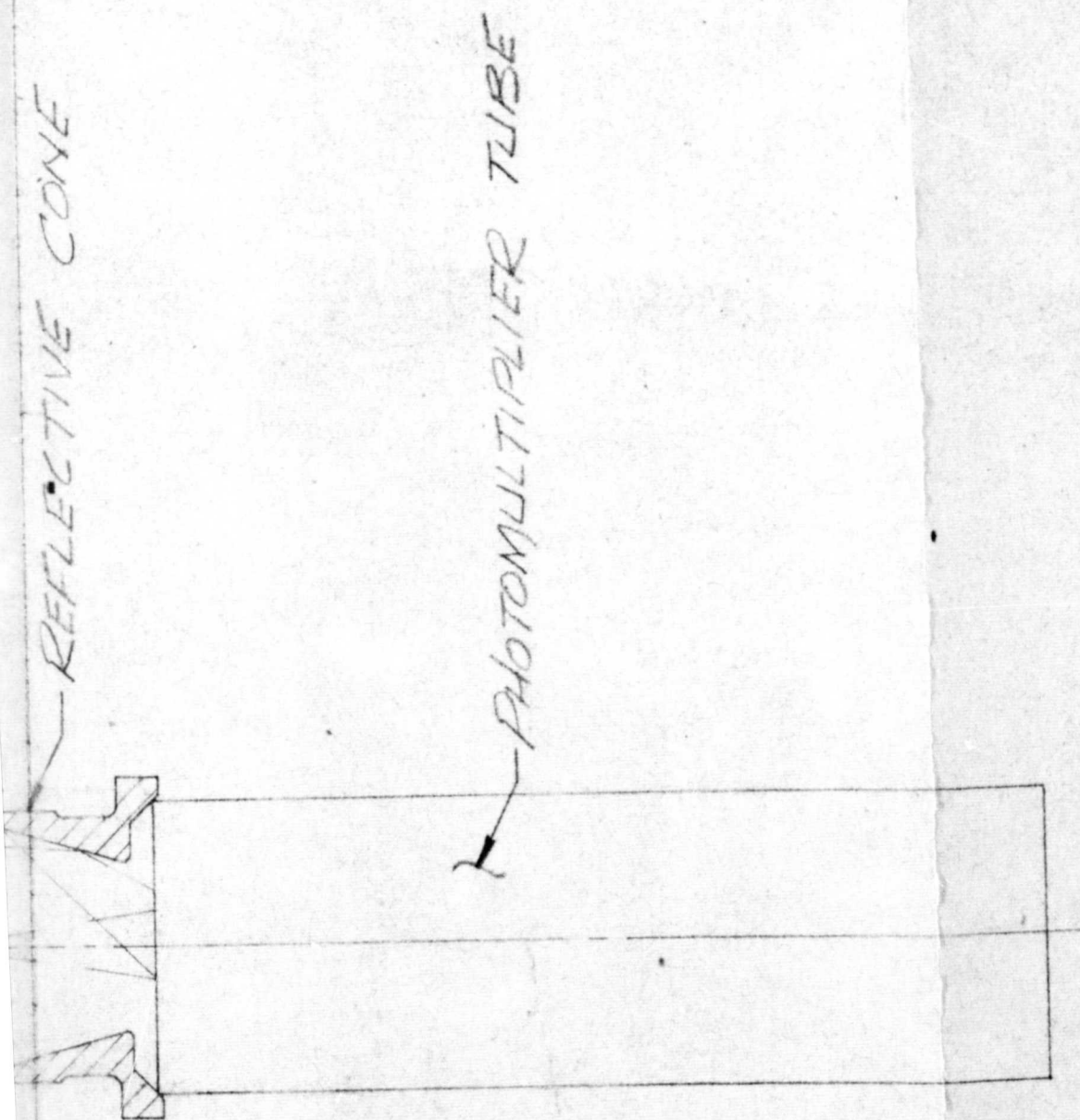
Second, considering primarily the overall length of the PM tube selected, the reticles were positioned along the optical center line to provide clearance between the PM tube and reticles for the necessary field lens or reflecting cone and to provide maximum length (within the housing envelope) for the primary optical system (see Figure 7 for the optical system arrangement). The maximum optical system length was established to be 4.3 inches.

Figure 8 shows the final optical design using a folded or Cassegrain system in order to obtain an effective focal length of 14 inches within the limited housing length.

The first element, or window, is plano-plano. While this is a refraction element and hence the system may be referred to as Catadioptric, the window has no optical effect except a slight transmission loss. This is true only in the case of collimated light such as that received from a target star. This window is included primarily as support for the secondary mirror while also affording protection against contaminants, which is an advantage over the commonly used "spider" type of mirror support. The effects of



FOLDOUT FRAME /



FOLDOUT FRAME 2

FIGURE 7.

OPTICAL SYSTEM ARRANGEMENT



Figure 8. Assembled Star Tracker

reflection and absorption losses through the window are virtually identical to those due to the loss of aperture area with the "spider" type support. Window material is pure fused silica. Surfaces are coated with the magnesium flouride for minimum reflection at 3500 Angstroms wave length. In subsequent models, this window is to be eliminated.

The second element is an ellipsoidal first surface mirror of "Cervit" material coated with aluminum and overcoated with magnesium flouride for maximum reflection over the range of 1750 to 5000 Angstroms.

The secondary mirror, or third element, is spherical. This mirror is also first surface coated with aluminum and magnesium flouride for maximum reflection.

The reticles, which have been described in a previous section, have the prescribed pattern vacuum deposited on 1/16 inch thick, pure-fused silica substrate material. These reticles are then coated on each surface with magnesium flouride to minimize reflective losses. The two reticles are spaced $.010 \pm .005$, $-.002$ inches apart. To obtain the smallest practical star image in the plane of each reticle pattern, which is necessary to obtain complete chopping of the incoming energy, the primary optical system focuses the star image midway between these reticles. The reticles are installed with their patterns face to face, or on adjacent surfaces, to minimize pattern to pattern spacing.

Since the PM tube cathode is one inch in diameter, the same as the image area at the reticle plane, a reflective cone is inserted between the reticles and the PM tube to gather the energy which would otherwise be lost due to the cone angle and the central ray angle beyond the reticles when the target star is at or near the edge of the field of view.

The reflection cone, shown in Figure 9 was chosen in lieu of a field lens to obtain maximum star tracker sensitivity near the null position. While there is lower transmission with a reflection cone than with a field lens, when misalignment causes the starlight to be reflected by the cone toward the PM tube cathode, losses at or near null which would have been encountered with a field lens are eliminated. This arrangement, coupled with the use of a 1-degree field stop to exclude as much background light as practical, appreciably increases the startracker's usefulness in tracking dimmer stars. The field stop is described in a later section.

In order to enhance sensitivity in the wavelength range previously mentioned, the PM tube selected utilizes a sapphire window.

As shown in Figure 7, baffles were mounted to the front window and to the primary mirror to occlude light entering the system from outside the 4° field of view.

The primary optical system housing, baffle tubes, retaining rings, and spacers are fabricated of aluminum, black anodized finished. The weight of the assembly is 1.43 pounds.



Figure 9. Disassembled Star Tracker Showing Subsystems

MECHANICAL DESCRIPTION

General System Description

The reticle drive system and the PM tube printed circuit board assembly are joined by four 4-40 screws and inserted into the main housing as a unit. (See Figure 10). The optical system is then installed in the housing, held in place with six 4-40 screws through its mounting flange, through plate number 1 of the drive assembly, and into the main housing. Shims are utilized between the optical system housing and plate number 1 for focusing, i.e., to position the minimum blur circle (best star image) midway between the two reticles.

The reticle drive assembly includes the following components:

- a. Reticles
- b. Drive Motor
- c. Gear train
- d. X-Y sampling chopper
- e. 1-degree field stop and circuitry

Figures 10 and 11 show the gearing arrangement used. Since each reticle disc extends beyond the center line of the other, it is necessary to utilize a series of idler gears to drive from each side of the pair of reticles. All shafting is stainless steel, mounted in miniature, precision ball bearings with duroid retainers. Bearing play, radial and axial, is taken up by inserting shims which cause preloading of the 'O' rings installed over each shaft.

All gearing is 120 diametral pitch, precision 2 (AGMA quality 13). The two 141-tooth gears are aluminum and all others are stainless steel, thus providing aluminum to stainless steel contact at each gear mesh. Gears are lubricated sparingly with Air Force Experimental Grease MCG 66-272 (Wright Patterson Field). With a motor speed of 8000 rpm and a 3.48/1 gear reduction, the reticle speed is 2299 rpm.

The X-Y sampling chopper consists of an assembly having a light bulb and a photo-transistor in line at each of the two positions, 90 degrees apart. As a two-bladed chopper wheel mounted on the upper reticle shaft revolves, each light is blocked by each of the blades for 32 degrees of rotation. This unit then produces alternate X- and Y- sampling periods 90 degrees apart. The assembly is baffled to prevent light from reaching the PM tube.

The one-degree field stop is simply a rotary solenoid with a blade attached. When this solenoid is energized, the blade is rotated 45 degrees into the optical path. Under this condition, a .250 inch diameter hole is aligned along the center line, reducing the imaging area from one inch to .250 inches and reducing the field of view from four degrees to one degree.

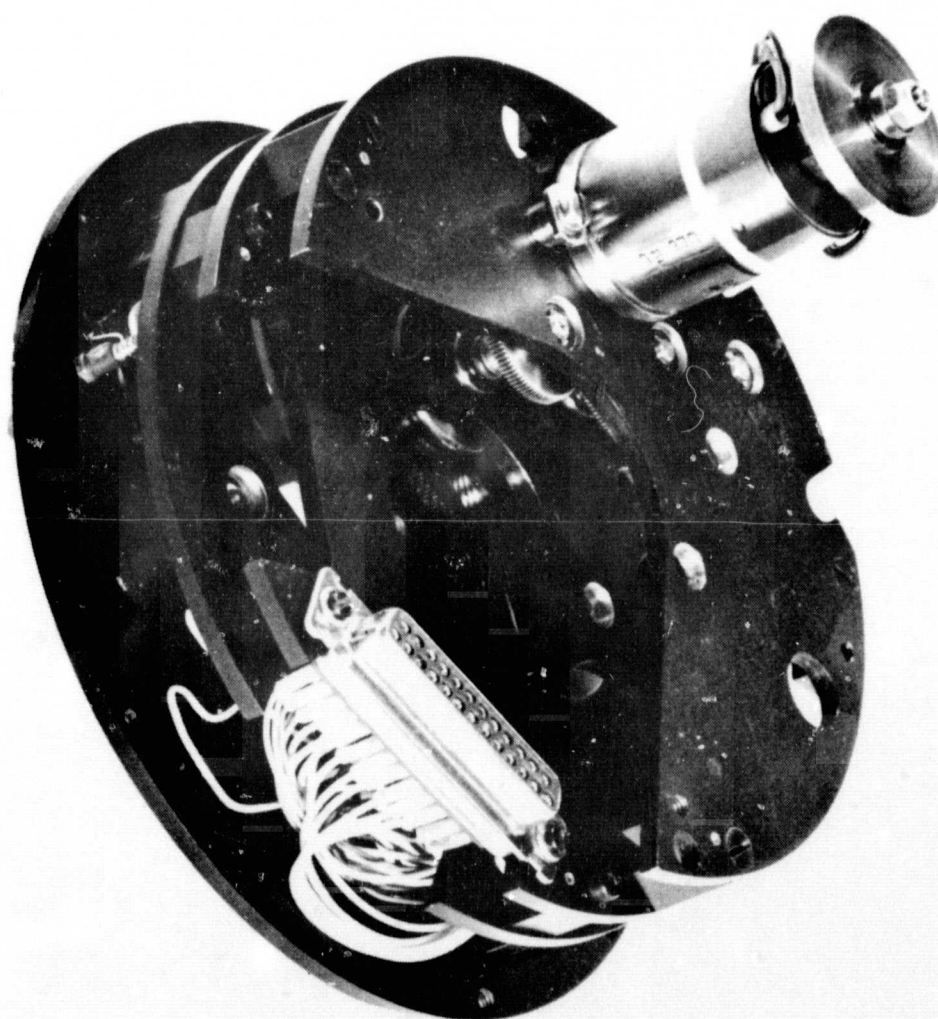


Figure 10. Photograph Showing Gearing Assembly

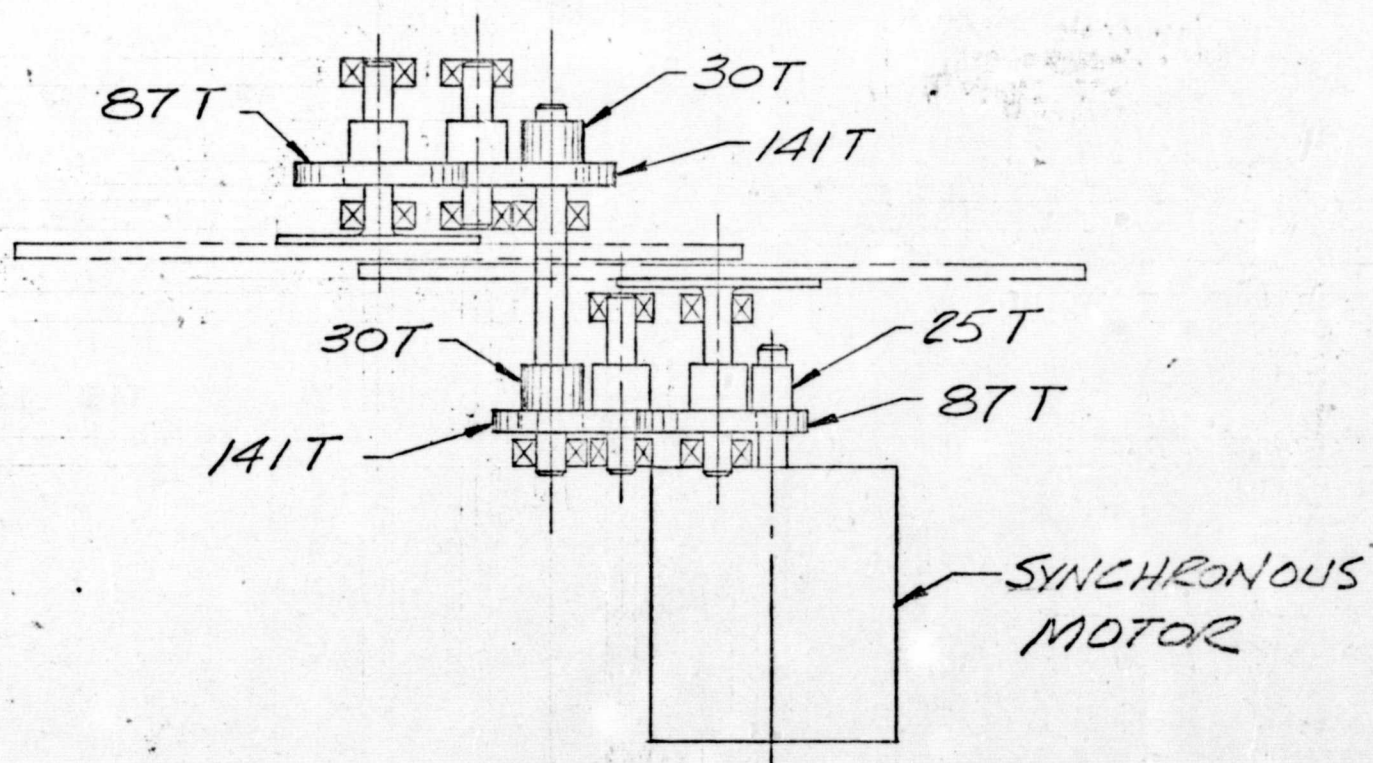
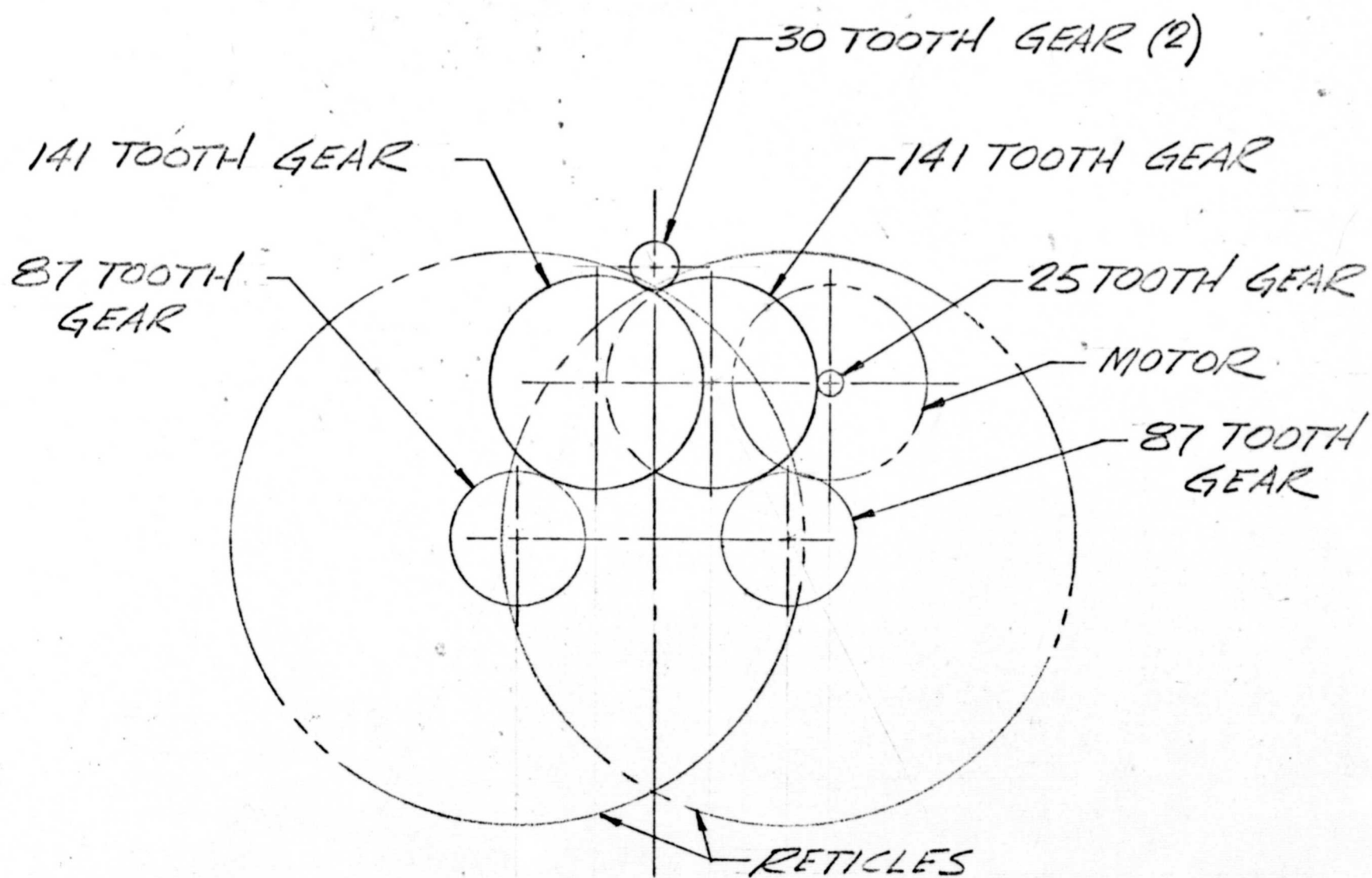


FIGURE 11.

RETICLE DRIVE GEARING ARRANGEMENT

The printed circuit board assembly consists of six PC boards, an upper mounting plate, and a baseplate upon which is mounted the PM tube and the high voltage power supply. The top or upper plate serves as the mounting interface to the reticle drive assembly and as the mounting surface for the reflective cone. The reflective cone, when threaded into this plate, secures the PM tube by clamping it against the baseplate.

The top plate, the baseplate and the PC boards are assembled with hollow spacers and through bolts; see Figure 12 for details. Dams, fabricated of fiberglass, are glued to the baseplate for potting of the high voltage circuit.

High Voltage Supply Encapsulation

The HV supply, capacitors C1 and C2, and resistor R1 (See schematic diagram, Appendix I) are encapsulated to prevent corona problems at low pressures. The supply and the components are enclosed in the fiberglass potting dam. The components were cleaned with methyl alcohol preparatory to encapsulation. After cleaning, the inside of the form, the supply, and the components were coated with Sylgard 1332 barrier coat; this was degassed in a vacuum, air dried for 30 minutes, and baked at 150°F for 4 hours. Next, a primer coat of Sylgard primer was applied, the assembly was again degassed, air dried for 30 minutes, and baked at 150°F for one hour. The encapsulant, Sylgard 184, was mixed and degassed. The mixture was carefully poured into the dam and again degassed, being "bumped" several times during this process. It was then air dried for 24 hours and baked for 4 hours at 150°F.

The under side of the base plate, around the terminals, was encapsulated in a similar manner at a different time.

Conformal Coating

The six PC boards were conformal coated with a 50/50 (weight) mixture of Thiokal Solithane 113 and drier. The boards were painted on both sides with this mixture and baked for 10 hours at 150°F and air dried for 48 hours.

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through Creative Engineering

W T A

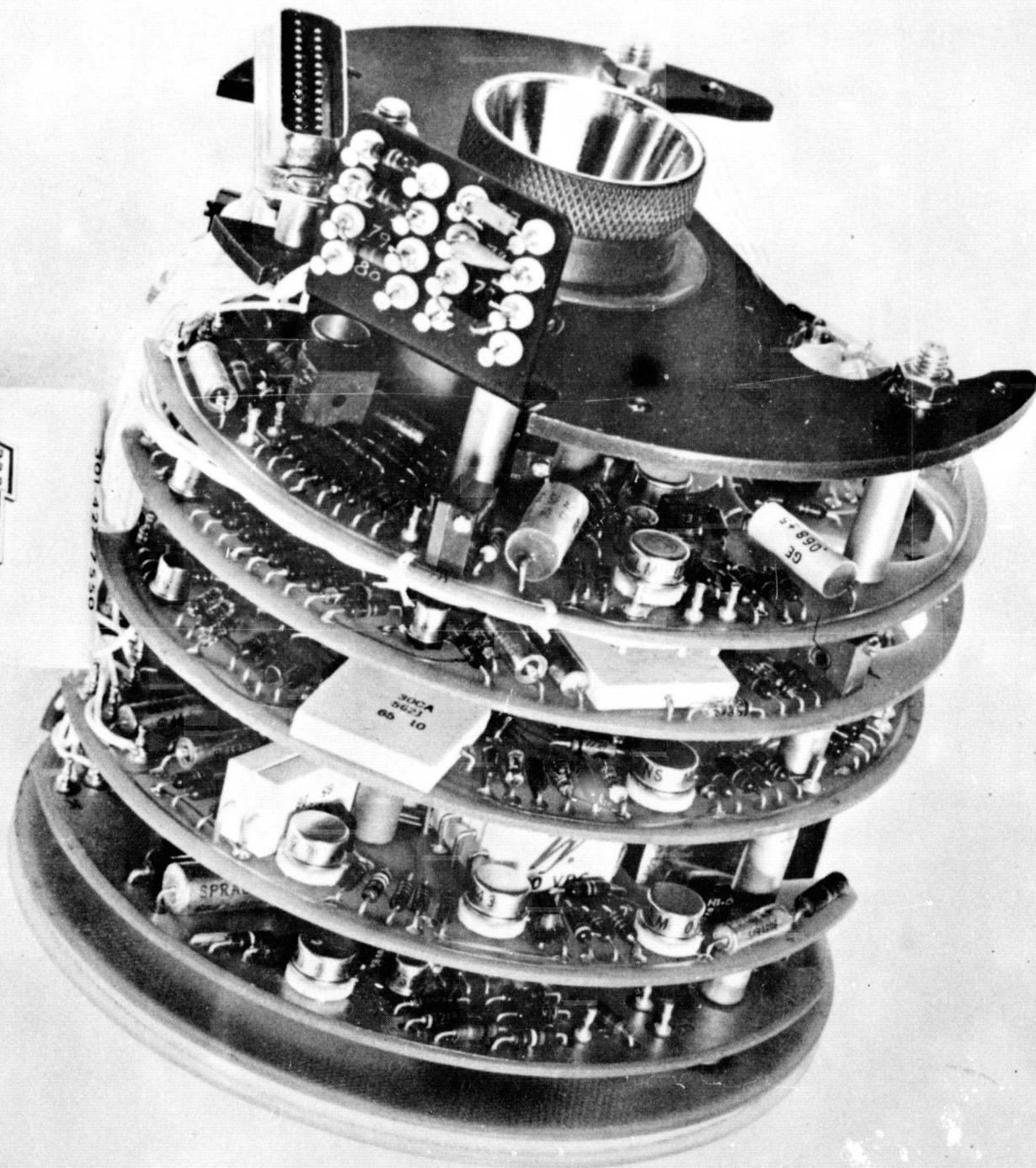


Figure 12. Electronic Assembly

DETAILED CIRCUIT DESCRIPTION

The schematic diagram showing the electrical wiring of the startracker is shown on drawing number GE1066676, Appendix I. The discussion in this section is keyed to this drawing.

Preamplifier and PM Tube Circuit

The PM tube is connected as shown so that the sensitive photocathode is subjected to a minimum of ion bombardment by keeping it at the same potential as the frame of the startracker. The signal is generated across R1, the PM tube load resistor and is coupled into the preamplifier through capacitors C1 and C2, .002 mfd., 6000V units. This coupling arrangement, assisted by R1, isolates the preamplifier from the high voltage and provides common mode rejection of the power supply ripple. R2 is required to equalize the resistive path from the plus side of the HV supply to FET's (Field Effect Transistors) Q1 and Q2. Diodes CR1 through CR4 protect Q1 and Q2 from transients generated when the high voltage supply is turned on or off. FET's Q1 and Q2 provide an impedance transformation between the 500k load resistor and the 10K input impedance of LM1. An attempt was made to keep the impedances in this section as low as possible to reduce stray noise pick-up. Also, the leads from the PM tube load resistor to the preamplifier are twisted together, shielded, and glued to the base plate to reduce microphonic effects generated when these leads are vibrated.

AGC and Bandpass Amplifier

The low impedance output of the preamplifier drives the AGC amplifier. The signal is connected to the gate of Q4 through R14, C9, and C10. As the signal gets larger, the voltage across R17 is amplified by the AC coupled amplifier, LM2, and again by the DC coupled amplifier, LM3. The signal is rectified by the network formed by CR5, R23, R19 and C16. As the magnitude of the signal into Q4 increases, the magnitude of the voltage across C16 becomes increasingly negative. As this negative bias increases, Q4 is further biased off causing its source DC voltage to increase; this increasing source voltage is connected to the gate of Q3 causing it to be biased on slightly. When Q3 is biased on, it acts as a shunt resistor, causing some of the signal power to be shunted through it instead of into Q4. This causes the negative DC level on the gate of Q4 to decrease, establishing the constant gain condition of the amplifier. Q3 is biased into the resistive range by shorting C16 and adjusting R16 to give maximum signal without distortion at R17 (R16 ranges from 1K to 25K). The output voltage amplitude is adjusted by R24 which ranges in value from 10K to 100K; it is adjusted by monitoring the voltage output at the junction of C29 and R46, or output pin D, setting this level to about 4 to 20 volts peak-to-peak at 4kHz. Care should be exercised to keep R24 as close as possible to 20K/40K to keep the AGC amplifier stable.

The dynamic range of this circuit is about 70 db when properly adjusted.

The constant amplitude signal voltage is AC coupled through C15 to LM4, the first stage of the bandpass amplifier.

Stage 1 of the bandpass amplifier is tuned to 2990 Hz, with a Q of 3.57 and a gain of 4. Stage 2 is tuned to 3830 Hz, with a Q of 1.57 and a gain of 4. The gain and Q of stage 3 are 4 and 3.57, respectively, tuned to 4900 Hz. Each stage of the circuit is a standard multiple feedback filter/amplifier. If the components listed in the parts list are used, no adjustment is required for either gain or frequency response. The bandpass shifts no more than 5% over temperature excursions from - 20° to + 60° Centigrade.

Note that the 15-volt bus is filtered by RC networks and each separate circuit is fed by an independently filtered power line, as are all other circuits.

The AGC and bandpass amplifiers are mounted on one printed circuit board.

Limiter and One-Shot

The band-limited signal from the bandpass amplifier drives the limiter stage, LM7. The gain of this stage is greater than 60 db and when driven by an 8 to 20 volt peak-to-peak input, is completely saturated in either direction. The square wave output is differentiated by C31 and R50 and R52. The negative going spike through CR6 turns off Q5 of the trigger one-shot and when Q5 goes off, Q6 turns on through R54 and R53. This negative going edge is differentiated by C34 and R59. After about 3 microseconds, the one-shot resets to the state where Q5 is on and Q6 is off. Note that the negative-going pulse from the limiter causes a negative-going pulse out of the trigger one-shot with only a very small delay between the negative edges. The negative-going pulse at R59 is coupled into the information one-shot.

The information one-shot is a very critical circuit in that any small changes in its on-time can cause a significant shift in the null of the tracker. The circuit is temperature compensated and buffered against power supply variations.

The circuit operates in the following manner. If no trigger pulse occurs at the cathode of CR16, the circuit will settle to its off condition. In this condition, pin 6 of LM8 is at a potential of about 12 to 14 volts. This voltage is dropped to 6 volts by the limiting action of CR13 and CR14. This positive voltage is fed back through R65 and R66/CR12 to pin 2, the inverting input of LM8. Pin 3, the non-inverting input, is also positive -- more positive than pin 2 since the voltage at pin 2 is divided by R66/CR12 and R58/CR11 to about 1/2 the voltage at CR13/CR14 while the voltage at pin 3 is never any less than 51/63 times the voltage at CR13/CR14. Since pin 3 is more positive than pin 2, the output is held at the positive level and the loop is complete. If a negative-going trigger pulse is applied to the cathode of CR10, the pin 3 will be more negative than pin 2 and the output, pin 6, will go negative. The amplitude of the trigger voltage must

be $V_1 > V_3 - V_2$ to initiate the on cycle. Note that just before the one-shot changed state, C35 was charged to a positive voltage, V_2 . When pin 6 goes negative, pin 2 is held positive by C35 while pin 3 goes negative. C35 discharges through R65 until $V_2 = V_3$, when the circuit returns to its initial state. The negative pulse is accurately timed by R65 and C35, both low temperature drift components. The magnitude of V_3 can be varied slightly by R62 to vary the negative pulse duration. R66, CR12, CR11 and R58 serve several purposes. First of all, CR11 assures that V_2 is smaller than V_3 when the circuit is in the off condition; however, due to the temperature drift of CR11, the initial voltage on C35 varies, causing pulse width instability. Adding R58, R66, and CR12 forms a divider network that still allows the circuit to work, but due to the divider action, renders the voltage on C35 practically independent of the temperature drifts of CR11 since as the voltage across CR11 gets smaller, so does the voltage across CR12 -- and one cancels the other. Also, and just as important, R66 and CR12, in the off state, cause C35 to charge very rapidly so that the negative pulse width is unaffected by high duty cycles. (Recall from Figure 3 that the negative pulse width is longer than the positive pulse width in some cases.)

CR13 and CR14 are used to insure that the discharge of C35 during the on time is always between a potential of ground and the stable voltage at the cathode of CR13 even though the voltage at pin 6 may vary due to power supply variations; this insures that the discharge time is very stable. The type of diode used for CR13 and CR14 was chosen so that the positive drift of the Zener voltage of one is cancelled by the negative drift of the forward voltage of the other; no matching of these two diodes is required. CR11 and CR12 were selected for identical forward voltages so that the temperature drifts are equal and therefore cancel. These two diodes, along with the four similar ones in the gate one-shot are the only selected components in the unit.

The pulse train from the one-shot is therefore amplitude and period stabilized to about ± 2 or 3 seconds of arc equivalent over a temperature change of -15°C to 65°C and is virtually insensitive to power supply variations of $\pm 5\%$.

Discriminator Circuit

The one-shot pulse train is connected to the X- and Y- channel gate FET's and then to the X and Y discriminator. Q18, the X gate, either blocks the pulse train or passes it to the discriminator according to the polarity of the gate pulse on the cathode of CR41. If the cathode is at -12 volts, the FET is biased off and no signal gets through to the drain and then into the discriminator. If the cathode of CR41 is at a plus voltage, say $+15$ volts, the FET is on and the pulses are gated through to the discriminator.

R102 is the gain trimming resistor for the X channel; its nominal value is about 2K.

The discriminator extracts the DC average value from the polar pulse train input in the following manner. (Refer to Figure 13.) The voltage at the junction of R122 and R121, labeled V_{R122} , is applied to the inverting input of LM11, pin 2. The same voltage

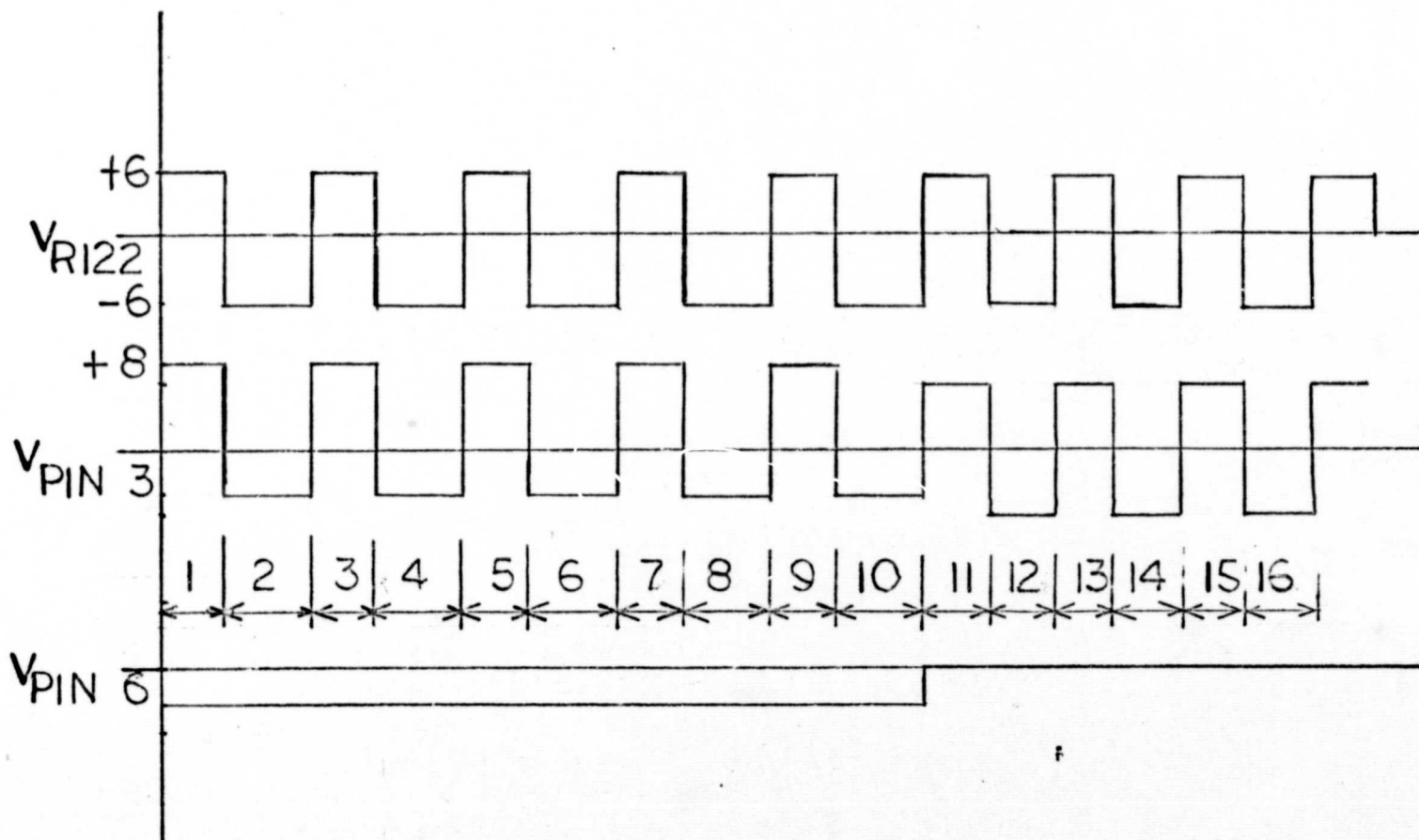


FIGURE 13. VOLTAGE WAVEFORMS-DISCRIMINATOR

is applied to one side of C46; the other side of C46 is connected to pin 3 and to R125. The voltage at pin 3 is shown as $V_{\text{pin 3}}$. Note that the voltage has settled to a zero DC average about the voltage baseline. The voltage at pin 6 is given by the equation

$$V_6 = - (V_3 - V_{R122}) \frac{R121}{R12T} = - (V_3 - V_{R122}) K.$$

where K is a constant, representing the DC gain of the discriminator amplifier. The voltage at pin 6 for the period labeled 1 is therefore

$$V_6 = - (8 - 6) K = - 2K.$$

The voltage at the same point during period 2 is

$$V_6 = - (-4 - (-6)) K = - 2K.$$

The same condition exists until period 11 when the average value of the pulse train becomes 0. In this interval, $V_6 = (6 - 6) = 0$. The discriminator output goes positive when the DC average value is positive and the analysis is identical to the one just presented.

From a practical standpoint, the voltage at pin 6 is always either increasing from ground to plus and back to ground or from ground to minus and then back to ground. The wave forms are not smooth but have spikes riding on them due to the unequal frequency response of the plus and minus inputs.

The time constant of R125 and C46 determines the response of the circuit while R124 and R121 determine (partially) the gain of the stage. R122 is used to balance the circuit so that the amplitude of a symmetrical input causes 0 volt output. R152 is used to null out the DC offset of the discriminator, the low pass filter, and the inverter to 0 volts with a symmetrical wave in and the wiper of R169 grounded.

The Y-channel discriminator is identical to the X-channel discriminator.

Low Pass Filter and Inverter

The low pass filter, made up of LM12 for the X channel and LM14 for the Y channel, smoothes the output of the discriminator to a steady signal. These filters are multiple feedback, low pass filters with a response from DC to 4.86Hz, the 3 db point. The phase shift at 1Hz is 15°.

The null adjustment, for boresight alignment, is controlled by R169 for the X channel and R170 for the Y channel. These resistors are mounted on the top plate assembly and are accessible from the outside of the housing. The wiper of R169 is connected to R166 which, in turn, is connected to pin 3 of LM12. The ends of R169 are

connected to CR46 and CR47 through R129 and R130. The two diodes provide a stable voltage to shift the offset of LM12. This causes a shift in the null point of LM12 and LM15, effectively shifting the boresight null.

C66 and C67 are bypass capacitors that keep pin 3 of the two filters at AC ground, eliminating pick-up from the long leads on R169 and R170.

The output of LM12 drives the inverter, LM15, and also is connected to pin A_x . The output of the inverter, LM15, is connected to pin B_x . The polarity of the error signal is selected by connecting C_x to either A_x or B_x , but not both. Point C_x is connected to the output of the tracker through R149. CR50 and CR51 limit the magnitude of the error signal in both directions. The X- error signal and a ground is carried to the output connector.

The Y channel is implemented in a similar manner.

Gate Pulse Generator

The gate pulse circuitry generates gate pulses that are properly synchronized and are of the proper time duration. The circuitry for this circuit is mounted on PC 483 except for the pulse amplifiers which are mounted on PC 437A.

The operation of the X- channel pulse generator is explained in the following paragraphs; the Y- channel gate pulse generator operates in an identical manner.

The photo-transistor Q13 is turned off when the shutter moves between it and the light source. When Q13 is not conducting, there is no base drive for Q15, which is therefore biased off through R106 which is connected to - 15 volts. The collector of Q15 rises to 15 volts for the period of time when the shutter is closed. This pulse is the basic timing pulse to gate the X channel on. Since the length of this pulse is somewhat unsteady, and since it is only indirectly related to the pulse train from the information one-shot, it is not used directly to gate the X channel. Instead, this pulse is used as one input to an and gate, on PC 483, formed by CR71, CR72, and Q23.

The other input to this and gate is a differentiated pulse train from the information one-shot. This pulse train enters the board at pin H and drives Q24, an emitter follower, through R207. Diode CR76 clamps the base to a potential greater than 0, thereby clamping the emitter at the same point. The emitter of Q24 drives the differentiating network C78/R213 which puts a 0-volt pulse on the cathode of CR72. The coincidence of these two high pulses causes the emitter of Q23 to rise, triggering the one-shot; LM17, through CR70. This one-shot is identical to the information one-shot except that its off state is negative and its on state is positive. When LM17 is positive, a positive voltage level through CR67 and R189 sets the gate flip-flop, Q20 and Q21. This high level also turns on Q22, pulling the cathode of CR73 to - 14 volts. When LM17 goes negative, Q22 is turned off, the set level is removed from the base of Q21, and the next positive-going

information pulse, generated by C76/R205, resets the X- gate flip-flop. The output of the flip-flop is taken from the collector of Q20 to pin D of PC 483.

The timing for this circuit is shown in Figures 5 and 6.

Star Magnitude Detector Circuit

The star magnitude detector (SMD) circuit measures the amplitude of the PM tube output and generates a star-present signal if it exceeds a certain amplitude.

The circuitry for the SMD is mounted on two boards, PC 437A and PC 513.

The output of the preamplifier, pin H of PC 435A, is connected to the input of the SMD bandpass filter, pin D of PC 513. This filter is identical to the bandpass filter used in the error circuitry except that the voltage gain is 1.75 and the bandwidth is somewhat less, $3830 \pm 900\text{Hz}$. The center section is tuned to 3830Hz, the first section is tuned to 3050Hz, and the end section is tuned to 4610Hz. It was necessary to add this filter section because the preamplifier circuit has a low frequency response down to 100Hz, adding a large amount of noise to the star magnitude circuit.

The output of the filter, at pin E of PC 513, is connected to pin G of PC 437A, the input of the SMD variable gain amplifier, LM9. The gain of this amplifier is selected by one of the four FET's, Q7, Q8, Q9 or Q10, each of which selects one of the four feedback resistors, R77, R78, R79 or R80. The output of LM9, pin 6, drives two rectifier circuits: the rectifier made up of R73, CR15, etc. provides to telemetry a DC level that is representative of the magnitude of the star in the field of view and an identical circuit, R76, CR30, etc. provides the same DC level to pin 3 of LM10, a level sensor. The rectifier circuit has a time delay to hold off the star-present signal until the error channels have adequate time to generate a legitimate error signal; this time delay is caused by the time constant of R76 and C41. The discharge time constant is controlled by R73 and C41. Diode CR30 is the rectifier. CR31 is used to balance the thermal shift of CR30, the net effect of the variation of V_f with temperature of the diodes being zero. Also, these diodes, CR15, CR16, CR30, and CR31 are germanium, selected for their low forward voltage.

As the level at pin 3 of LM10 increases above the voltage at pin 2, the output at pin 6 of LM10 goes positive -- this is the star present signal. This signal is either 5 volts or - 0.6 volts at pin N of PC 437A, limited by CR32, a Zenor diode, and R89. R90, the feedback resistor, causes the level sensor to have some hysteresis, about 200 mv, to prevent erratic operation of the SMD. The reference voltage at pin 2 of LM10 is derived from R82, R83 and CR33/CR34. The two back-to-back Zenor diodes provide a temperature stable reference due to the cancelling action of their forward and reverse temperature coefficients.

The gain select circuitry, also mounted on PC 437A, is commanded by inputs at pins O and P. The command, A on pin P and B on pin O, is either 0 volts or 26 volts. The selection of the four FETs is in accordance with the following sequence:

<u>A (Pin P)</u>	<u>B (Pin O)</u>	<u>FET selected</u>
0 volts	0 volts	Q10
0 volts	26 volts	Q9
26 volts	0 volts	Q8
26 volts	26 volts	Q7

The circuit operation for each of the FET's is very similar; the selection of Q8 is representative. If Q8 is to be selected, there is 0 volts on pin O and 26 volts on pin P. The 0 volts on pin O is translated to - 14 volts at the anode of CR 38 causing Q12 to turn off since its emitter is - 12 volts. The collector of Q12 is pulled toward 26 volts through R94 which is connected to the filtered + 26 volt input on pin Q. The 26 volts on pin P forward biases the base of Q11 through CR39 and R99. The collector of Q11 is at - 11 volts since its emitter is at - 12 volts through the action of CR36 and R92, which is returned to - 15 volts. The collector of Q12, being at 26 volts, raises the cathodes of CR19 and CR23 to this voltage. Also, the + 26 volt level on pin P raises the cathode of CR23 and CR25 to this same voltage. Since the anode of CR23 and CR24 are free to rise to a positive voltage, R85 pulls them to 26 volts. When this happens, CR28 is reverse biased and the gate of Q8 is free to float; under these conditions, Q8 conducts. Note that the gates of Q7, Q9 and Q10 are held at - 11 volts either by the collector of Q11 or by the negative voltage at the anode of CR38.

With Q8 selected, and therefore conducting, R78 is the feedback resistor for the SMD amplifier, LM9. The gain is therefore approximately $R78/1000$.

ALIGNMENT PROCEDURE

Required Equipment

The alignment procedure is straightforward, requiring only standard laboratory equipment. The required equipment is:

- Oscilloscope, Tektronix type 564 or equivalent and a 4-channel plug-in, such as a type 3A74
- Signal generator, 2000 to 5000 Hz range
- Counter, 2000 to 5000 Hz range
- VOM, calibrated to at least 1%
- DVM with a three-digit readout
- Clip leads, as required
- Three power supplies: two 15-volt, 200 ma; and one 28-volt, 500 ma
- Static inverter, 400 Hz, 2 phase, 270 ma per phase .01% stability

Preliminary Steps

The alignment is to be accomplished prior to potting or encapsulation.

Disconnect or somehow prevent the HV power supply from being turned on. Connect + 15 volts to the indicated terminals (see schematic). Connect the signal generator to pins $\bar{C}$ and D of PC 435A and set the frequency to 3833Hz, using the counter to assist this setting. Temporarily connect 2K resistor into the circuit at R102 and R108.

AGC Amplifier Adjustment

There are two AGC amplifiers adjustments, the bias and the output level adjustments. The bias adjustment is done first.

Ground the minus side of C16, located on PC 436A and replace R16 with a variable resistor (start at about 25K). Monitor the output of Q4 at its drain terminal and adjust the variable resistor downward until a maximum voltage or a plateau occurs. Pick the next smaller, standard 5% resistor and solder it in place of the variable resistor.

Insert a variable resistor in place of R24 (start at 100K) and remove the ground from C16. Monitor the voltage at the output of LM2, pin 6, and adjust this variable resistor downward until the voltage is about 1/2 to 1 volt peak-to-peak. Then solder a standard 5% resistor in place of the variable resistor; this resistor is selected in the same manner as was R16.

Vary the amplitude of the signal generator from 0 to about 1/2 volt peak-to-peak. The output of LM2 at pin 6 should vary only about 2 or 3 to 1.

Information One-Shot Adjustment

Using the test set-up described in the previous paragraph, set the amplitude of the signal generator to about 1/4 volt. Verify that the frequency is still at 3833Hz. Connect the DVM to the cathode of CR13, located on PC 437A, set the DVM to the DC range, and adjust R62 until 0 volts is read.

Again vary the amplitude of the signal generator; the DVM should read 0 volts $\pm$ 2mv over the full frequency range. The wave shape should approximate a symmetrical square wave with a fundamental frequency of 3833Hz at pin 6 of IM8. (The symmetry of the wave about 0 volts and the symmetry about the vertical may not be exact, but should be within 10% of symmetry.)

This alignment establishes the electrical null of the startracker.

Discriminator Adjustment

There are two adjustments for each discriminator -- the balance and the offset adjustment.

Connect the 400Hz to the proper terminals (see schematic). Trigger the scope on pin S or T of PC 437A; these points are the outputs of the gate pulse amplifiers. CAUTION: DO NOT SHORT THESE POINTS TO GROUND. Monitor test point 1, the output of the X discriminator. With a 3833Hz input to the preamplifier, adjust the balance potentiometer, R122, for an amplitude null. Ground the wiper of R169 at pin L of PC 438A. Monitor the output of the low pass filter, LM12 at point A_x, adjusting R154 until 0 volts is read. Repeat these procedures for the Y channel. The wiper of R170, which is connected to pin P of PC 438A, is grounded. The balance adjustment is accomplished with R155.

Channel Polarization

At this point it is necessary to polarize the tracker. This is most easily done by turning the tracker on in a dark room and moving the tracker in the + X direction noting the direction of the signal at A_x. The same procedure is repeated for the Y channel noting the polarity of the signal at A_y. If either or both are correct, jumper the A terminal to the C terminal; if not, jumper the A terminal to the B terminal to the C terminal. If the C terminal is jumpered to the B terminal on either channel, it is necessary to repeat the offset adjustment.

High Voltage Adjustment

In a Dark Room, connect + 26 volts to the high voltage supply, pin 17 on the output connector or pin 17 on the interbody connector, using a suitable meter or high voltage scope probe. Measure the voltage at the output of the HV supply. (A 100/1 probe is very

convenient for this adjustment since it is not a precision adjustment.) Adjust the voltage to 2500 volts by using the potentiometer on the top of the HV supply case. Since the supply used on the tracker has a range of about 2000 to 2800 volts, this adjustment can be performed before or after the alignment and polarization procedure. The results of these procedures are unaffected by the HV level -- only the sensitivity and the SMD are affected.

Gain Adjustment

The gain adjustment must be accomplished with an operating tracker and a star source. The tracker must be solidly mounted on a table that can be rotated. Null the tracker in the X direction by mechanically adjusting it until 0 volts is read at the output with the DVM. Pin L of PC 438A should be grounded. Move the tracker to the extremes of the proportional region, noting the output voltage at either extreme. The total swing should be about 7.2 volts $\pm$ 10%; if it is not within this region, adjust R230 on PC 483 until it is obtained. If the adjustment cannot be made with R230, make R102 either larger or smaller to decrease or increase the gain as required. Repeat for the Y channel, adjusting R231 or changing R108. (R102 and R108 are mounted on PC 437A.)

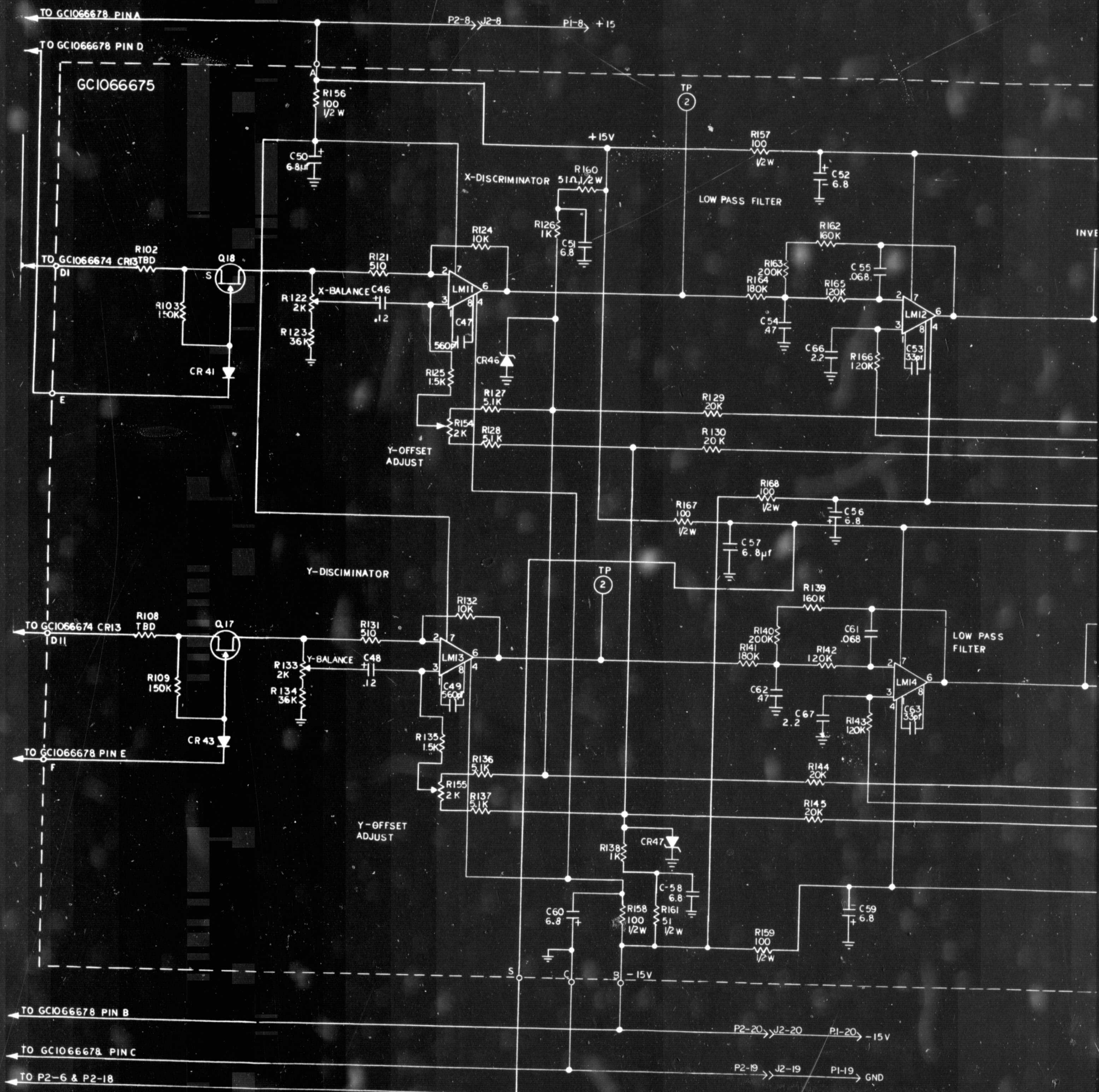
After the gain is properly adjusted, solder R102 and R108 permanently in place.

Star Magnitude Detector Adjustment

Solder leads in place of R77, R78, R79 and R80 on the SMD resistor gain trimming block and connect them to four variable resistor boxes. Select the proper resistor values by placing + 26 volts on the appropriate gain terminals (see Appendix II) and adjust RXX until the star-present signal appears when the star of the selected magnitude is present but disappears when a star 1/2 magnitude dimmer is present. Do this for all four resistors. Note that in the absence of any gain command, R80 is selected.

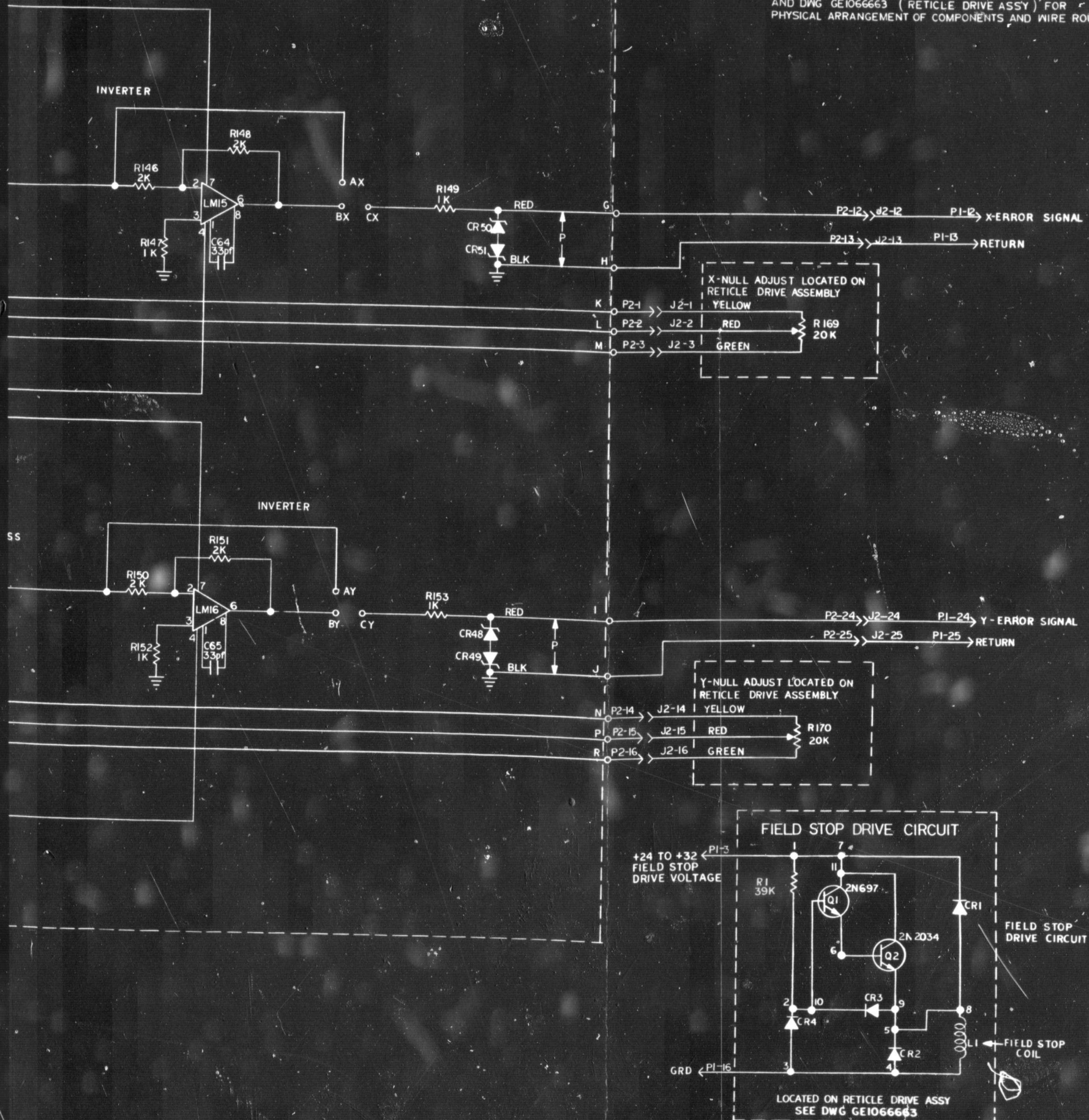
APPENDIX I

Schematic Diagram, Drawing GE 1066676

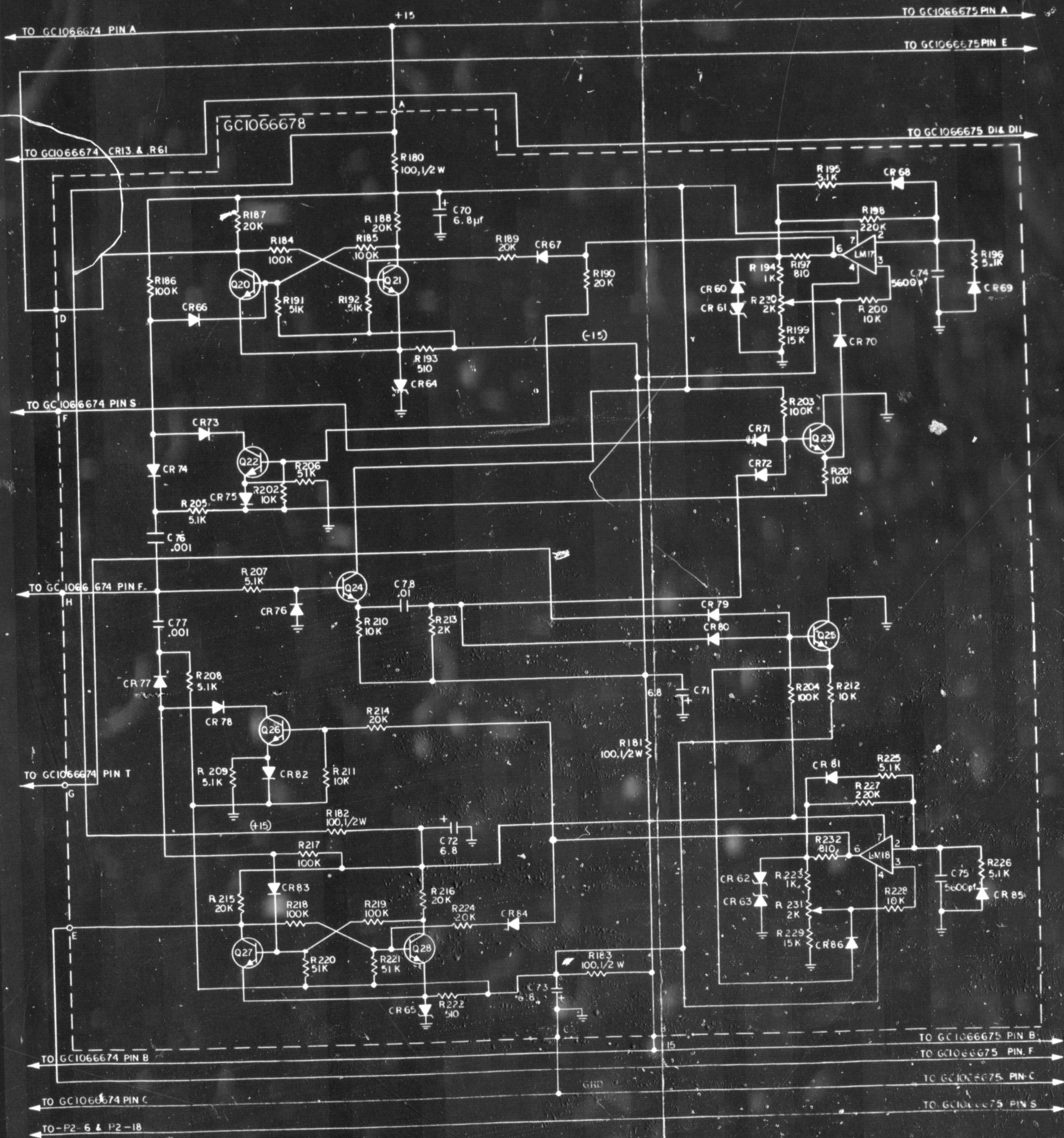


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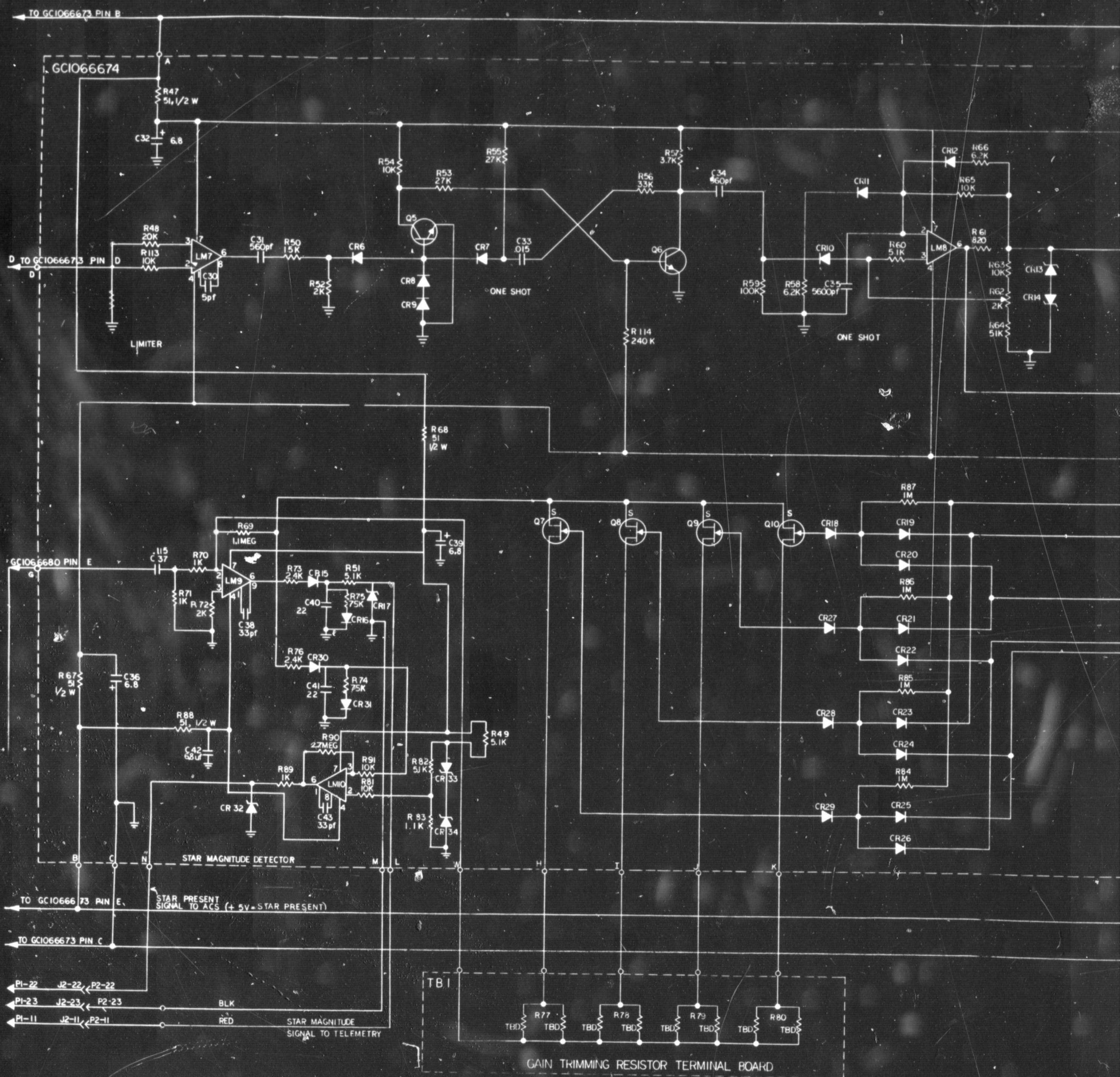
- NOTES:
1. UNLESS OTHERWISE SPECIFIED, RESISTANCE VALUES ARE IN OHMS, CAPACITANCE VALUES ARE IN MICROFARADS.
 2. SEE DWG. GE1066650 (PRINTED CIRCUIT ASSY) AND DWG. GE1066663 (RETICLE DRIVE ASSY) FOR PHYSICAL ARRANGEMENT OF COMPONENTS AND WIRE ROUTING



APPENDIX I
Schematic Diagram, Drawing GC1066676



APPENDIX I
Schematic Diagram, Drawing GC1066676
I-2







APPENDIX I
Schematic Diagram, Drawing GC1066676

APPENDIX II

Pin Designations for J1 Connector

<u>Pin No.</u>	<u>Signal Nomenclature</u>
1	400 cps, Phase 1
2	400 cps, Phase 1 common
3	Field Stop Drive
4	No Connection (N/C)
5	N/C (an output from SMD filter is temporarily on the pin)
6	N/C
7	+ 28V unregulated
8	+ 15 VDC 1% regulated
9	Gain command A
10	Gain command B
11	Star present signal
12	X error signal
13	X error return
14	400 cps Phase 2
15	400 cps Phase 2 common
16	Field stop return
17	+ 26 VDC reg. HV supply source
18	Frame ground
19	Power supply ground
20	- 15V unregulated
21	N/C
22	SMD Analog Signal
23	SMD Analog Return
24	Y error signal
25	Y error signal return