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**Final Report** F-A2435-01

# DEVELOPMENT OF A SKYSCREEN COMPUTER

*by*

Anthony Marmarou
Richard H Field
Charles A Belsterling

June 1, 1960 to July 12, 1962

*Prepared for*

**BALLISTIC RESEARCH LABORATORIES**
**U.S. Army Ordnance Proving Ground**
**Aberdeen, Maryland**

**Contract No. DA-36 034-509 ORD 3241-RD**

**THE FRANKLIN INSTITUTE**
**LABORATORIES FOR RESEARCH AND DEVELOPMENT**
**PHILADELPHIA PENNSYLVANIA**

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# DEVELOPMENT OF A SKYSCREEN COMPUTER

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## ABSTRACT

This report describes the functional requirements, development and test of a new electromechanical analog computer. Its purpose is to position blanking screens in a missile-tracking phototheodolite camera to avoid overexposure of the photographic plate. Azimuth and elevation information are continuously varying inputs from a tracking instrument. The Skyscreen Computer solves the trigonometric equations necessary to transform the spherical coordinates of the target with respect to the tracking instrument into rectilinear coordinates of the focal plane in the phototheodolite.

The Skyscreen Computer System was developed successfully using ultra-precise electromechanical devices, all solid-state electronic circuits and high-quality mechanical components. Laboratory tests show that the System positions the aperture in the camera screens with an average error of 0.4 mm and a maximum error of 1.0 mm. These results indicate an overall average accuracy of one part in 320 which approaches the reasonable limit of a complex analog system.

The Skyscreen Computer is now ready for evaluation in field use.

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LIST OF ILLUSTRATIONS

# I. INTRODUCTION

One form of missile range instrumentation utilizes two or more precision theodolites whose position and orientation are accurately known to obtain position data by triangulation methods. The Wild BC-4 phototheodolite with its shutter synchronized in time is used for this purpose. At night many exposures can be made on one plate without fogging it because of the low level of background illumination. In the daytime the situation is entirely different,and the "Skyscreen System" was developed at Ballistic Research Laboratories as an answer to the problem of taking multiple exposures in daylight. It consists of two crossed curtains which cover the photographic plate, each having a narrow slit (as in a focal plane shutter). Thus, only a small area of the plate is exposed where the two slits cross. If the curtains (Skyscreens) are then made to track the image of the missile, many separate exposures may be made without overexposing the whole plate.

The Franklin Institute was assigned the task of developing a computer and servo drives for the Skyscreens which will accept missile bearing and elevation information from a tracking instrument and position the curtains properly. A design study for the Skyscreen Computer was performed in the period June through October 1958 as Phase I of the development under Contract No. DA-36-034-509-ORD-10. The results were described in Interim Report I-A2191-1. The second phase of the work covering the detail design, fabrication, and laboratory test of a prototype system was initiated in June 1960 under Contract No. DA-36-034-509-ORD-3241-RD. The results of the entire Skyscreen Computer Development are included in this final report.

## II. EQUATIONS FOR SOLUTION

The problem of converting from relative azimuth and elevation orientation of the tracking instrument to rectangular coordinates on the photographic plate was analyzed in detail in BRL Report No. 880, "An Analytical Treatment of the Orientation of a Photogrammetric Camera" by H. H. Schmid.

Equations 44A of Report No. 880 were simplified for the purposes of the Skyscreen Computer through the following assumptions:

1. The azimuth angle of the principal axis (center line) of the camera is the zero or reference azimuth angle for the Skyscreen Computer.

2. The camera and the tracking device are both leveled and are very close together so their azimuth-elevation coordinate systems are considered to be identical in orientation and location. These assumptions permit equations 44A of BRL Report No. 880 to be simplified to the following:

$$-x = C \frac{X \cos \nu - Z \sin \nu}{X \sin \nu + Z \cos \nu} \qquad (1)$$

and

$$y = C \frac{Y}{X \sin \nu + Z \cos \nu} \qquad (2)$$

where: $\nu$ is the coelevation or zenith angle.

x and y are the rectilinear coordinates in the focal plane.

X, Y and Z are the cartesian coordinates of the target.

We now introduce a new notation as follows:

$E_p = 90^\circ - \nu$ = elevation angle of the principal point of the camera.

$E_t$ = elevation angle of the target.

$A_t$ = azimuth angle of target relative to azimuth angle of principal point of the camera.

In the spherical coordinate system of E and A the cartesian coordinates become at unit radius:

$$X = \cos E_t \cos A_t$$

$$Y = \cos E_t \sin A_t$$

$$Z = \sin E_t$$

Substituting this notation into equations (1) and (2) gives

$$-x = C \frac{\sin E_t \cos E_p - \cos E_t \sin E_p \cos A_t}{\cos E_t \cos E_p \cos A_t + \sin E_t \sin E_p} \qquad (3)$$

and

$$y = C \frac{\cos E_t \sin A_t}{\cos E_t \cos E_p \cos A_t + \sin E_t \sin E_p} \qquad (4)$$

These are the equations which are to be solved by the Skyscreen Computer.

To illustrate the significance of this notation, Figure 1 was prepared as a schematic diagram of the geometry of the Skyscreen Computer. Note that $E_p$ is the angle from the horizontal to the principal axis of the camera lens and focal plane system. Z defines the axis through the focal point of the lens system. The angle $E_t$ is the elevation of the target from the horizontal. Thus, a target above this center line will be reflected through the focal point to a distance + x which will be below the horizontal center-line of the screen. Similarly, $A_t$ defines the azimuth angle of the target relative to the center-line of the lens camera system. In this case, a positive angle of azimuth to the target is reflected as a positive deflection in y to the left of the vertical center-line of the screen.

The Skyscreen Computer is capable of continuous solution of the coordinate transformation equations through unlimited angles of travel of the input. This capability is important in order to have the screens in the proper position when the target initially comes into the field of view. Except for this the solution is useful in this application only so long as the x and y coordinates are within the limits of travel of the screens across the photographic plate (approximately 125 mm).

## III. SKYSCREEN COMPUTER DESIGN AND CONSTRUCTION

A schematic diagram of the entire Skyscreen Computer System is shown in Figure 2. The trigonometric functions are generated by a set of

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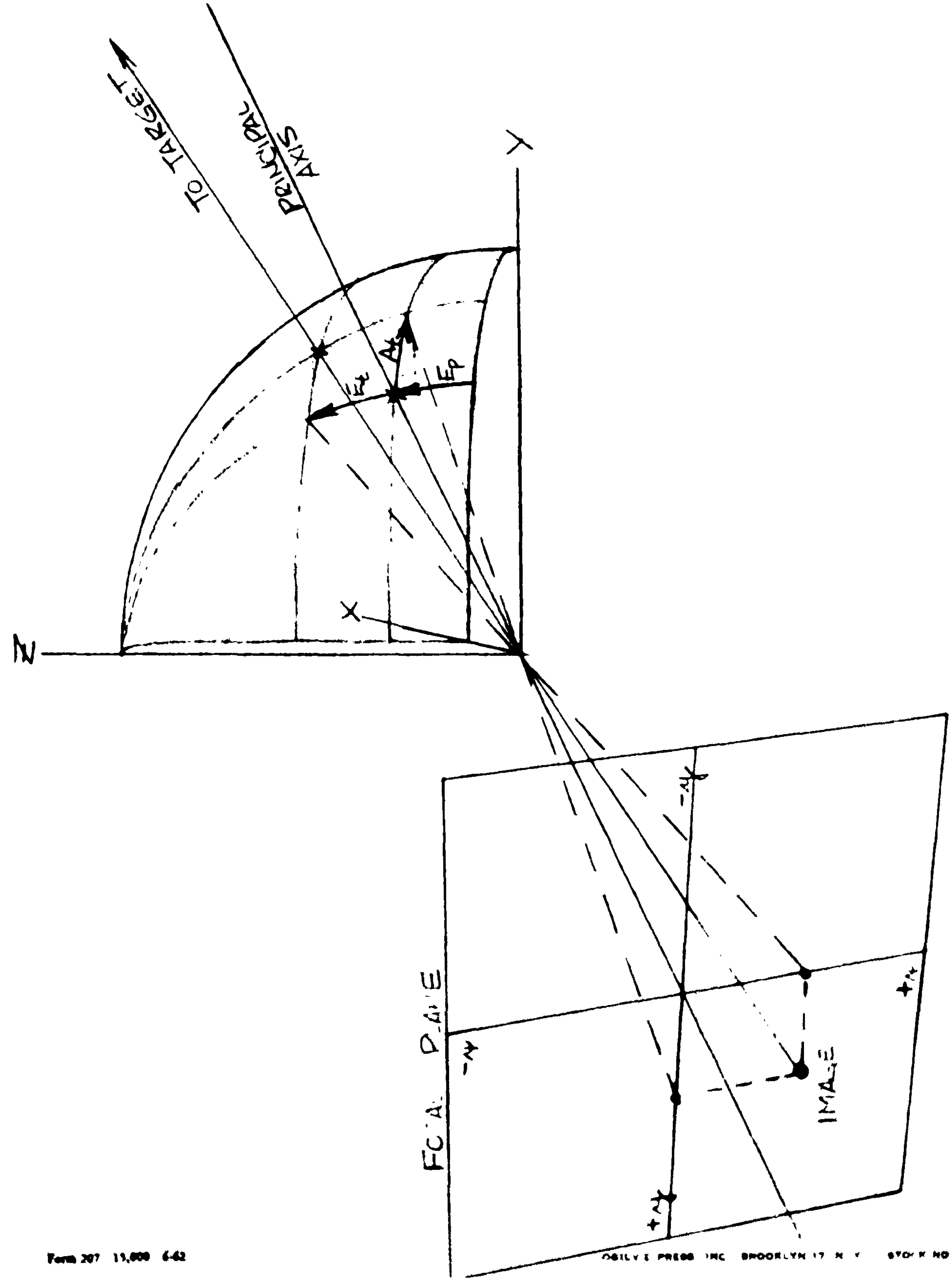
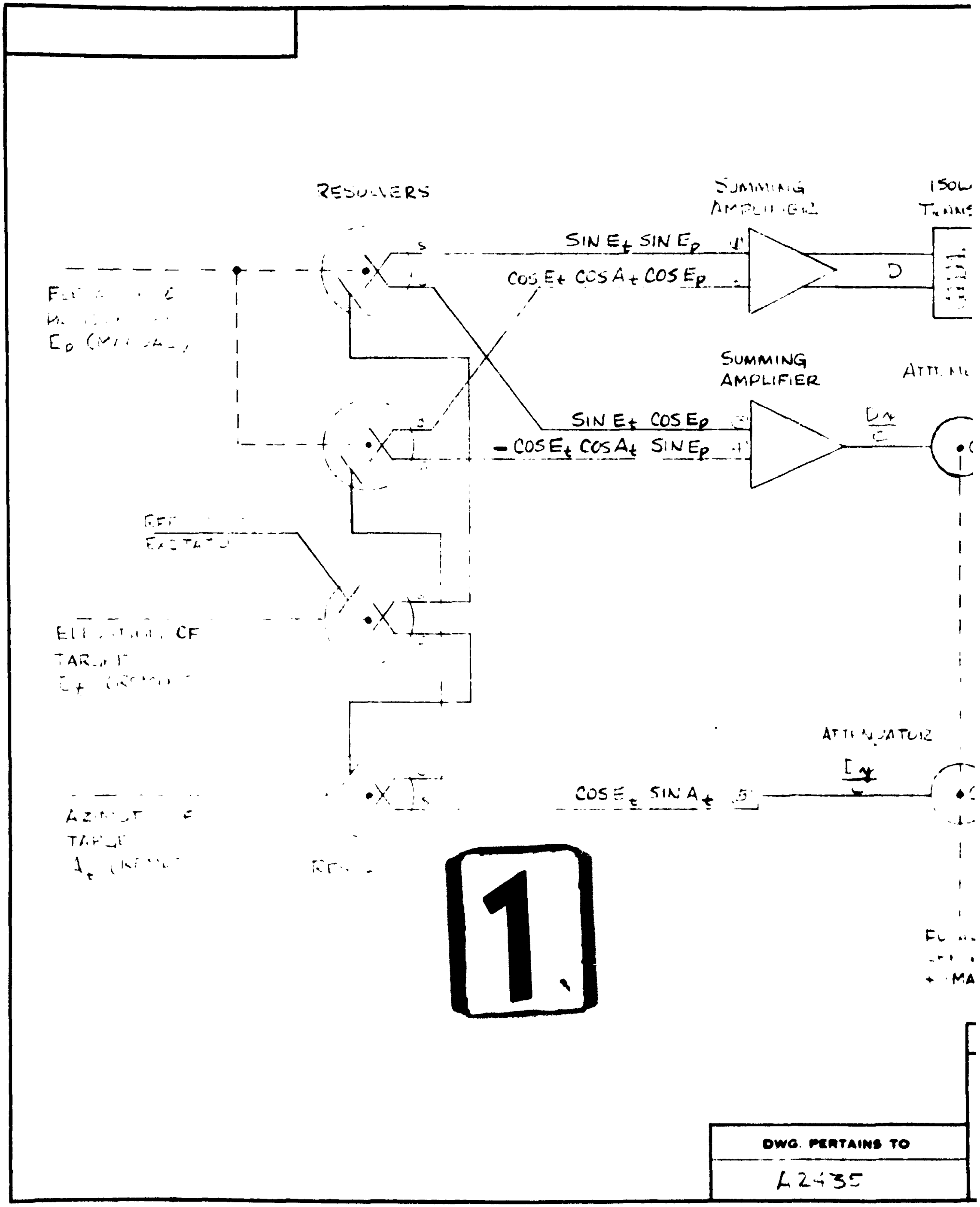
TITLE FIGURE 1- SCHEMATIC OF FOCAL PLANE (FROM REAR)

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D
SUMMING AMPLIFIER
SIN $E_t$ COS $E_p$
− COS $E_t$ COS $A_t$ SIN $E_p$
$E_p$
ATTENUATOR
COS $E_t$ SIN $A_t$
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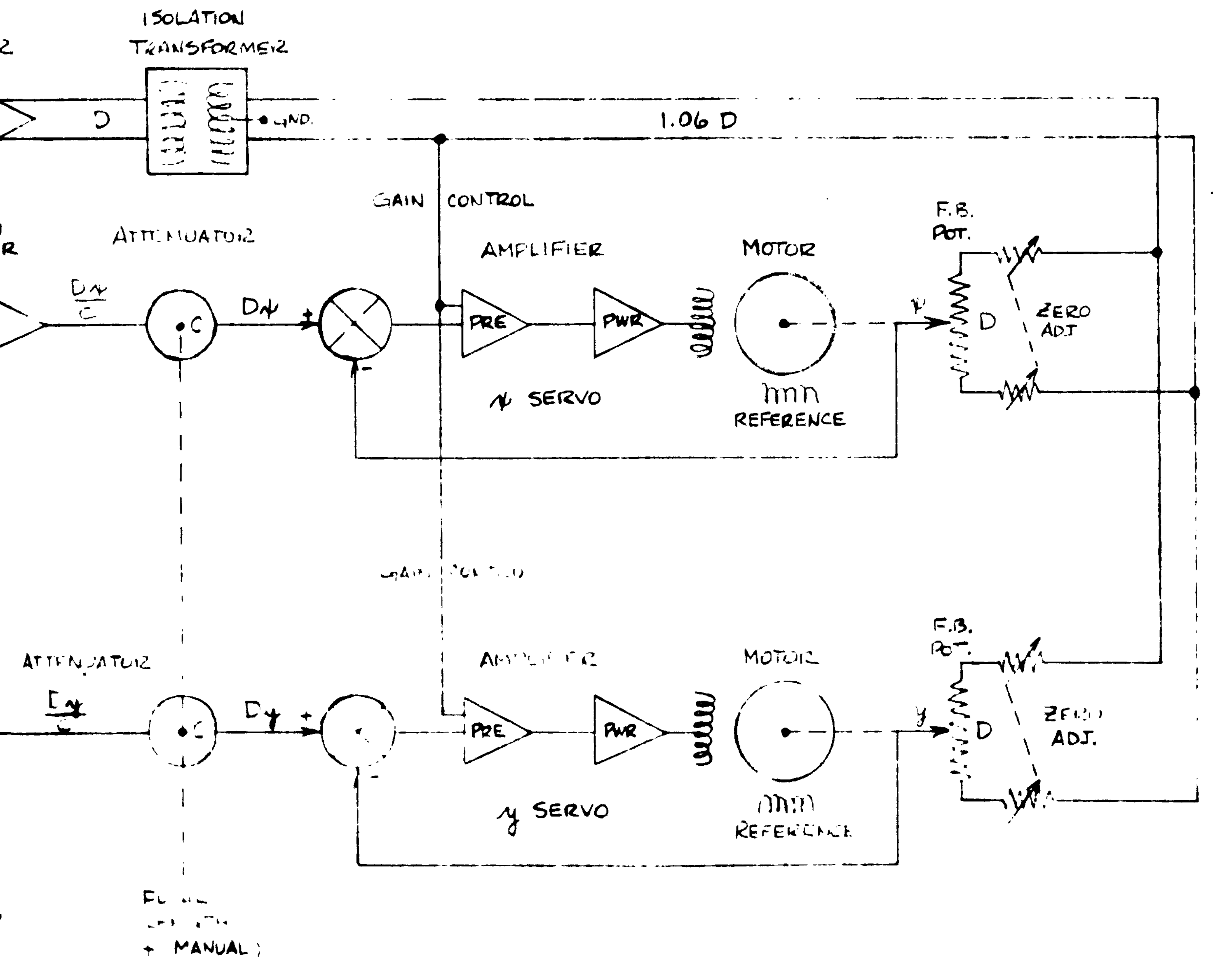


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SKYSCREEN COMPUTER SCHEMATIC

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FIGURE TWO

four precision resolvers. The angle $E_p$ is inserted into two resolvers manually. The angles $E_t$ and $A_t$ are continous rotations of resolver shafts remotely located on the tracking instrument. The $E_t$ resolver is excited with a fixed 400 cycle reference voltage. Tracing the schematic through the upper path to point 1, we first generate a voltage proportional to the sine of $E_t$ which is multiplied in the second resolver times the sine of $E_p$, and at point 1 we have a voltage representing sine $E_t$ times sine $E_p$. From the $E_t$ resolver the cosine $E_t$ is fed to the $A_t$ resolver. From this unit voltages representing cosine $E_t$ times cosine $A_t$ are fed to the second $E_p$ resolver to generate at point 4 the quantity minus cosine $E_t$ cosine $A_t$ sine $E_p$. At point 3 the quantity sine $E_t$ cosine $E_p$ is generated from the $E_p$ resolver. At point 2 the quantity cosine $E_t$ cosine $A_t$ cosine $E_p$ is produced. From the cosine winding of the $A_t$ resolver we obtain cosine $E_t$ sine $A_t$ at point 5. Referring back to equations (3) and (4) and representing the denominator by the symbol D, the voltage at point 5 represents $\frac{Dy}{C}$. Similarly, by adding the voltages at points 3 and 4 in a precise summing amplifier, the quantity $\frac{Dx}{C}$ is obtained. Adding the voltages at 1 and 2 in a precise summing amplifier provides the denominator voltage, D, which is supplied to the feedback potentiometers on the Skyscreen servo drives. The quantity $\frac{Dx}{C}$ is passed through an attenuator network adjusted to the quantity C from which is obtained a voltage representing the product D times x. In the y channel the voltage $\frac{Dy}{C}$ is passed through an attenuator adjusted to the quantity C from which is delivered a voltage representing Dy.

The screen servo drives perform a dual function of a servo divider and a positioning power drive. When the input D times x is compared with the feedback voltage representing D times the position of the screen, the denominator D is canceled and the screen assumes a position x, a solution for the proper vertical coordinate in the focal plane. Similarly, in the y channel the denominator D is divided out of the signal representing D times y to produce a screen position y, a solution for the proper horizontal coordinate in the focal plane.

Since the servos are performing as dividers with a variable voltage on the feedback potentiometer, the total loop gain (which includes a factor proportional to the voltage on the potentiometer) is constantly varying. This implies that stability conditions within the servo loop are also varying. In order to maintain optimum stability characteristics in the presence of varying D voltage, an automatic gain-controlled preamplifier is provided in each channel whose gain is adjusted automatically to be inversely proportional to the potentiometer voltage, D.

This method of coordinate conversion is unique and has a number of important original features. A patent disclosure of the method has been made.

The Skyscreen Computer equipment is separated into three physical locations as illustrated in Figure 3. Two remote resolvers are attached to the tracking instrument to provide signals which are functions of the elevation angle to the target, $E_t$, and the azimuth angle to the

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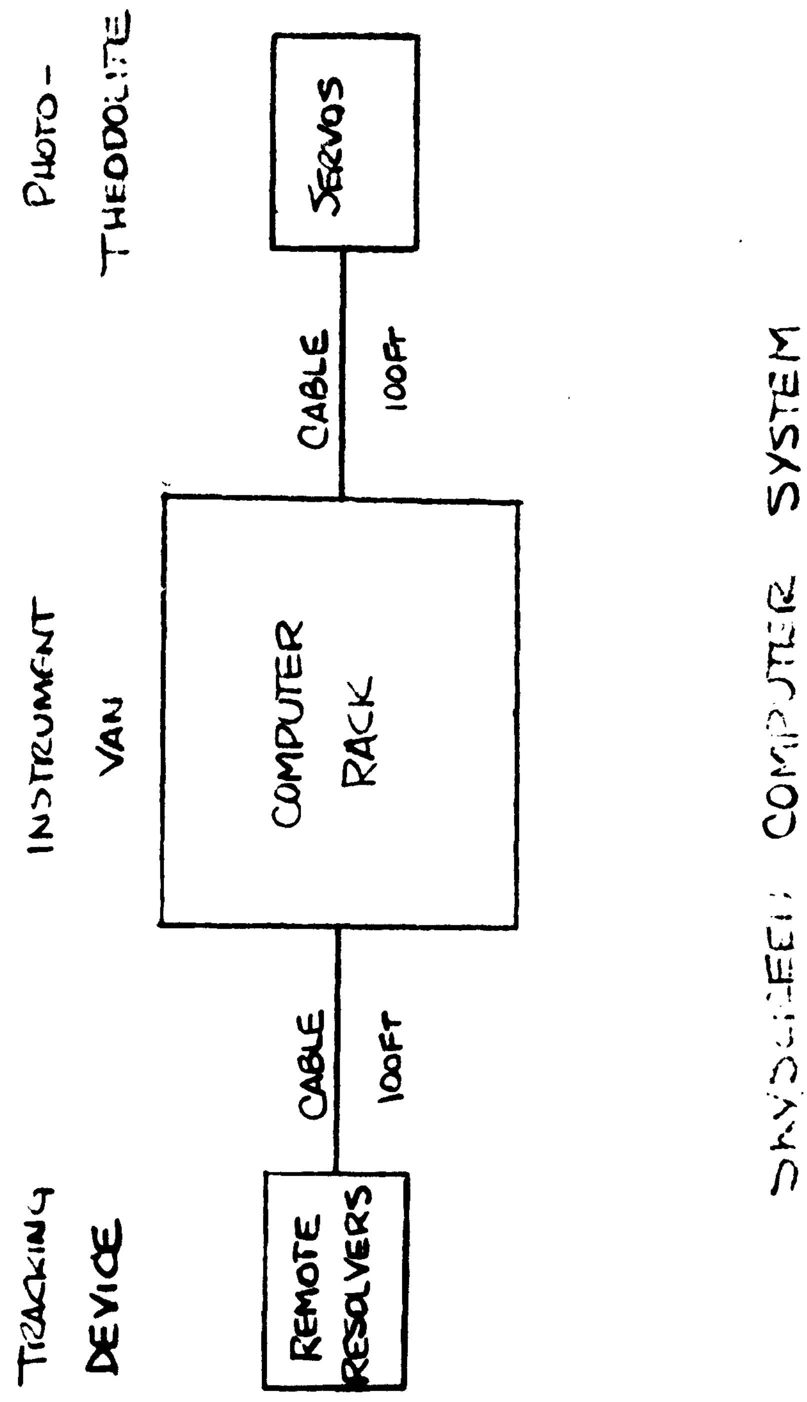
TITLE FIGURE 3 – SYSTEM BLOCK DIAGRAM



target, $A_t$. These signals are connected through cabling to the Computer, in which is housed the manual input resolvers, the summing and servo amplifiers, the attenuator networks, and the power supplies. The Computer is coupled through a second cable to the phototheodolite camera on which is mounted a dual servo package to drive the x and y screens. A photograph of the complete system is illustrated in Figure 4. A test box containing the Remote Resolvers is shown at the lower left, connected through a 100 ft cable to the Computer Rack. The Aviogon lens cone and Skyscreen assembly is at the right with the Servo Drive package (white) mounted on top and connected through a 100 ft cable to the Computer Rack.

## A. Resolver Section

### 1. Remote Resolvers

The resolver section where the trigonometric computation is performed is made up of a set of four precision resolvers and two precision summing amplifiers. Two of the resolvers are remotely located on the tracking device to give an electrical indication of (1) the angle of elevation to the target, $E_t$, and (2) the angle of azimuth to the target, $A_t$. The reference excitation is applied to one of the rotor windings of the $E_t$ resolver. The sine and cosine windings go to other resolvers in the chain.

There are two important adjustments which must be made on these windings in order to preserve the inherent accuracy of the resolvers. First, the loads on the sine and cosine windings must be equal to prevent

FIGURE 4 - SKYSCREEN COMPUTER SYSTEM

changes in loading of the primary winding as the resolver is rotated. Second, in order to maintain proper phase shift and minimum cascading load, the load on each winding must be adjusted for zero power factor. These adjustments are accomplished by means of the shunt capacitors and resistors.

The remote resolvers must be properly related to the azimuth and elevation orientation of the tracking instrument. This relation includes alignment for proper zero and rotation in the proper sense. For zeroing, the voltage on the sine winding must be made a minimum when the resolver shaft is coupled to the tracking shaft at zero elevation. The convention for positive sense of the elevation angle has been chosen to be clockwise rotation when looking at the shaft end. The azimuth resolver, $A_t$, is aligned in the same way and positive azimuth angles are obtained with clockwise rotation of the shaft viewed from the shaft end.

The manual resolvers are similar to the remote resolvers in construction and accuracy. They are used to insert an angle of reference into the Computer, that is, the angle of the elevation of the principal axis of the camera. Both resolvers must be set to exactly the same angle. The most obvious way to do this would be to couple the resolver shafts together physically, but this scheme proved too costly. Therefore, in the prototype model, these resolvers are independently set by means of precise dial assemblies.

With reference to the photograph, Figure 5, the dial assemblies

FIGURE 5 - MANUAL RESOLVER INPUT PANEL

have rather coarse scales on the front panel. These scales are not adequate for setting the resolvers precisely. Therefore, a second set of precision glass dials are located beneath the metal cover, illuminated by an internal lighting system, and read by means of the microscope assembly. These dials are graduated in 4 minute of arc intervals within $\pm$ 30 seconds. Since it is impossible to see these graduations with the naked eye, the 20 power microscope assembly is necessary to set manual input angles to the proper degree of accuracy.

2. Summing Amplifiers

High stability amplifiers are necessary to perform the arithmetic operations of addition and subtraction. One amplifier is required to sum the trigonometric product terms for the denominator, D, of the equations. A second amplifier is required to subtract the trigonometric product terms in the numerator of the equation for vertical screen deflection, x.

Specifications for these amplifiers are unusually demanding. First, they must have an open loop gain of 10,000 volts/volt in order to provide the necessary computational stability of 0.01% with a closed loop gain of approximately 1.0. Second, they must have an open loop frequency response properly shaped to permit a feedback factor of 100%. Third, they must be capable of undistorted sinusoidal output of 20 volts rms (nearly 60 volts peak to peak). And finally, they must supply current to a 500 ohm load. Early in the design stage of the Skyscreen Computer it was found that the above requirements could not be met by any standard solid-state amplifier then on the market. Therefore, the amplifier was designed and developed in the Laboratories of The Franklin Institute.

The summing amplifier schematics are shown in Figures 6 and 7. The only differences between the two amplifiers are the load coupling network for 500 and 1000 ohm loads and the input resistor padding capacitance to compensate for phase shifts in other circuit components.

The performance of the basic summing amplifiers as illustrated with a Bode plot is shown in Figure 8. Note that the closed loop stability, as defined by the peaking at the frequency extremes, has been adjusted for a large margin.

Figure 9 is a photograph of the rear of the amplifier chassis of the Skyscreen Computer showing the physical form and location of the summing amplifiers. The two channels are fabricated on two long upright phenolic boards located crosswise on the amplifier chassis with two black anodized aluminum heat sinks for the power transistors between them.

B. Focal Length Attenuators

1. Horizontal (y) Channel Attenuator $C_y$

Referring to Figure 2 and to the detail of Figure 10, certain details of the y channel focal length attenuator can be pointed out.

The purpose of the attenuator is threefold: first, to adjust the scale factor of the y channel for proper ratio of screen travel to an increment of voltage representing the numerator of equation (4), second to provide for changes in the ratio to adjust for focal lengths of different lenses, and third to provide a trim on the fixed ratios representing

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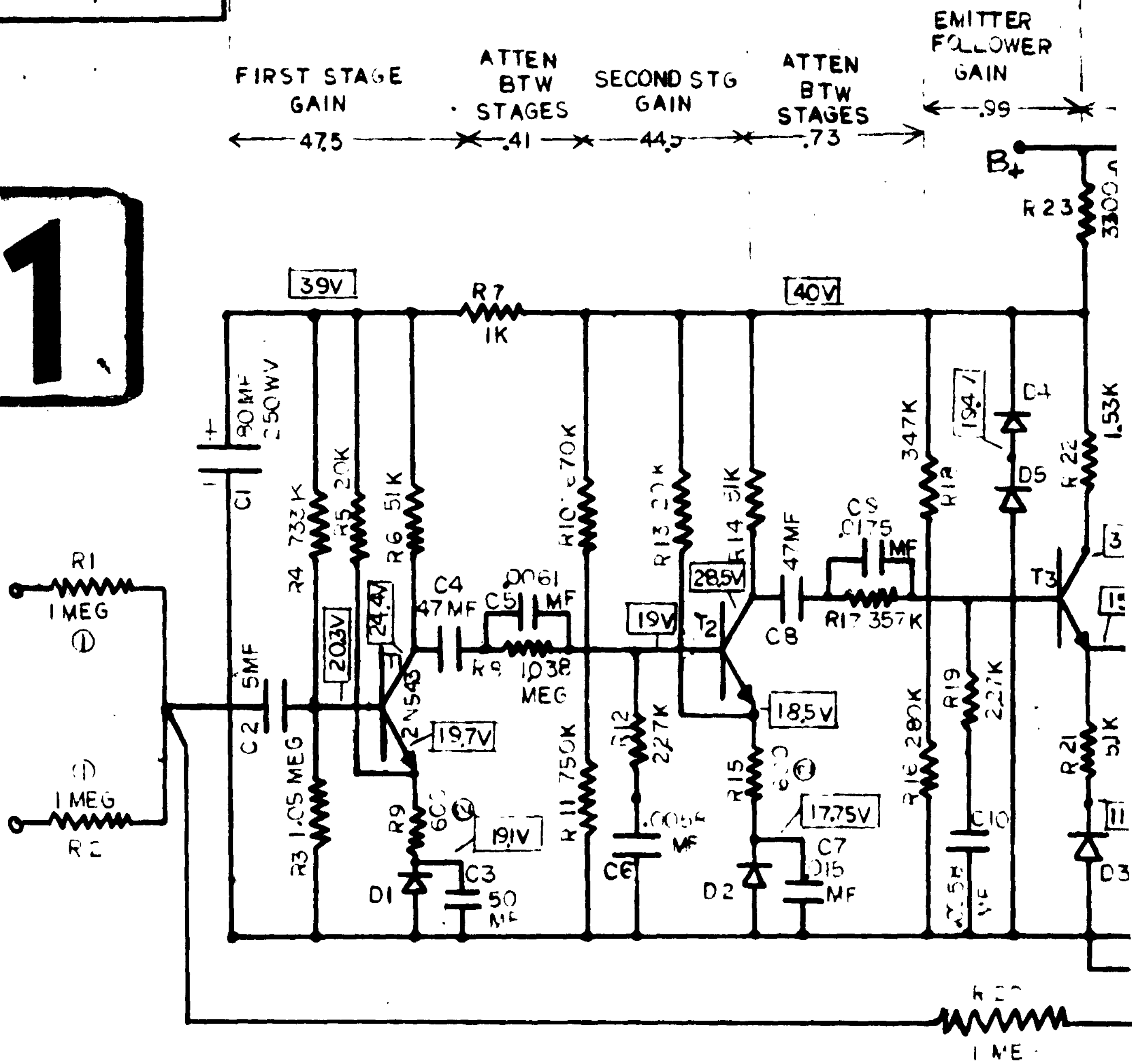


① 1MEG RESISTORS MATCHED .01%

② SILICON RESISTORS TYPE TM 1/8 (TEXAS INST)

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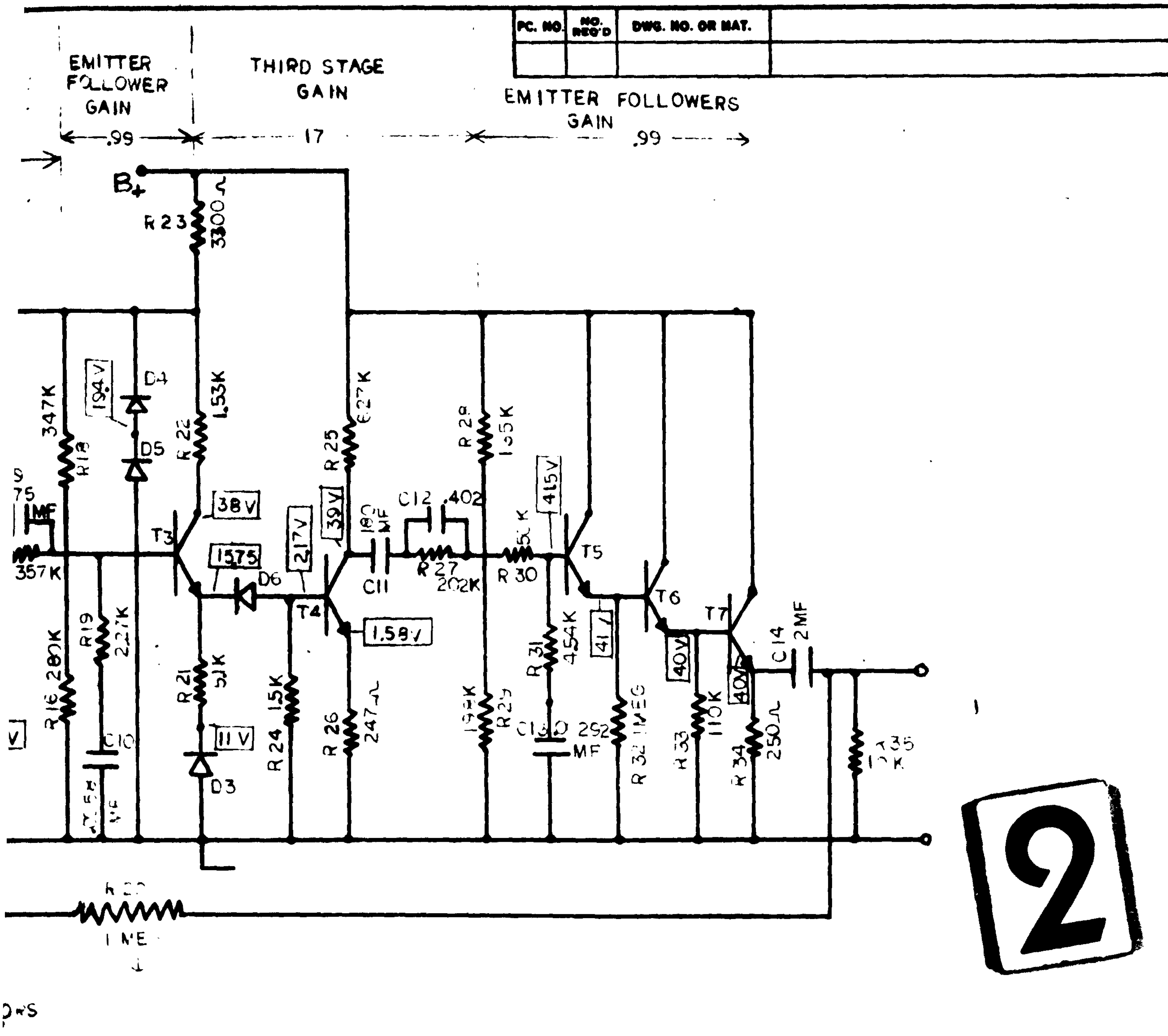


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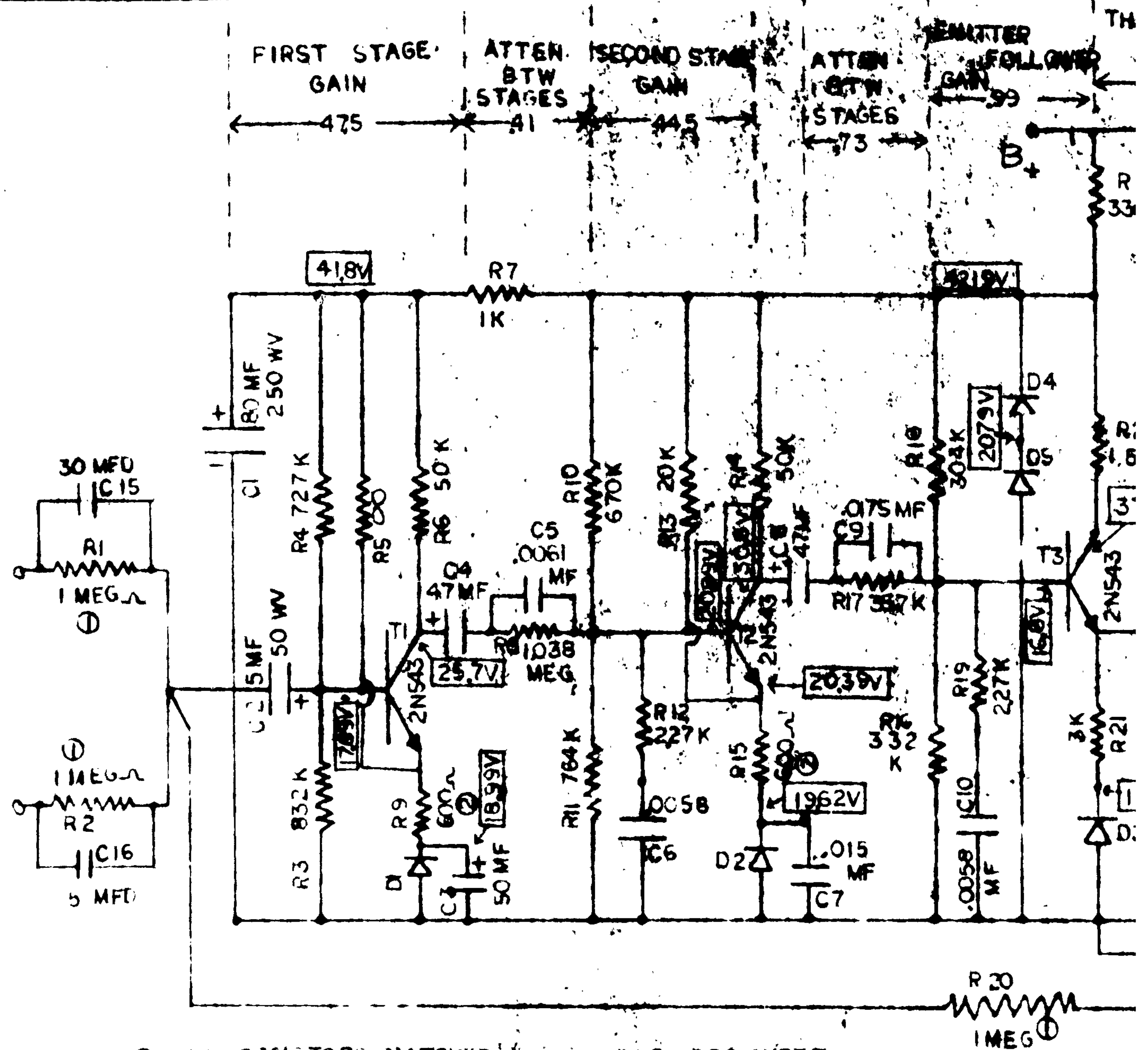
FIG.-6




① 1 MEG RESISTORS MATCHED ± .01 %

SEE SPEC SHEET FOR DIODES

② SILICON RESISTORS TYPE TM 1/8 (TEXAS INSTR)

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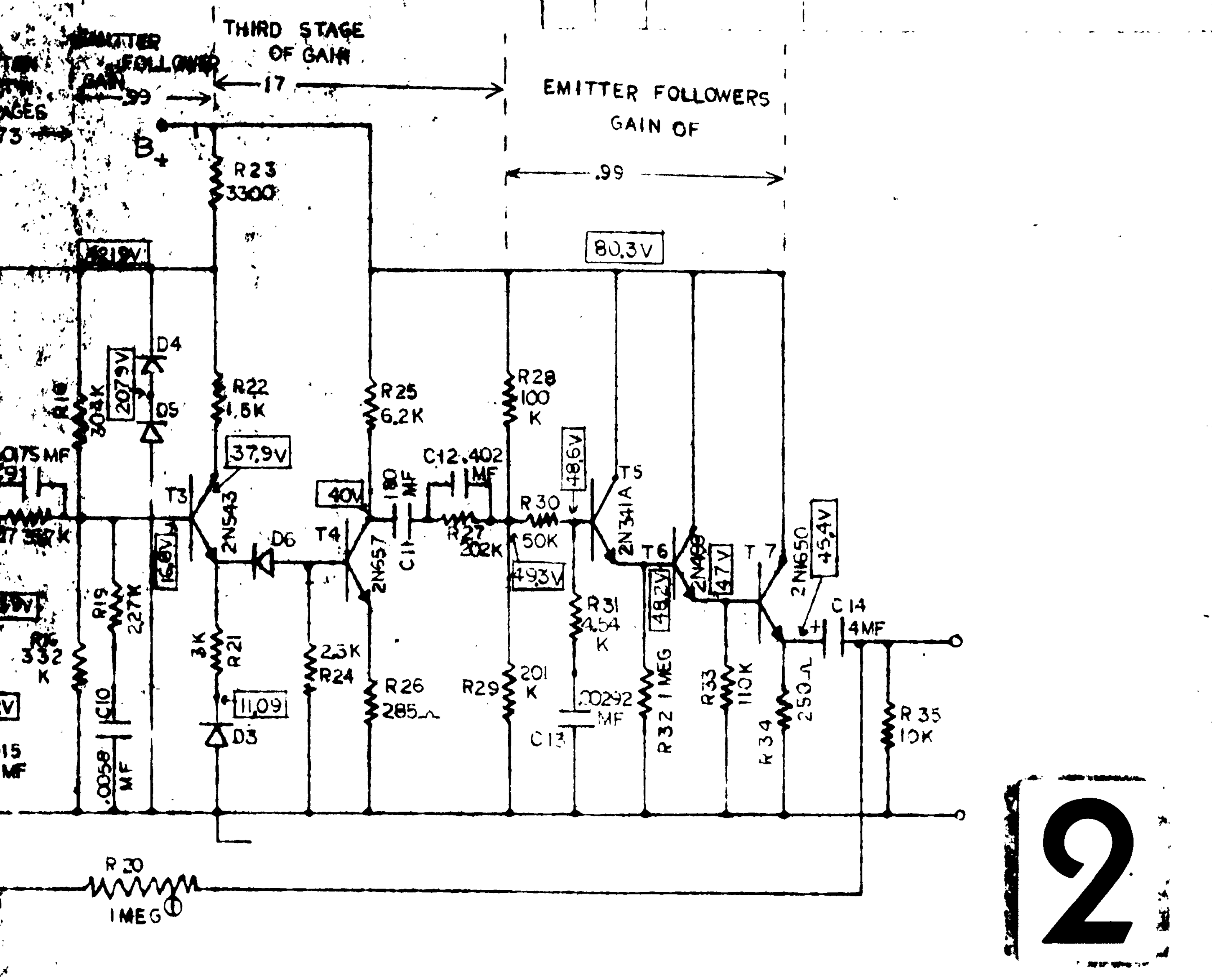


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FIG.-7

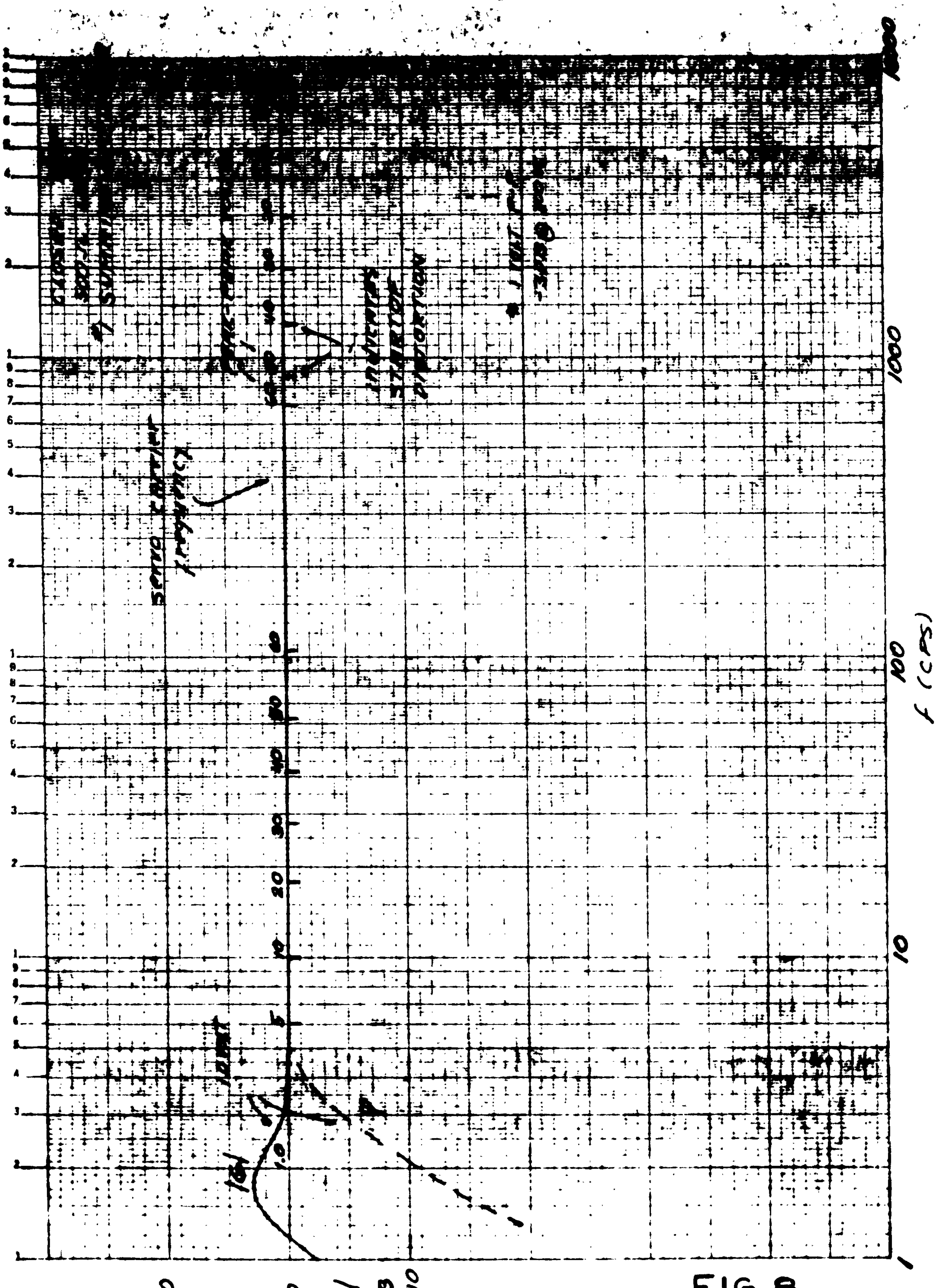


FIG 8

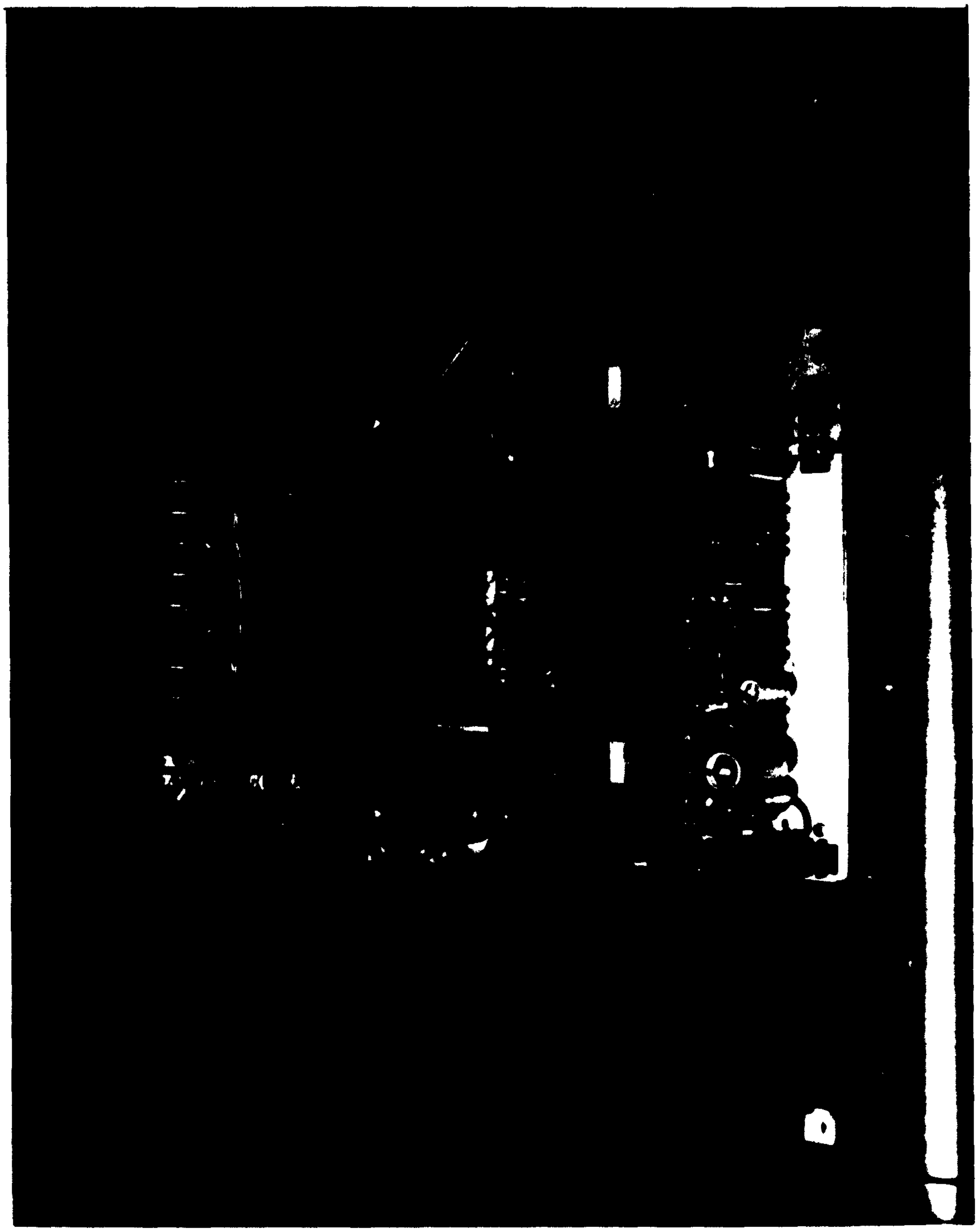

FIGURE 9 - AMPLIFIER CHASSIS (REAR VIEW)

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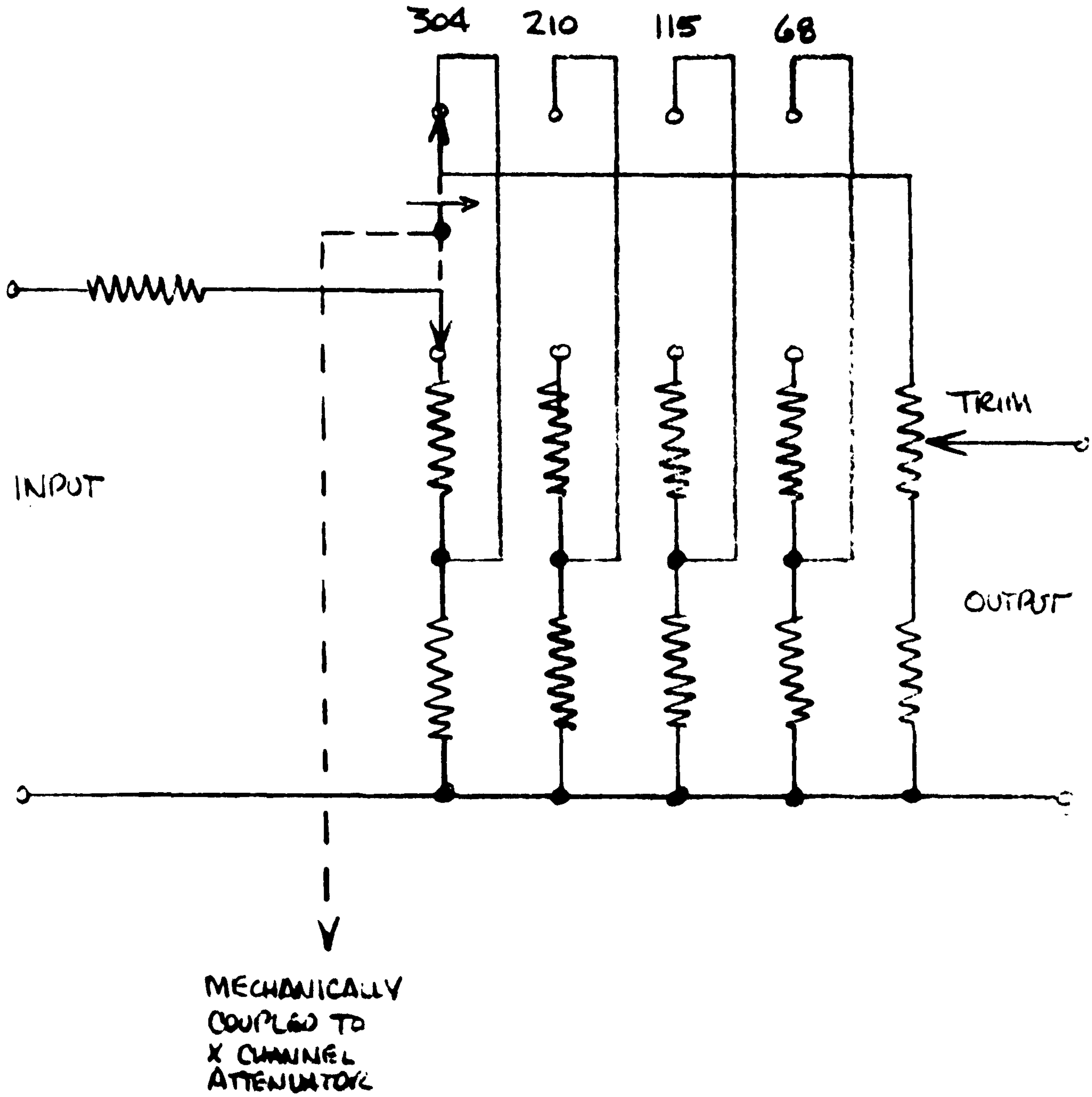


nominal focal lengths of standard lenses to allow for precise setting to actual focal length.

The series input resistor in combination with the constant-input-impedance network following it, sets the basic scale factor. The voltage dividers in each leg of the attenuator provide four major changes in focal length (304, 210, 115 and 68 mm). The adjustable voltage divider at the output is a three-turn precision potentiometer to provide for approximately ± 3% trim of the four major values of focal length.

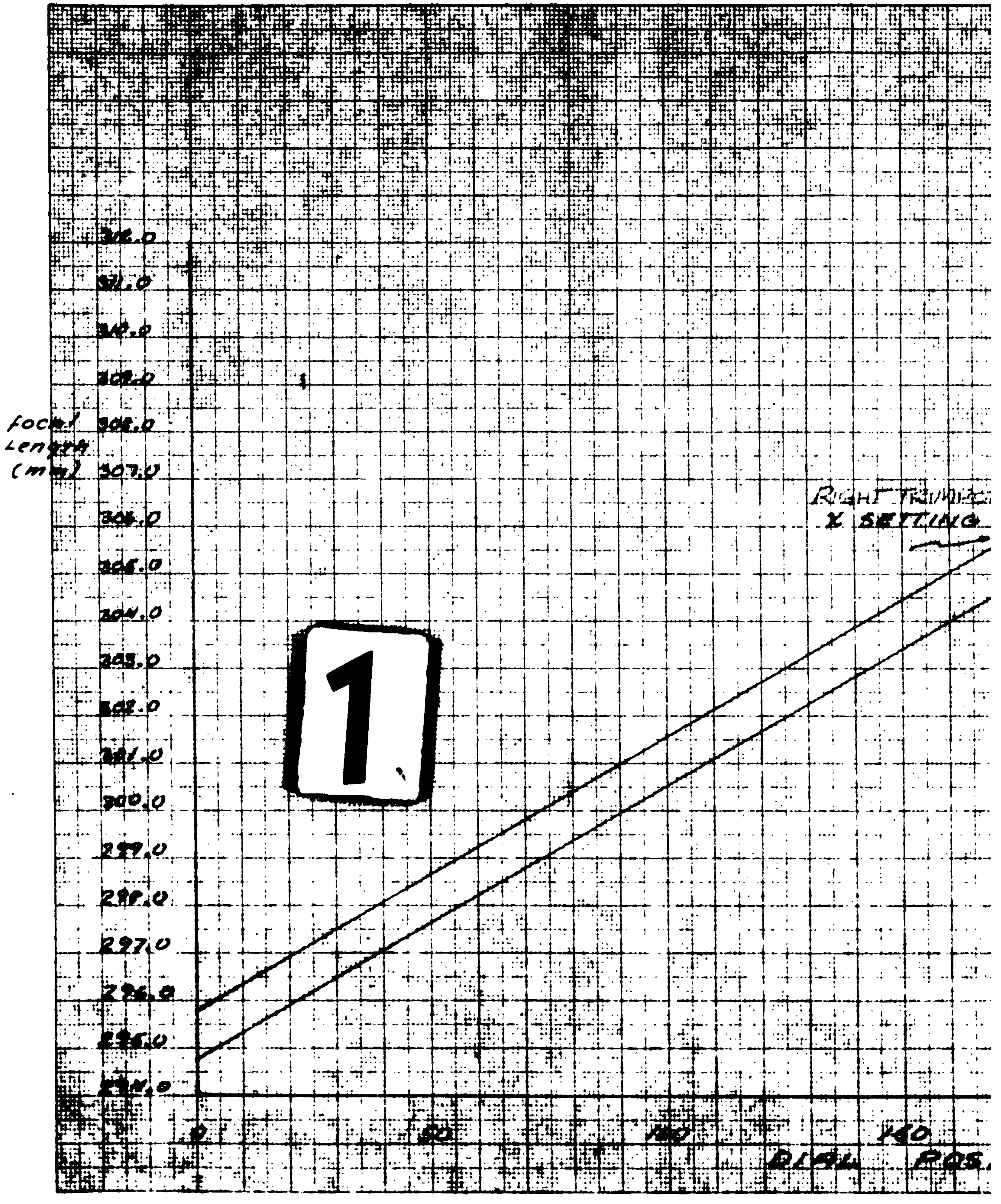
A typical calibration curve of the y channel focal length attenuator is shown in Figure 11.

2. Vertical (x) Channel Attenuator $C_x$

Referring again to Figure 2 and the detail in Figure 12, certain details of the x channel focal length attenuator can be discussed.

The function of the x channel attenuator is fourfold. First, it adjusts the scale factor for proper ratio of vertical screen travel for an increment of voltage representing the numerator of equation (3). Second, it steps up the voltage from the summing amplifier. Third, it provides for major changes in focal length for different standard lenses, and finally, it provides a trim adjustment to compensate for minor variations in nominal focal length of standard lenses.

The series input resistor in combination with a set of loading resistors sets the scale factor. The transformation ratio of the transformer steps up the voltage out of the summing amplifier. The transformer



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311.0
310.0
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306.0
305.0
304.0
303.0
302.0
301.0
300.0
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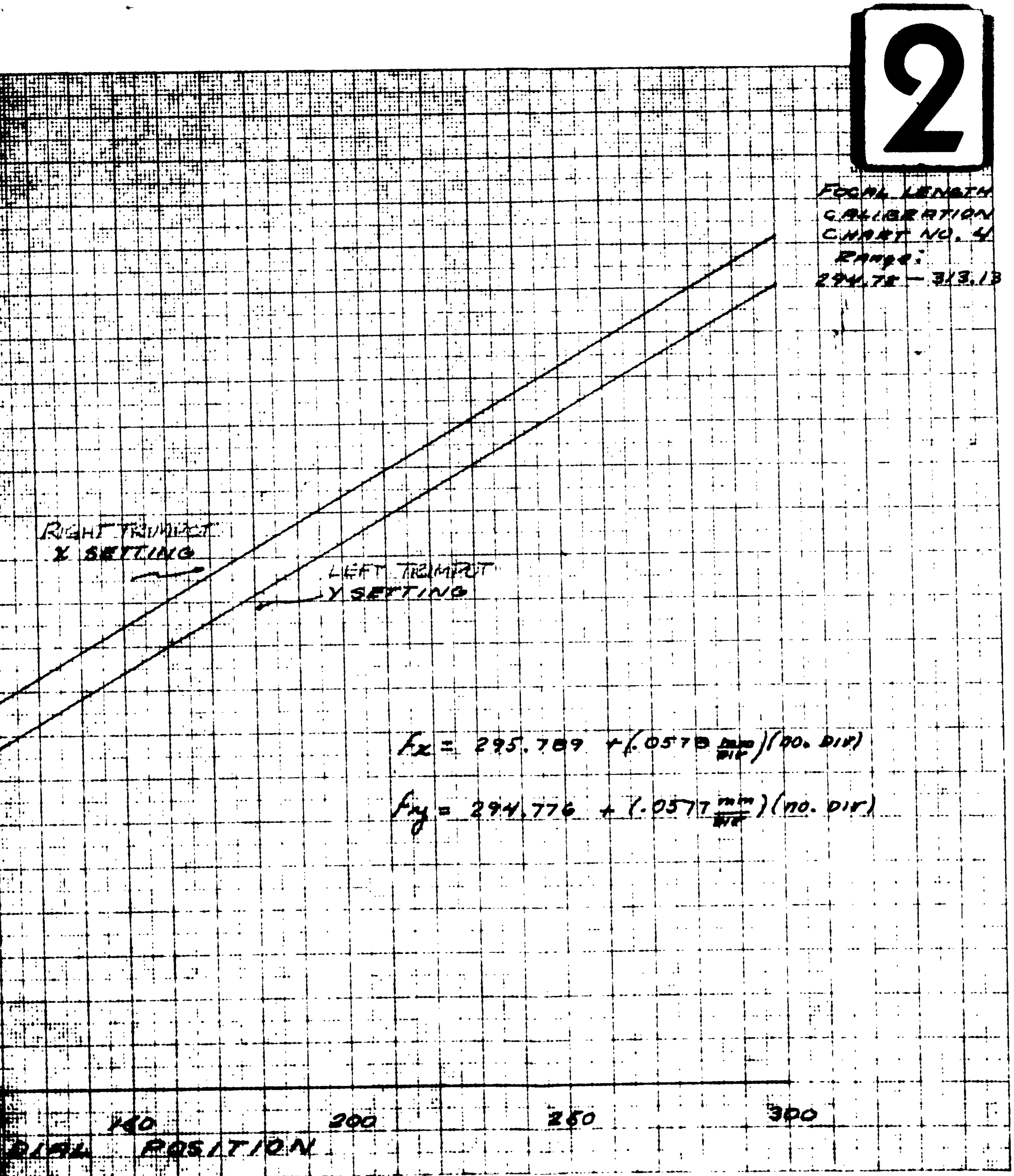
297.0
296.0
295.0
294.0
Focal Length (mm)
X SETTING
0
80
160
DIAL


2
FOCAL LENGTH CALIBRATION CHART NO. 4
Range: 294.78 — 313.13
RIGHT TRIMPOT X SETTING
LEFT TRIMPOT Y SETTING
$f_x = 295.789 + (.0578 \frac{mm}{div})(no. div)$
$f_y = 294.776 + (.0577 \frac{mm}{div})(no. div)$
150
200
250
300
DIAL POSITION

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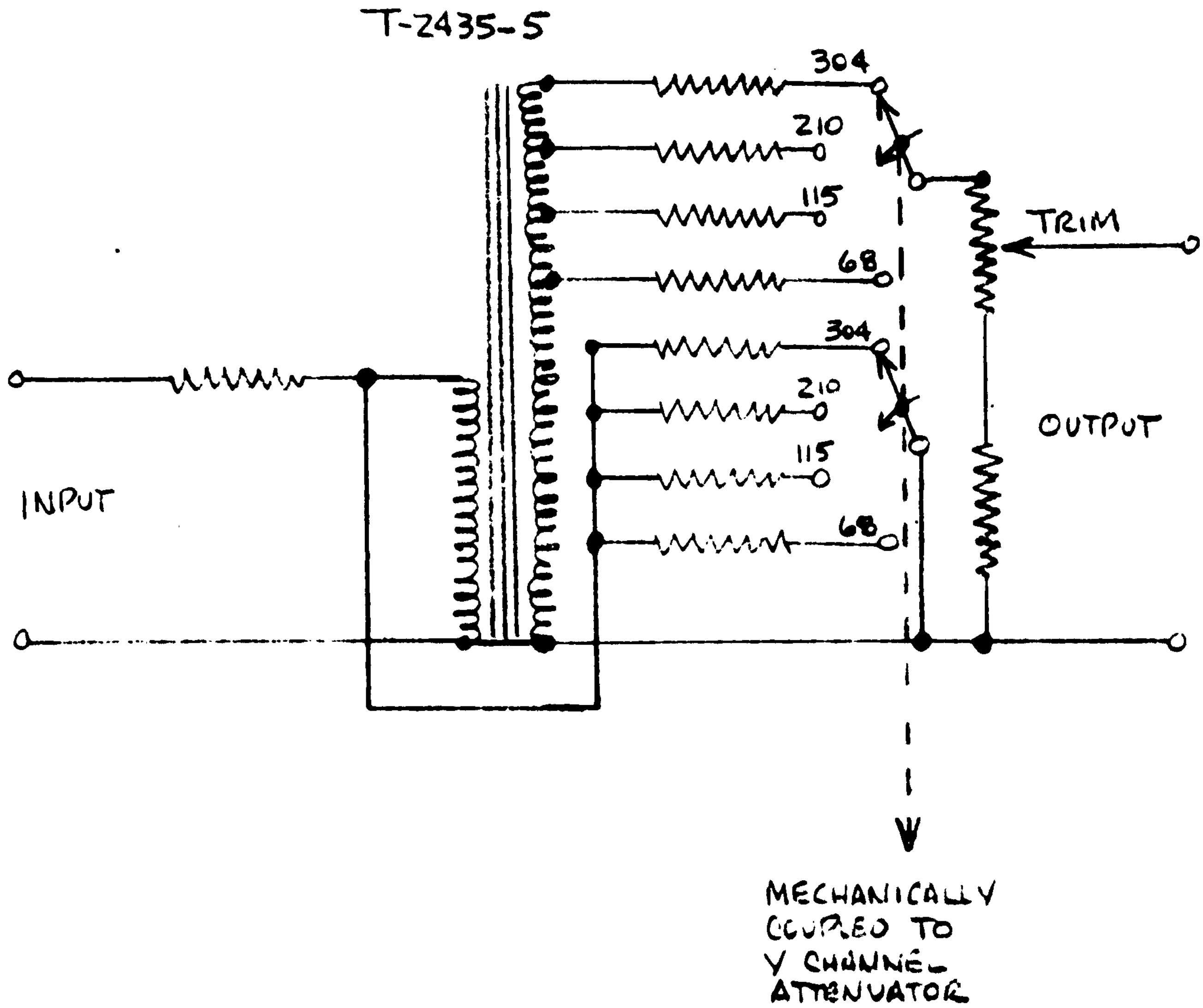
TITLE FIGURE 12 - X CHANNEL FOCAL LENGTH ATTENUATOR



taps and series resistors provide the steps for major changes in the focal length (304, 210, 115 and 68 mm) and the adjustable voltage divider at the output provides for ± 3% trim of the four major values of focal length.

A typical calibration curve of the entire x channel focal length attenuator is also shown in Figure 11.

In the photograph of Figure 9 the attenuator components can be seen mounted vertically on the rear of the front panel. Figure 13 is a view of the front of the amplifier chassis showing the focal length selector switch and the x and y trim pots. The x trim pot is at the right; the y trim pot is at the left.

C. Computing Servo Drives

The servo drives for the screens within the camera perform the triple function of dividing the input voltages representing Dx and Dy by the voltage representing the denominator D of equations (3) and (4) converting the signal voltages to screen positions, and providing the mechanical power to drive the screens. This is done with the servo loops illustrated in Figure 2. The major components of the x and y servos are similar and are (1) a variable gain preamplifier to compare the input signal with the feedback signal representing the screen position and automatically adjust the loop gain to compensate for changes in D voltage level, (2) a power amplifier to raise the level of error signal to drive the servo motors, (3) a servo motor to convert electrical power to mechanical power, (4) a feedback potentiometer to convert mechanical position to an

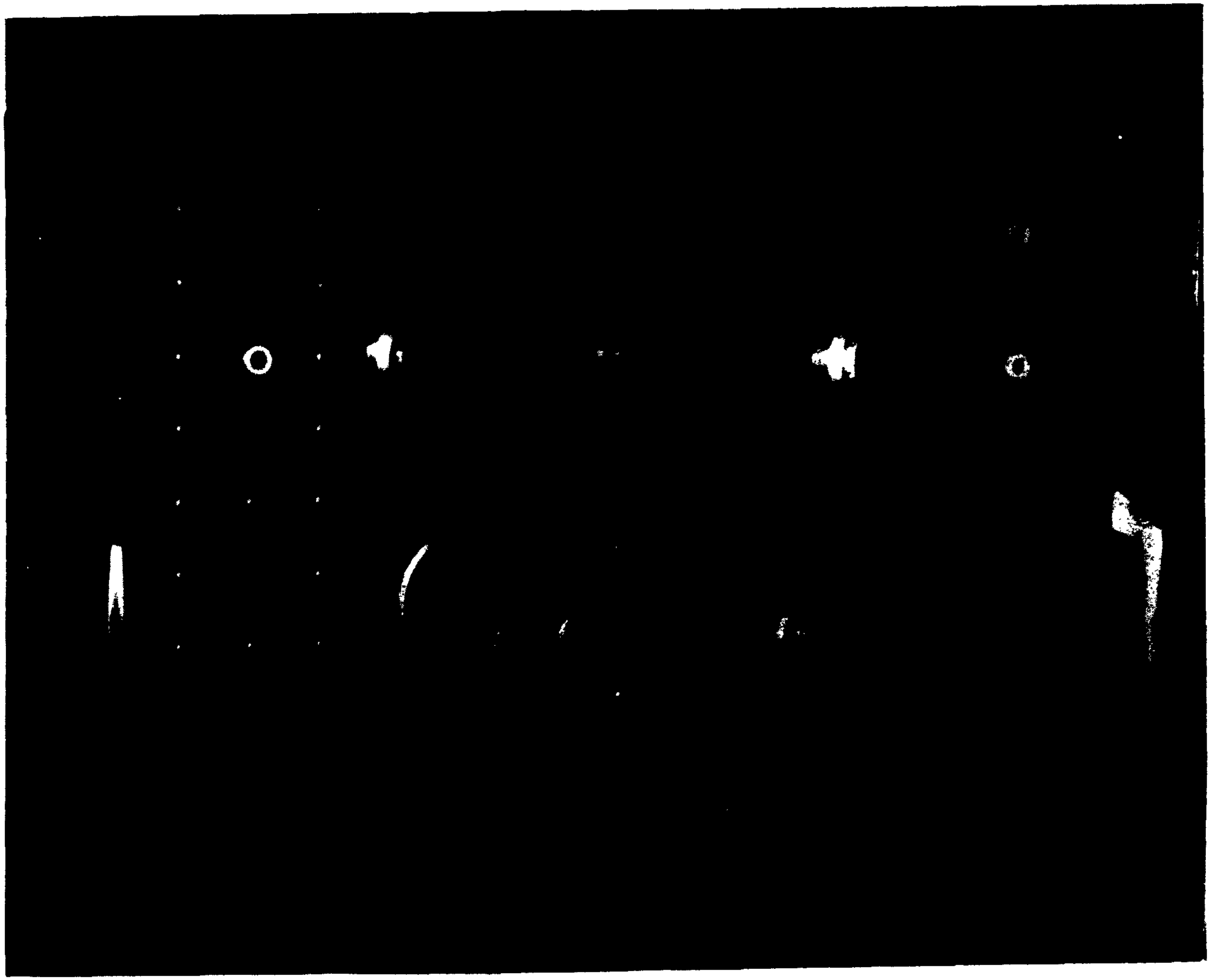


FIGURE 13 - AMPLIFIER CHASSIS (FRONT VIEW)

electrical signal, (5) a gear train to transfer power, provide the proper ratio, and mechanize a system of electrical and mechanical limits, and (6) dual gauged potentiometers for trimming electrical zero to agree with mechanical zero of screen position.

The circuit diagram of the variable gain preamplifier is shown in Figure 14. The ac input signal is compared with the feedback signal in the 100 K resistor network. The error is fed into an emitter follower circuit with high input impedance. The stage output is coupled to a stage of amplification whose gain is controlled by the rectified and filtered voltage representing D. The output is then coupled to the power amplifier through a capacitance. The static performance of this amplifier is illustrated in Figure 15.

The power amplifier is a standard component purchased from Kearfott Division of General Precision, Inc. It is a Model A3106 transistorized power amplifier with a capacity for delivering a maximum of 36 volts rms to a 400 cycle servo motor.

The servo motor was also purchased from Kearfott Division and is basically a standard Model R 1300-25 modified for proper operation with the A3106 amplifier (36 volts rms instead of 40 volts rms on the control winding). The motor is fitted with an inertial damper for mechanical compensation and a 77:1 gearhead with a maximum of 30 minutes of backlash.

The feedback potentiometer is a 3-turn wire wound unit purchased from Helipot Division of Beckman Instruments. It is basically a Model 9303

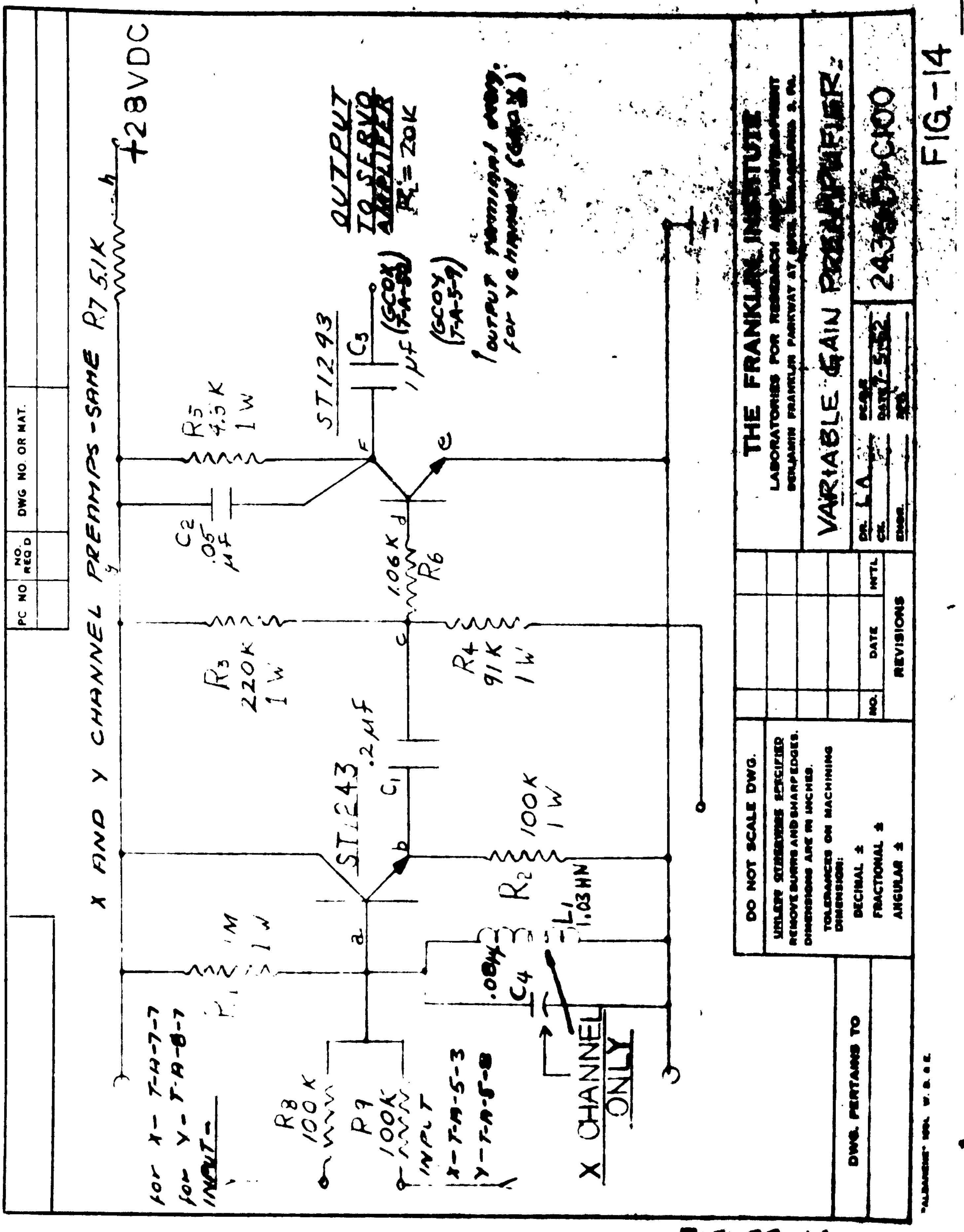
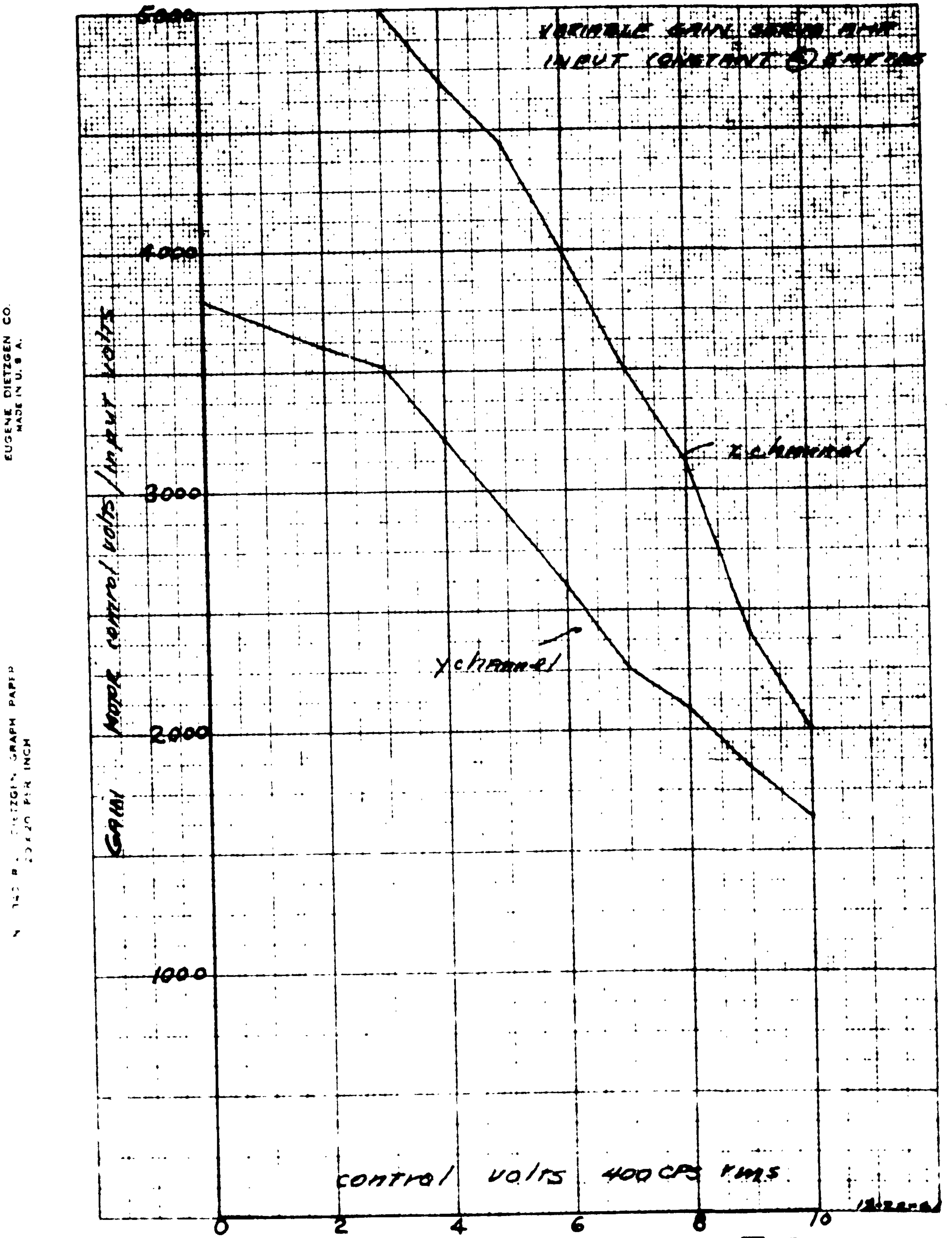

X AND Y CHANNEL PREAMPS - SAME
+28VDC
R7 5.1K
R5 4.3K 1W
C2 .05 μF
ST1293
C3 1μF
OUTPUT TO SERVO AMPLIFIER
R6 1.06K
R3 220K 1W
R4 91K 1W
ST1243
C1 .2μF
R2 100K 1W
L1 1.03 HN
C4
X CHANNEL ONLY
R8 100K
P9 100K
INPUT
THE FRANKLIN INSTITUTE
LABORATORIES FOR RESEARCH AND DEVELOPMENT
VARIABLE GAIN PREAMPLIFIER
FIG-14
DO NOT SCALE DWG.
PC NO
NO. REQ'D
DWG NO. OR MAT.
REVISIONS
DWG. PERTAINS TO

FIGURE 14



VARIABLE GAIN SERVO AMP
INPUT CONSTANT
GAIN MOTOR control volts / input volts
5000
4000
3000
2000
1000
x channel
y channel
control volts 400 CPS rms
0
2
4
6
8
10
EUGENE DIETZGEN CO.
MADE IN U.S.A.


FIG. 15

with 1000 ohms resistance, .05% linearity, modified with taps at 200 and 800 ohms and a double shaft extension to accommodate the limit mechanism.

The gear train between motor gearhead, feedback potentiometer, screen drive gear, and limit mechanism was designed and fabricated in the Laboratories. This train was carefully adjusted in assembly to eliminate all significant backlash.

The dual-ganged potentiometers for trimming zero position are standard 60 ohm model TP purchased from the Helipot Division. It is electrically connected at each end of the feedback potentiometer to increase the resistance on one side while decreasing the resistance on the other.

The limit system is activated near the end of screen travel by the limit mechanism depressing a miniature limit switch which first injects a reversing impulse then reduces motor torque by inserting a lamp bulb in series with the power amplifier supply voltage.

The servo package is shown in Figure 16 containing motors, gears, limit mechanisms, feedback pots, and trim pots for x and y screens. The controlled-gain amplifiers and power amplifiers can be seen in Figure 9 on the amplifier chassis between the summing amplifiers and the front panel. The servo package includes friction brakes on the screen drive shafts so the drive systems can be removed as a unit without losing alignment between electrical and mechanical positions.

FIGURE 16 - SERVO ASSEMBLY

1. Frequency Response

Frequency response tests were performed on the servo drives to establish their stability and bandwidth compared with the design analysis conducted in Phase I (I-A2191-1). The results are shown in Figures 17 and 18 as Bode plots of the amplitude and phase of the x servo for two conditions: (1) mounted on the camera driving the screens and (2) demounted with no external load. The results compare favorably with those predicted and indicate performance more than adequate to accurately track the moving target.

No precise tests were performed on the prototype system to determine accurately the maximum rates and accelerations. However, the performance has been correlated with the design to such an extent that those estimates can be considered as approximately valid. Thus, the maximum tracking rate is approximately 25 mm/sec and the maximum acceleration is approximately 100 mm/sec$^2$.

D. Power Supplies

All power supplies are located on the bottom chassis in the Skyscreen Computer Rack. A rear view photograph of the power supply chassis is shown in Figure 19. A front panel view is shown in Figure 20. In addition to an auxiliary 24-volt transformer for lighting, there are three major power supplies: (1) an 80-volt dc unregulated supply for the summing amplifier, (2) a 28-volt dc transistor-regulated supply for the servo amplifiers, and (3) a 60-400 cycle solid-state frequency changer to supply excitation for the resolvers and the servo motors.

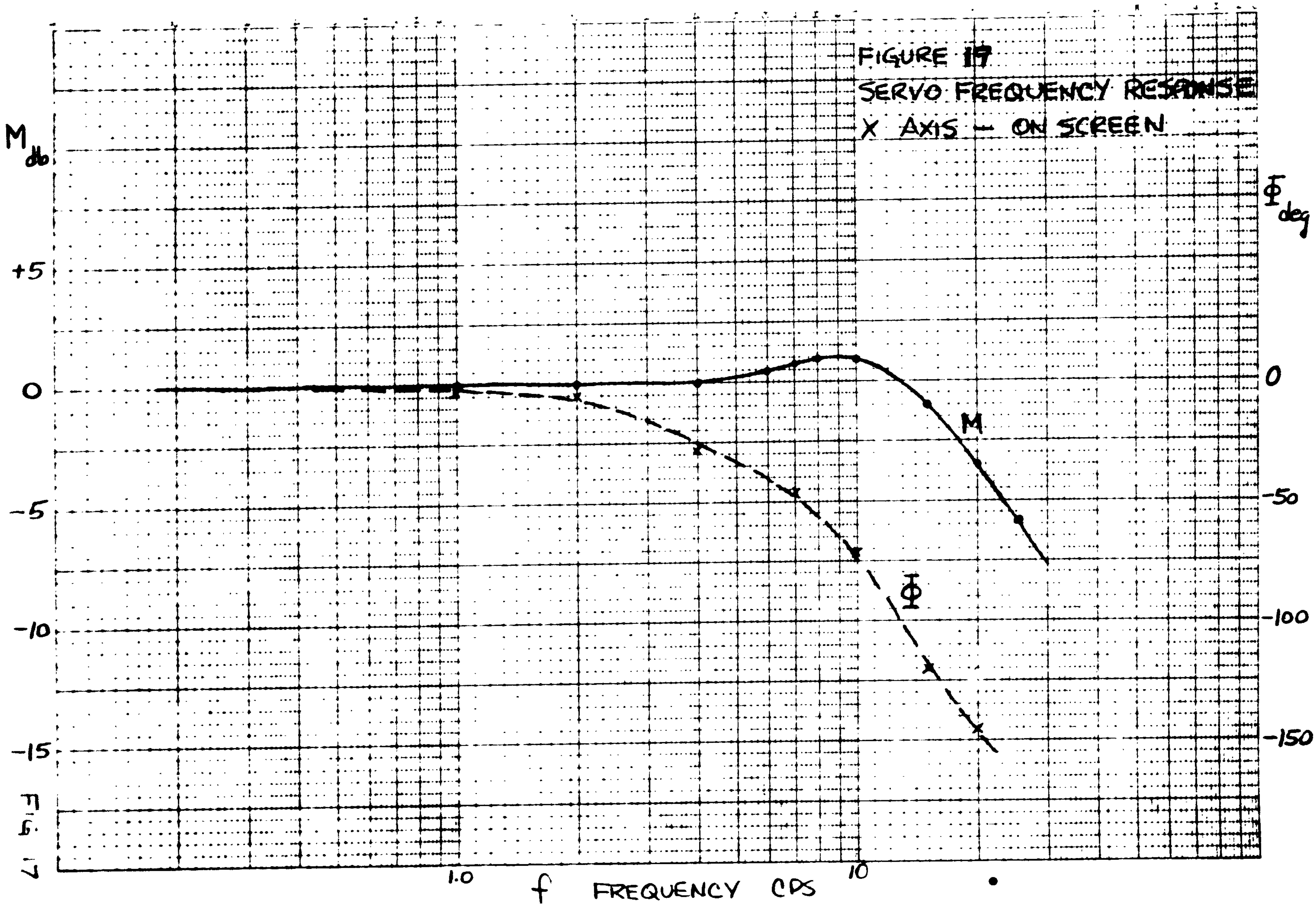
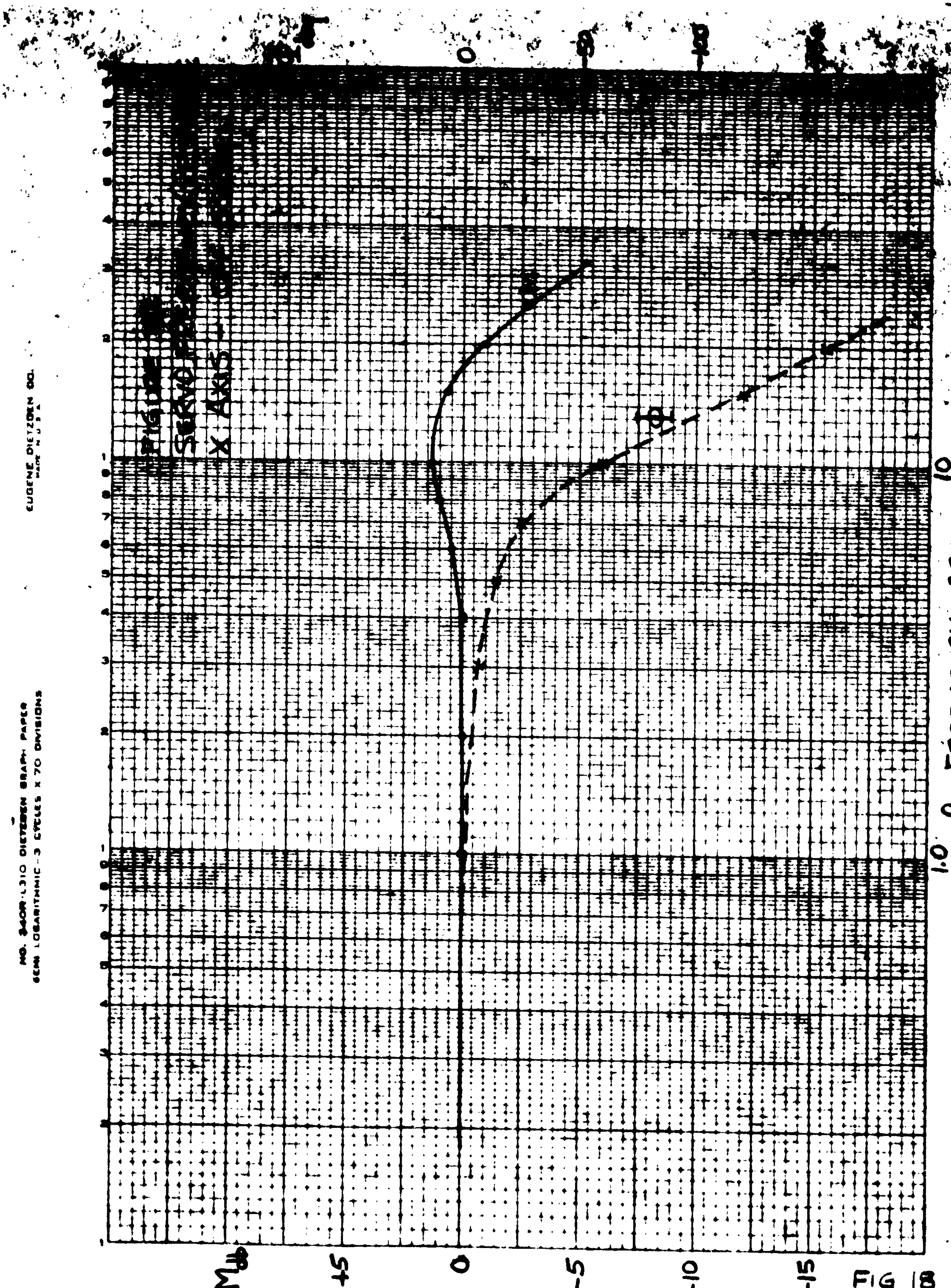


FIGURE 17
SERVO FREQUENCY RESPONSE
X AXIS — ON SCREEN
M db
+5
0
-5
-10
-15
Φ deg
0
-50
-100
-150
M
Φ
1.0
10
f FREQUENCY CPS

Fig 17



NO. 340R-L310 DIETZGEN GRAPH PAPER
SEMI LOGARITHMIC - 3 CYCLES X 70 DIVISIONS
EUGENE DIETZGEN CO.
MADE IN U.S.A.
M db
+5
0
-5
-10
-15
1.0
10
f FREQUENCY CPS
Φ


FIG 18

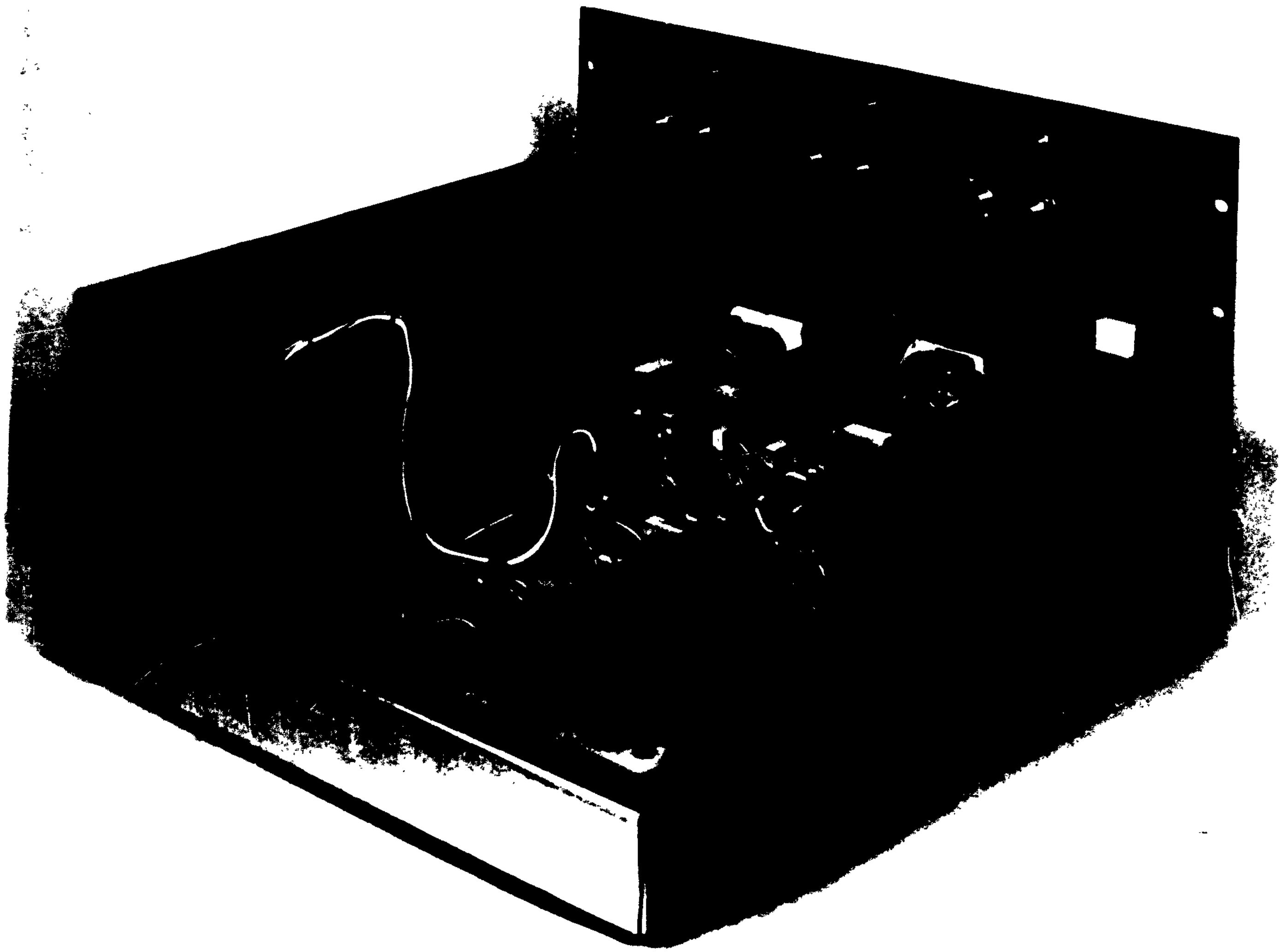


FIGURE 19 - POWER SUPPLY CHASSIS (REAR VIEW)

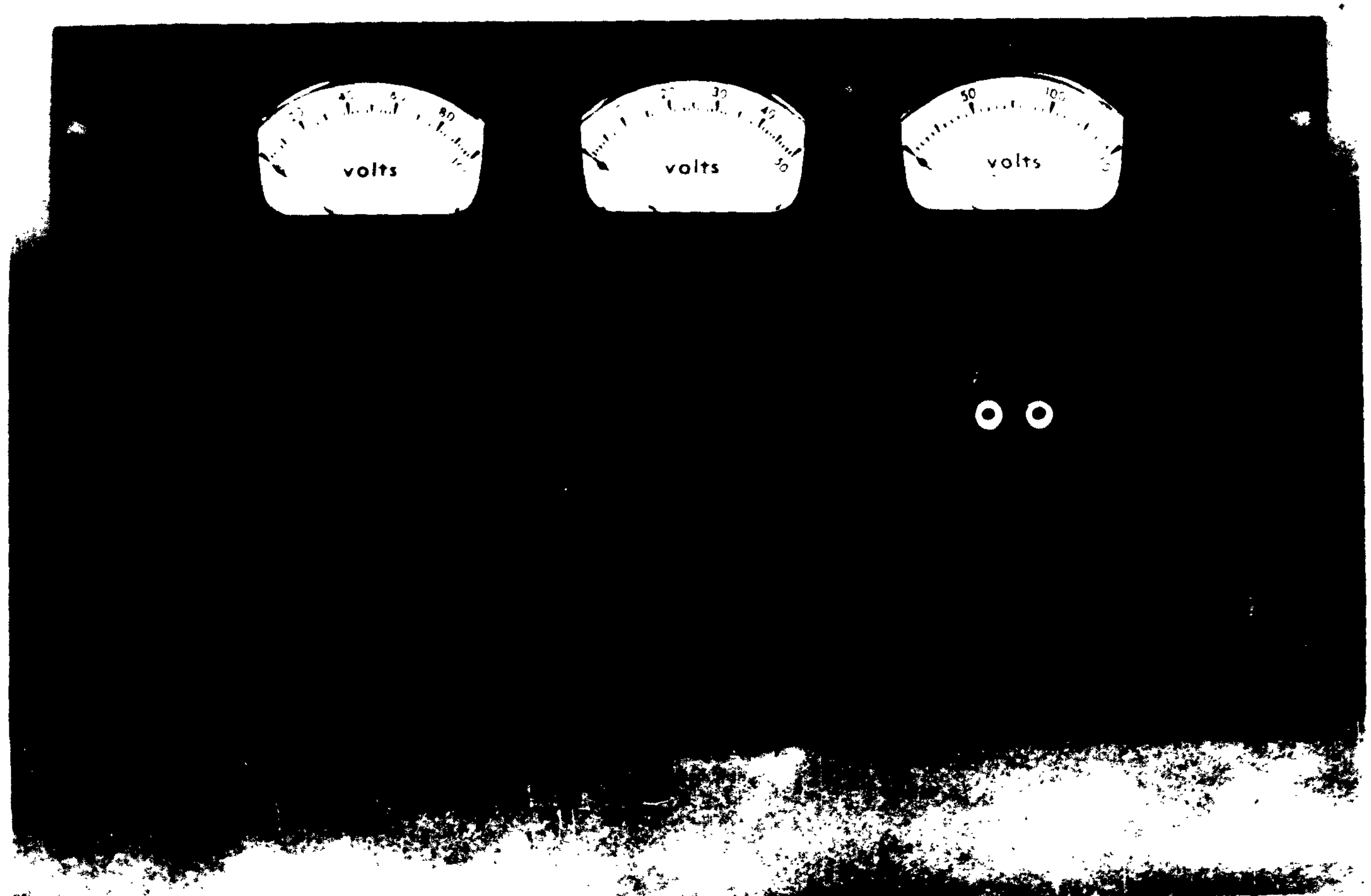



FIGURE 20 - POWER SUPPLY CHASSIS (FRONT VIEW)

1. Unregulated 80-Volt DC Power Supply

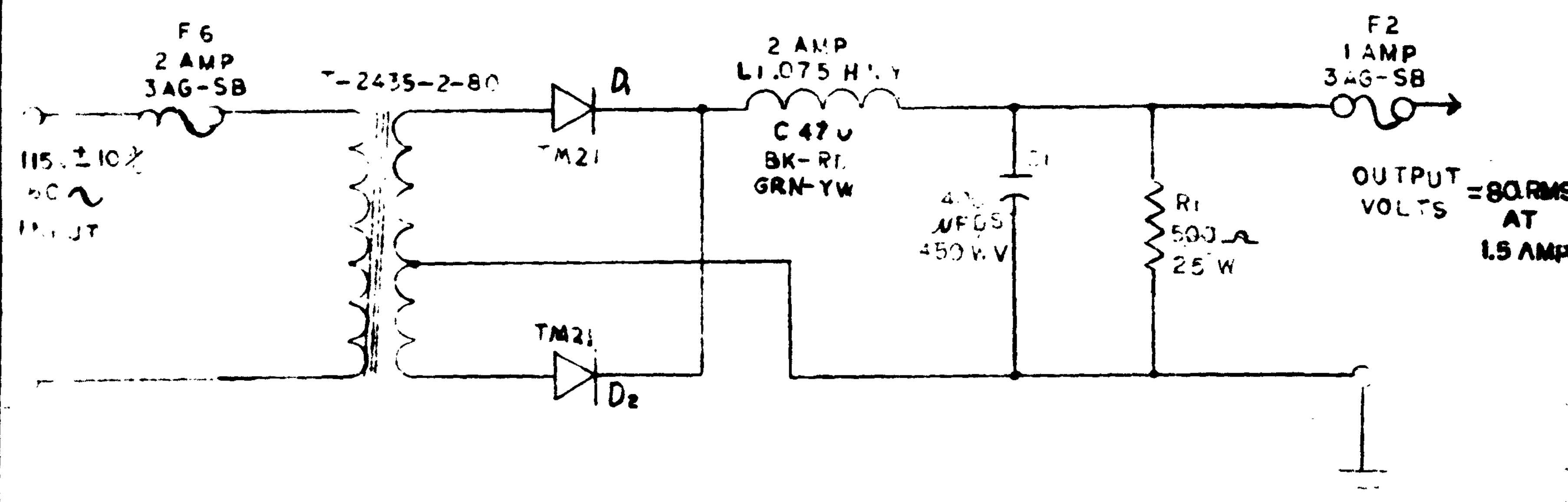
Early in the design stage it was decided that the use of solid-state circuits throughout the Skyscreen Computer would result in the most reliable and trouble-free system. On this basis, the maximum signal level at the input to the servos was limited to 20 v rms. To provide the necessary peak-to-peak voltage swing from the single-ended output stage of the summing amplifier the dc collector supply voltage must be 80-volts. Since decoupling and individual stage regulation are provided within the summing amplifier itself at all critical points, no additional regulation is necessary. To satisfy this need a special dc supply was developed within the Laboratories. Design for low regulation and low ripple in the passive circuits results in more than adequate performance.

A schematic of the 80-volt dc supply is shown in Figure 21. It is physically located in the center of the power supply chassis shown in Figure 19. The transformer was designed especially for the application using standard laminations and magnet wire. The secondary is center-tapped to provide full-wave rectification with two silicon rectifiers. The ripple filter is a LC combination of standard components. The supply carries a dummy load for proper operation of the ripple filter.

The unregulated power supply is rated at 1.5 amps, 80-volts with 1% ripple and 10% load regulation.

2. Regulated 28-Volt DC Power Supply

To make use of standard transistorized servo amplifiers a 28-volt dc power supply is required with good regulation to prevent loss of torque




| PC. NO. | NO. REQ'D | DWG. NO. OR MAT. |
|---|---|---|
| | | |

DO NOT SCALE DWG.

UNLESS OTHERWISE SPECIFIED REMOVE BURRS AND SHARP EDGES. DIMENSIONS ARE IN INCHES.

TOLERANCES ON MACHINING DIMENSION:

DECIMAL ±

FRACTIONAL ±

ANGULAR ±

DWG. PERTAINS TO

| NO. | DATE | INT'L |
|---|---|---|
| | | |

REVISIONS

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LABORATORIES FOR RESEARCH AND DEVELOPMENT

BENJAMIN FRANKLIN PARKWAY AT 20TH, PHILADELPHIA 3, PA.

# 80 VOLT POWER SUPPLY

DR. LA — SCALE

CK. — DATE

ENGR. — APP.

2435-01-C104

"ALBANENE" 100L. W. D. & E.

FIG.-21

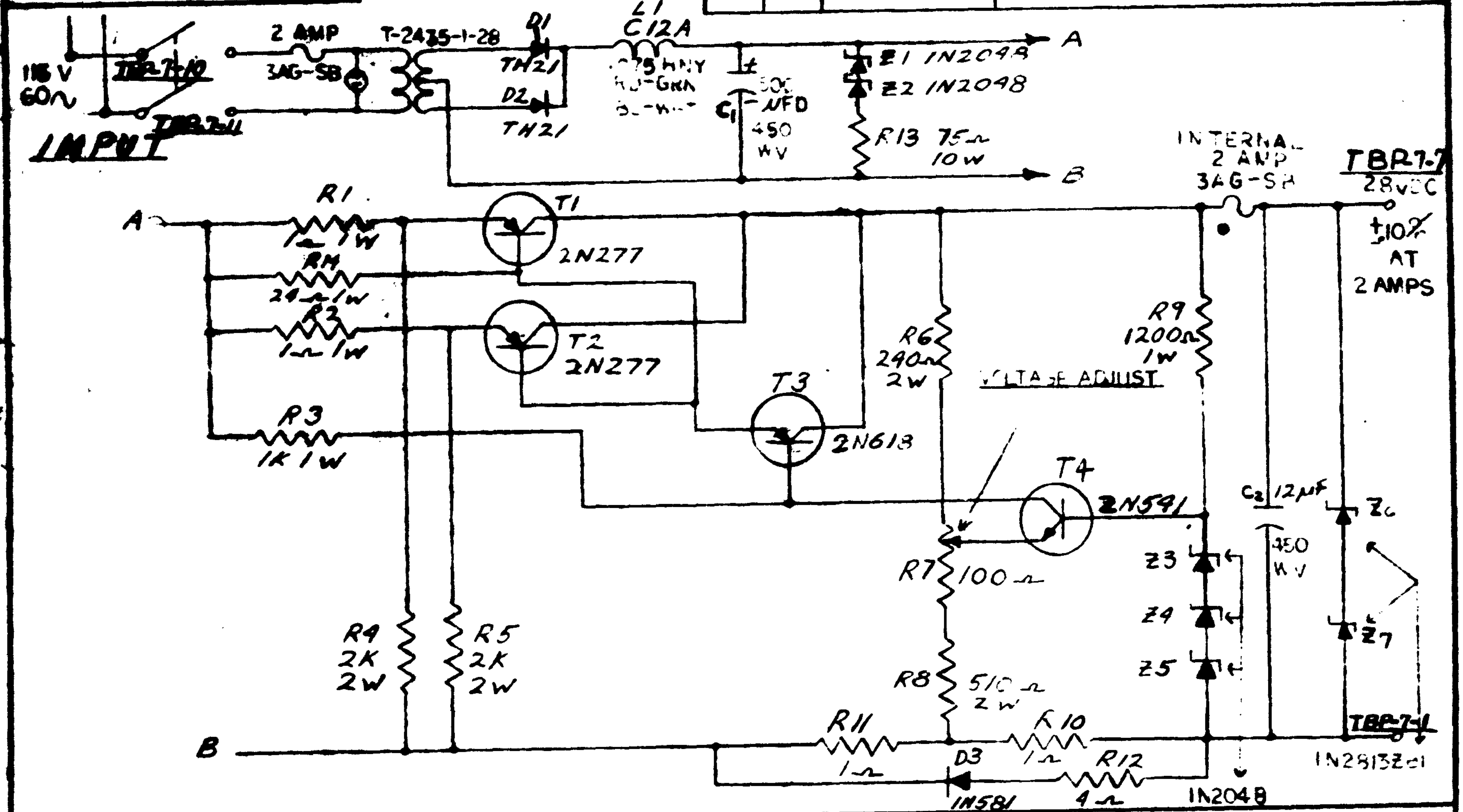
FIGURE 21

and loop gain in the servo systems. Standard power supplies are available which would satisfy requirements but would be poorly matched to the needs of two servo systems. Therefore, in the interest of efficient use of power and space the 28-volt regulated dc supply was designed and fabricated in the Laboratories.

A schematic diagram of the regulated 28-volt dc supply is shown in Figure 22. (It is also seen in its physical location at the right side of Figure 19.) The transformer is a special design using standard laminations and wire. It provides a center-tapped secondary for full-wave rectification with two silicon diodes. The ripple filter is a LC combination of standard components. Two zener diodes act as a controlled load for proper operation of the ripple filter.

The active portion of the regulator is a transistorized series circuit using zener references, two stages of error amplification and parallel pass transistors. Across the output are a smoothing capacitor and peak limiting diodes. The circuit is a conventional type with the exception of a unique nonlinear current feedback circuit which automatically compensates for the nonlinear characteristics of the regulating loop, in particular the reduction of $\beta$ in the pass transistors at low values of load current. This feature was developed from an original idea and a patent disclosure has been made, for the record.

The regulated power supply is rated at 28-volts dc, 2.5 amps, 1.0% regulation for line and load and .01% ripple.




| PC. NO. | NO. REQ'D | DWG. NO. OR MAT. |
|---|---|---|
| | | |

DO NOT SCALE DWG.

UNLESS OTHERWISE SPECIFIED REMOVE BURRS AND SHARP EDGES. DIMENSIONS ARE IN INCHES.

TOLERANCES ON MACHINING DIMENSION:
DECIMAL ±
FRACTIONAL ±
ANGULAR ±

DWG. PERTAINS TO

| NO. | DATE | INT'L. |
|---|---|---|
| | | |

REVISIONS

**THE FRANKLIN INSTITUTE**
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BENJAMIN FRANKLIN PARKWAY AT 20TH, PHILADELPHIA 3, PA.

28 V POWER SUPPLY

DR. LA
CK.
ENGR.
SCALE
DATE 6-10-62
APP.

2435-01-C107

FIG. - 22

FIGURE

"ALBANENE" 1001 W. & D.E.

3. Solid-State Frequency Changer

In order to take advantage of the smaller induction components available for use on 400 cycles and yet have the Skyscreen Computer independent of all field supplies except that for basic utility power, a converter has been included. The device is a purchased solid-state unit using conventional transistorized switching circuits and "brute-force" harmonic filter. It can be seen at the left side of Figure 19. Since the excitation voltage is a factor which cancels out of the computation and total load is relatively constant, specifications for the frequency changer were made extremely flexible. However, the unit as received proved poorer in voltage and frequency regulation and harmonic content than is now believed reasonable. These characteristics have made precise alignment and null of signals extremely difficult.

Tests show voltage regulation with line and load of 200% and 50% respectively and frequency regulation with load of 10%. These characteristics should be held to 5-10%.

TITLE E. LIST OF DRAWINGS - SKYSCREEN COMPUTER

CAMERA SERVO ASSEMBLY

| DRAWING NO. | DESCRIPTION | REMARKS |
| --- | --- | --- |
| A2435-01-C1 | Camera Servo Assembly | |
| A2435-01-C2 | Servo Drive Assembly | |
| A2435-01-B3 | Limit Stop Switch Assembly | |
| A2435-01-A4 | Index Pawl | |
| A2435-01-A5 | Pawl Bearing Stud | |
| A2435-01-A6 | Locating Stud | |
| A2435-01-A7 | Pawl Washer | |
| A2435-01-B8 | Input Connector Plate | |
| A2435-01-B9 | Sub Mounting Plate | |
| A2435-01-B10 | Sub Chassis B | |
| A2435-01-B11 | Sub Chassis A | |
| A2435-01-C12 | Chassis | |
| A2435-01-C13 | Servo Cover | |
| A2435-01-C14 | Chassis Mounting Plate | |
| A2435-01-A15 | Limit Stop Pinion | |
| A2435-01-A16 | Upper Pot Clamp | |
| A2435-01-A17 | Limit Stop Gear Stud | |
| A2435-01-A18 | Limit Stop Gear | |
| A2435-01-A19 | Motor Gear | |
| A2435-01-A20 | Limit Stop Gear Bushing | |
| A2435-01-A21 | Retainer Screw | |
| A2435-01-A22 | Limit Stop Centering Spring | |
| A2435-01-A23 | Miniature Connector | |
| A2435-01-B24 | Limit Stop Actuator | |

Form 307 12,000 9-41 GOLVIN PRESS, INC., BROOKLYN 17, N.Y. STOCK NO 480

TITLE

E. LIST OF DRAWINGS - SKYSCREEN COMPUTER

CAMERA SERVO ASSEMBLY CONTINUED

| DRAWING NO. | DESCRIPTION | REMARKS |
|---|---|---|
| A2435-01-B25 | Limit Stop Body | |
| A2435-01-A26 | Limit Stop Stud | |
| A2435-01-A27 | Lower Pot Clamp | |
| A2435-01-A28 | Handle Adapter Screw | |
| A2435-01-C29 | Handle | |
| A2435-01-A30 | Locking Pin | |
| A2435-01-A31 | Spring Stud | |
| A2435-01-A32 | Index Collar | |
| A2435-01-A33 | Pawl Actuating Pin | |
| A2435-01-B34 | Mounting Plate Skirt | |
| A2435-01-A35 | Feedback Pot | |
| A2435-01-A36 | Trim Pot | |
| A2435-01-A37 | Gearhead Motor | |
| A2435-01-A38 | Transfer Cluster "A" | |
| A2435-01-A39 | Transfer Cluster "B" | |
| A2435-01-A40 | Lock Screw (Sub Cover) | |
| A2435-01-A41 | Spring Washer (Sub Cover Screw) | |
| A2435-01-A42 | Retaining Ring (Sub Cover Screw) | |
| A2435-01-A43 | Handle Screw | |
| A2435-01-A44 | Pawl Spring | |
| A2435-01-B45 | Sub Cover | |

TITLE

E. LIST OF DRAWINGS - SKYSCREEN COMPUTER

MANUAL INPUT FOR ELEVATION OF PRINCIPAL POINT

| DRAWING NO. | DESCRIPTION | REMARKS |
|---|---|---|
| A2435-01-A46 | Reinforcing Rod | |
| A2435-01-A47 | Locking Screw | |
| A2435-01-C50 | Assembly of Manual Input for Elevation of Principal Point with Microscope Assembly | |
| A2435-01-C51 | Assembly of Manual Input for Elevation of Principal Point | |
| A2435-01-B52 | Microscope Assembly | |
| A2435-01-A53 | Stand-Off Bushing | |
| A2435-01-A54 | Window Retainer Ring | |
| A2435-01-A55 | Resolver Clamp | |
| A2435-01-A56 | Dial Adjustment Screw | |
| A2435-01-A57 | Locating Stud | |
| A2435-01-A58 | Lead Hold-Down Washer | |
| A2435-01-A59 | Hold-Down Screw | |
| A2435-01-A60 | Dial Gasket | |
| A2435-01-A61 | Pilot Light Bushing | |
| A2435-01-A62 | Knob | |
| A2435-01-A63 | Detent Washer | |
| A2435-01-A64 | Shaft | |
| A2435-01-A65 | Detent Spring | |
| A2435-01-A66 | Cap Screw | |
| A2435-01-A67 | Slide Retainer Plate | |
| A2435-01-A68 | Rack | |
| A2435-01-A69 | Slide | |
| A2435-01-A70 | Gear | |
| A2435-01-A71 | Microscope Platform | |
| A2435-01-B72 | Dial Assembly | |

TITLE E. LIST OF DRAWINGS - SKYSCREEN COMPUTER

MANUAL INPUT FOR ELEVATION OF PRINCIPAL POINT CONTINUED

| DRAWING NO. | DESCRIPTION | REMARKS |
|---|---|---|
| A2435-01-B73 | Adapter Plate (Glass Dial) | |
| A2435-01-B74 | Support Plate | |
| A2435-01-B75 | Microscope Bracket | |
| A2435-01-C76 | Resolver Dial Case | |
| A2435-01-C77 | Dial Case Lid | |

ELECTRICAL COMPONENTS

| DRAWING NO. | DESCRIPTION | REMARKS |
|---|---|---|
| 2435-01-C100 | Variable Gain Preamplifier | |
| 2435-01-C100S | Parts List - Variable Gain Preamplifier | |
| 2435-01-C102 | Wiring Diagram for Servo Motor | |
| 2435-01-C103 | Resolver Transformer | |
| 2435-01-C104 | 80 Volt Power Supply | |
| 2435-01-C104S | Parts List - 80 Volt Power Supply | |
| 2435-01-C105 | 80 Volt Power Transformer | |
| 2435-01-C106 | "Auxiliary" 24 Volt Power Supply | |
| 2435-01-C106S | Parts List - 24 Volt Power Supply | |
| 2435-01-C107 | 28 Volt Power Supply | |
| 2435-01-C107S | Parts List - 28 Volt Power Supply | |
| 2435-01-C108 | 28 Volt Power Transformer | |
| 2435-01-B109 | Skyscreen Block Diagram | |
| 2435-01-B110 | "X" Channel Summing Amplifier | |

TITLE

## E. LIST OF DRAWINGS - SKYSCREEN COMPUTER

ELECTRICAL COMPONENTS CONTINUED

| DRAWING NO. | DESCRIPTION | REMARKS |
|---|---|---|
| 2435-01-B110S | Parts List - X Channel Summing Amplifier | |
| 2435-01-B111 | "D" Channel Summing Amplifiers | |
| 2435-01-B111S | Parts List - "D" Channel Summing Amplifier | |
| 2435-01-A112 | Manual Resolver Panel | |
| 2435-01-A113 | Wiring Diagram for Servo Package | |
| 2435-01-A114 | Power Supply Panel | |
| 2435-01-A115 | Amplifier Panel | |
| 2435-01-E116 | Interconnecting Cable Diagram | |
| 2435-01-A117 | Remote Resolver Wiring Diagram | |
| 2435-01-E118S | Amplifier Chassis | |
| 2435-01-E118S | Parts List - Amplifier Chassis | |
| 2435-01-E119 | Internal Computer Wiring Diagram | |
| 2435-01-E120 | Power Chassis | |
| 2435-01-E121 | Skyscreen Computer Schematic | |
| 2435-01-C122 | Feedback Transformer | |
| 2435-01-C123 | "C" Attenuator Transformer | |

TITLE

# F. LIST OF PHOTOGRAPHS - SKYSCREEN COMPUTER

| F.I.L. NO. | TITLE | REMARKS |
|---|---|---|
| H70-2 | Skyscreen Computer System | General View |
| 15022 | Computer Rack, Front | Preliminary |
| 15021 | Computer Rack, Front | Preliminary<br>Scope Raised |
| 14934 | Computer Rack, Rear | Preliminary<br>Cover Removed |
| 14935 | Computer Rack, L. Side | Preliminary<br>Cover Removed |
| 14936 | Computer Rack, R. Side | Preliminary<br>Cover Removed |
| 15025 | Power Chassis, Front Panel | |
| 14940 | Power Chassis, Rear | |
| 15026 | Power Chassis, Rear Quarter | |
| 15027 | Amplifier Chassis, Front Panel | Preliminary |
| 14941 | Amplifier Chassis, Rear | Preliminary |
| 15028 | Amplifier Chassis, Rear Quarter | Preliminary |
| 15023 | Manual Input Chassis, Front Quarter | Preliminary |
| 14937 | Manual Input Chassis, Front | Preliminary |
| 14938 | Manual Input Chassis, Rear | Preliminary |
| 15024 | Manual Input Chassis, Rear Quarter | Preliminary |
| 13717 | Servo on Camera, Side | Showing Handle |
| 13716 | Servo on Camera, Rear | Showing Screens |
| 13662 | Servo Removed from Camera | |
| 13663 | Servo, Cover Removed | Preliminary<br>Showing One Drive<br>Removed |

TITLE

## F. LIST OF PHOTOGRAPHS - SKYSCREEN COMPUTER

| F.I.L. NO. | TITLE | REMARKS |
|---|---|---|
| 13664 | Servo Limit Stop Mechanism | |
| 14308 | Manual Input Assembly | |
| 14309 | Manual Input Assembly, Cover Removed | Showing Glass Dials |
| H70-6 | Skyscreen Computer Rack | General View |
| H70-5 | Amplifier Chassis, Front Panel | |
| H70-8 | Amplifier Chassis, Rear | |
| H70-4 | Manual Input Panel | Closeup |
| H70-10 | Manual Resolver Chassis, Rear | |
| H70-12 | Power Supply Chassis, Rear | Showing Cable Attachment |

## IV. SKYSCREEN COMPUTER SYSTEM TESTS

A number of series of tests have been made on the Skyscreen Computer to define its capabilities and limitations. These include the following:

Independent axis tests to define

(1) hysteresis

(2) linearity

(3) accuracy

(4) effect of cable length

(5) off-screen performance

and combined axis tests to define

(1) overall random accuracy

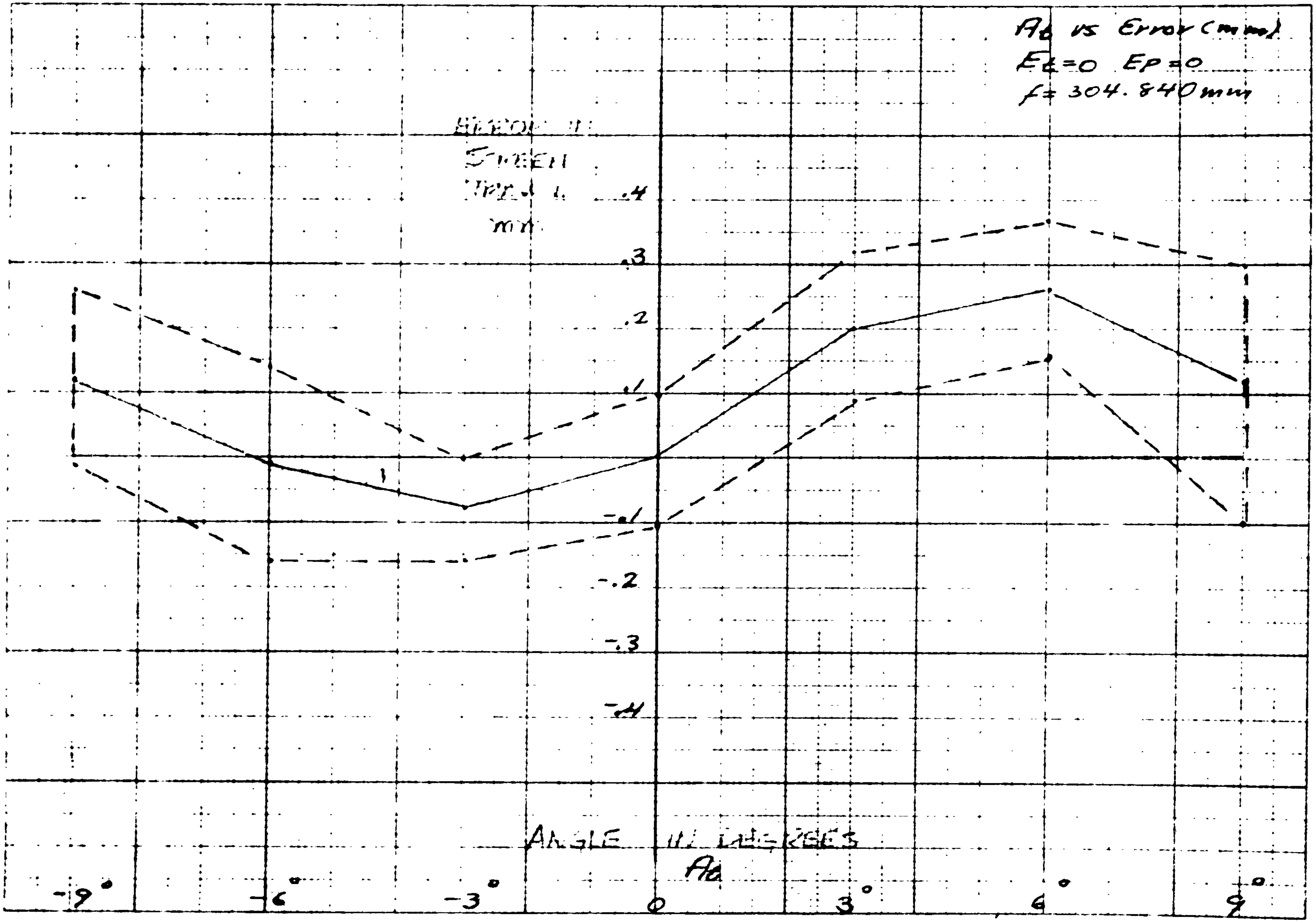
(2) error gradients

### A. Independent Axis Tests

1. Separation of Errors

To define and separate the magnitude of certain component parts of the error, a number of tests were run considering each axis independently. The method was to take two readings at the extremes of travel approaching from opposite directions to include hysteresis, average the readings and calculate an arbitrary focal length $f = \frac{x_1 + x_2}{2 \tan E_t}$ and compute errors from reference points defined by this focal length.

In Figure 23 the composite error (0.63 mm) is shown in the y (horizontal) screen travel for an elevation of $0^{\circ}$ and a focal length


Aφ vs Error (mm)
Eε=0 Ep=0
f=304.840mm
ERROR IN
SCREEN
mm
.4
.3
.2
.1
-.1
-.2
-.3
-.4
ANGLE IN DEGREES
Aφ
-9°
-6°
-3°
0
3°
6°
9°

of 304 mm. Note that it is made up of several distinguishable components, namely,

(1) hysteresis (0.25 mm) indicated by the average vertical distance between error points,

(2) screen windup (0.12 mm) indicated by the average tendency toward curvature upward,

(3) nonlinearity (0.15 mm) indicated by the variation of the error about zero angle, and

(4) scaling error (0.00 mm) indicated as the non-symmetry of the average error about zero error at 9°.

Figure 24 illustrates y axis errors for another condition of focal length.

Similar tests were run on the x (vertical) axis with the results shown in Figure 25. In general the errors are greater than for the horizontal axis due to the more complex computation channel. The composite error is 0.72 mm which can be broken down into

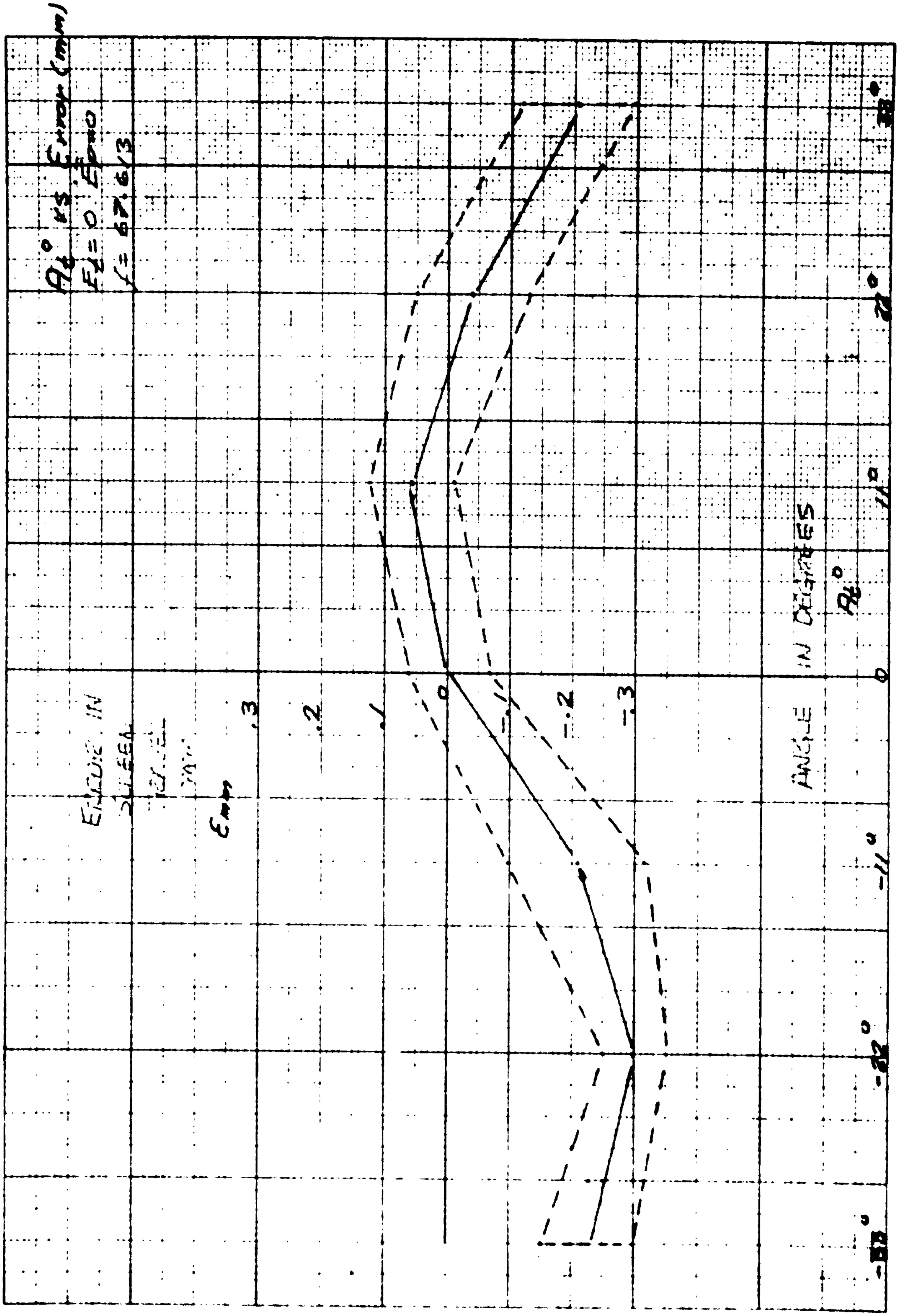
(1) hysteresis, 0.30 mm

(2) screen windup, 0.20 mm

(3) nonlinearity, 0.40 mm

(4) scaling, 0.02 mm

Figures 26 and 27 illustrate the composite errors in the vertical direction for other conditions of camera elevation and focal length.



$A_t^\circ$ vs Error (mm)
$F_t = 0$ $E_p = 0$
$f = 67.613$
ERROR IN
$E_{mm}$
.3
.2
.1
0
-.1
-.2
-.3
ANGLE IN DEGREES
$A_t^\circ$
33°
22°
11°
0
-11°
-22°
-33°


F GURE 24

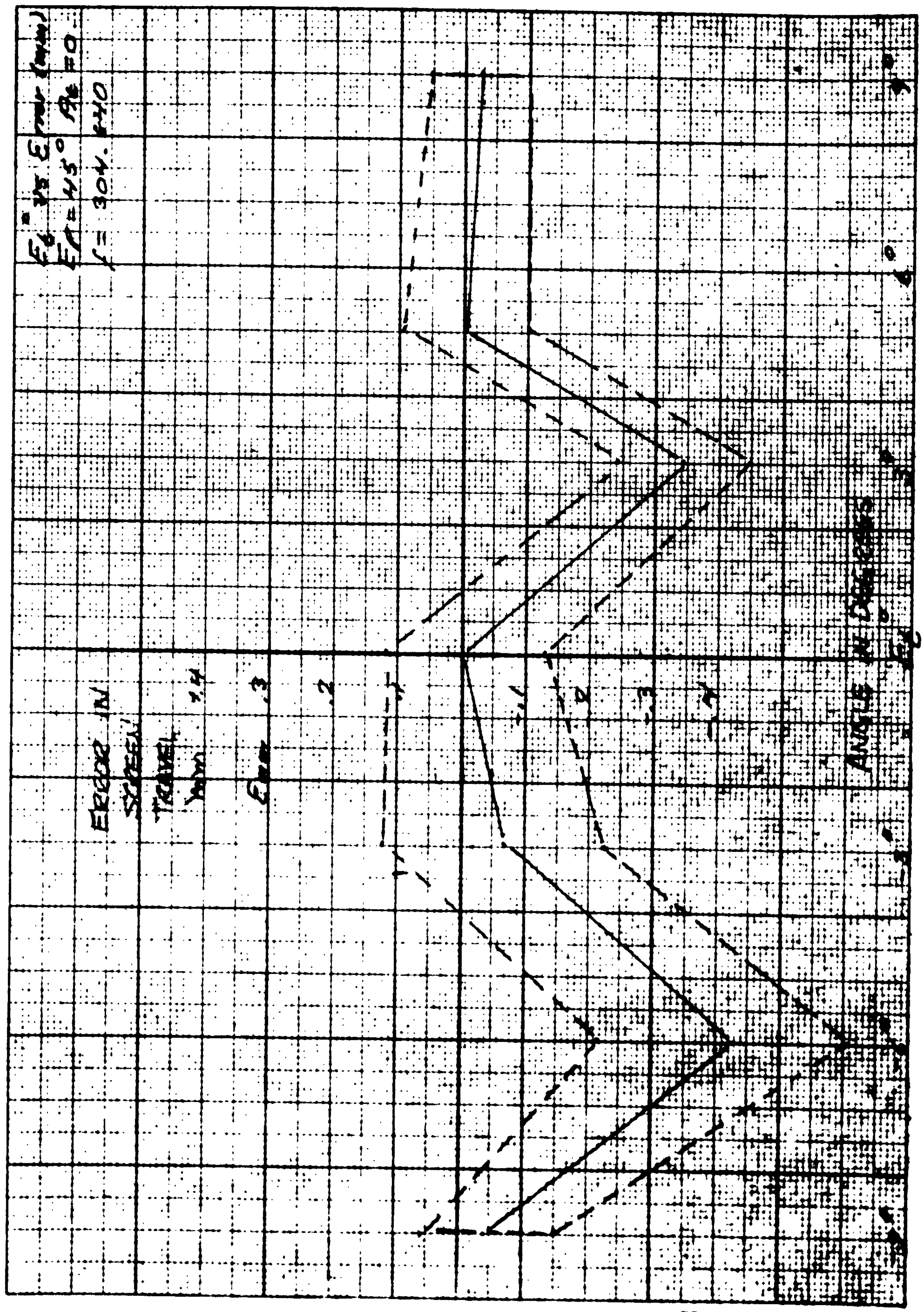



FIGURE 25

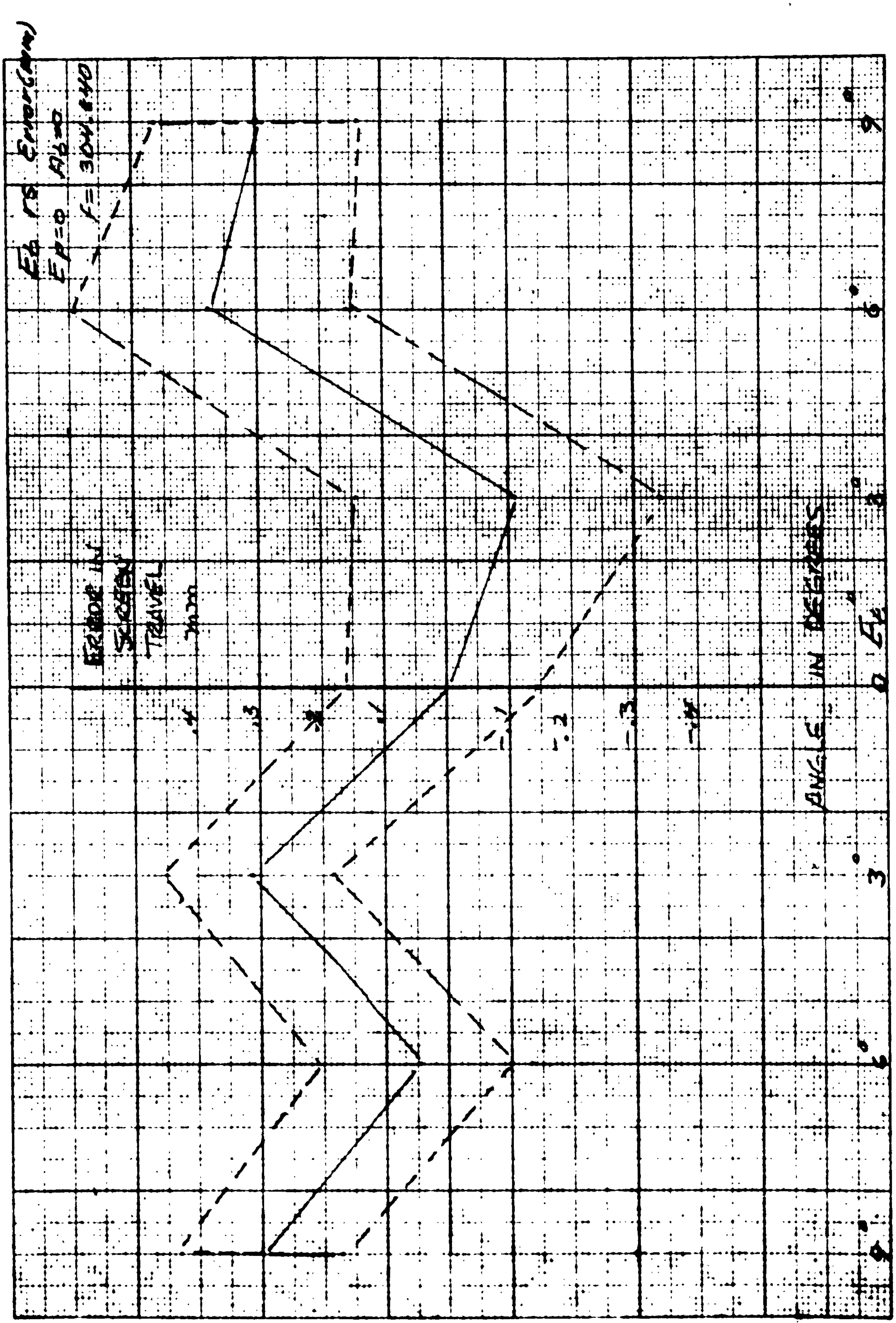

Eb vs Error (mm)
Ep=0 Ab=0
f = 304.840
ERROR IN SCREEN TRAVEL (mm)
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
ANGLE IN DEGREES Eb
9
6
3
0
3
6
9

FIGURE 26

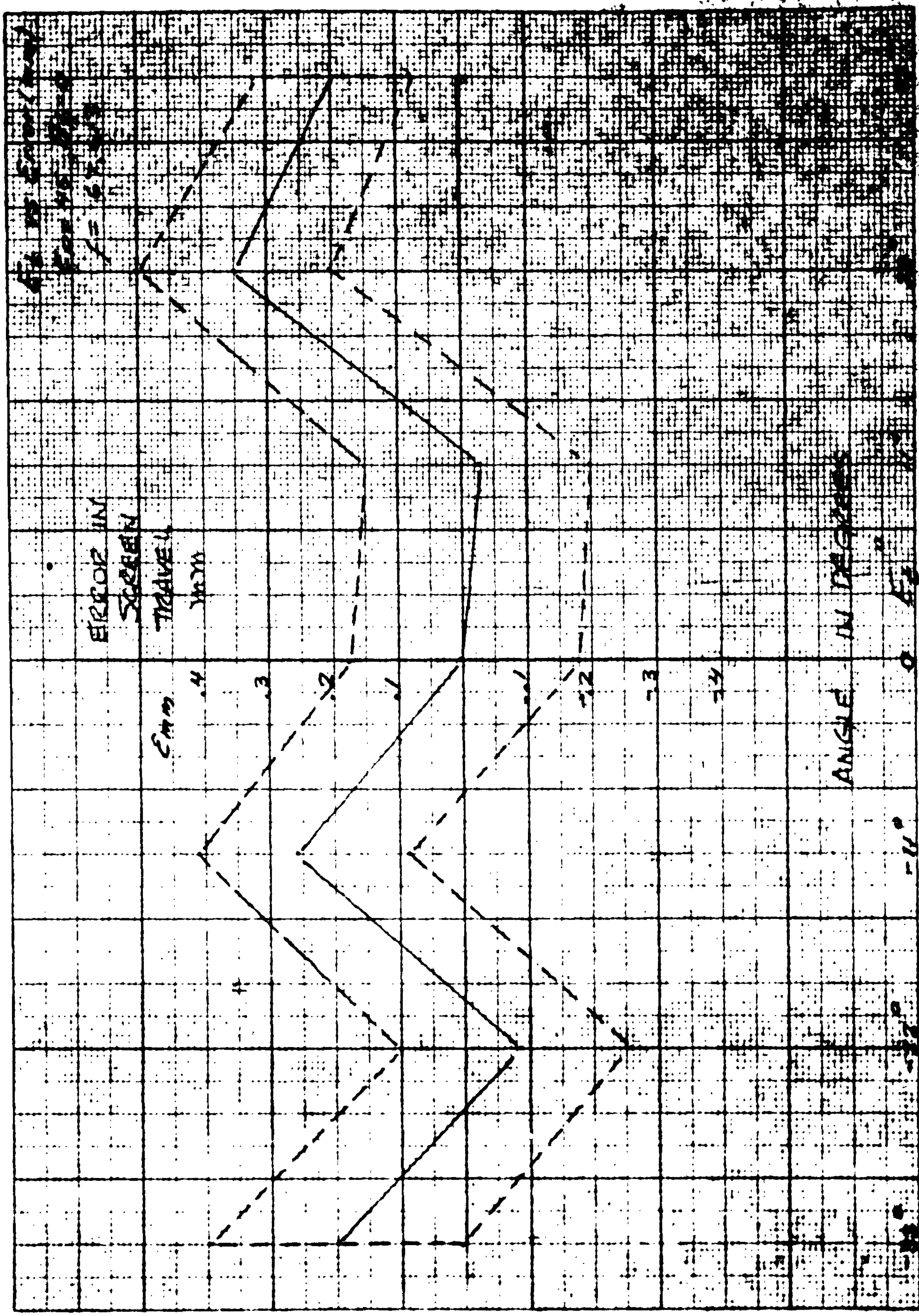

ERROR IN SCREEN TRAVEL mm
Emm
.4
.3
.2
.1
-.1
-.2
-.3
-.4
ANGLE IN DEGREES
0
-11°
-22°

FIGURE 27

2. Effect of Cable Length

To determine the effect of cable length, a comparison was made between errors obtained when the system was trimmed for short cables (less than 10 ft) and when long cables (approximately 100 ft) were substituted without retrimming. The results are shown in Figures 28 and 29 showing that the Skyscreen Computer performance is acceptable without readjustment for cable lengths up to 100 ft.

3. Performance Off-Camera

To eliminate the contribution of the Skyscreens from the performance of the Computer itself, a few tests were run with the Servo Package removed from the camera. The method of test was to use the final drive gear teeth as an indication of output position, advancing the input angle an increment necessary to advance one tooth width. The results are shown in Figure 30. The hysteresis is reduced to 0.15 mm, screen windup is eliminated, nonlinearity is 0.10 mm and scaling is not significant. Since the gears were not loaded with the Skyscreen springs, approximately half the hysteresis can be attributed to gear backlash.

B. Combined Axis Tests

A number of tests were made of the entire Skyscreen Computer System with 100 ft cables using complex inputs. That is, simultaneous deflections of the azimuth and elevation resolvers. The readings were taken randomly, eliminating some of the hysteresis, and compared with a set of hand calculated data supplied by the Ballistic Research Laboratories. Total error at each point was computed as a resultant of horizontal and

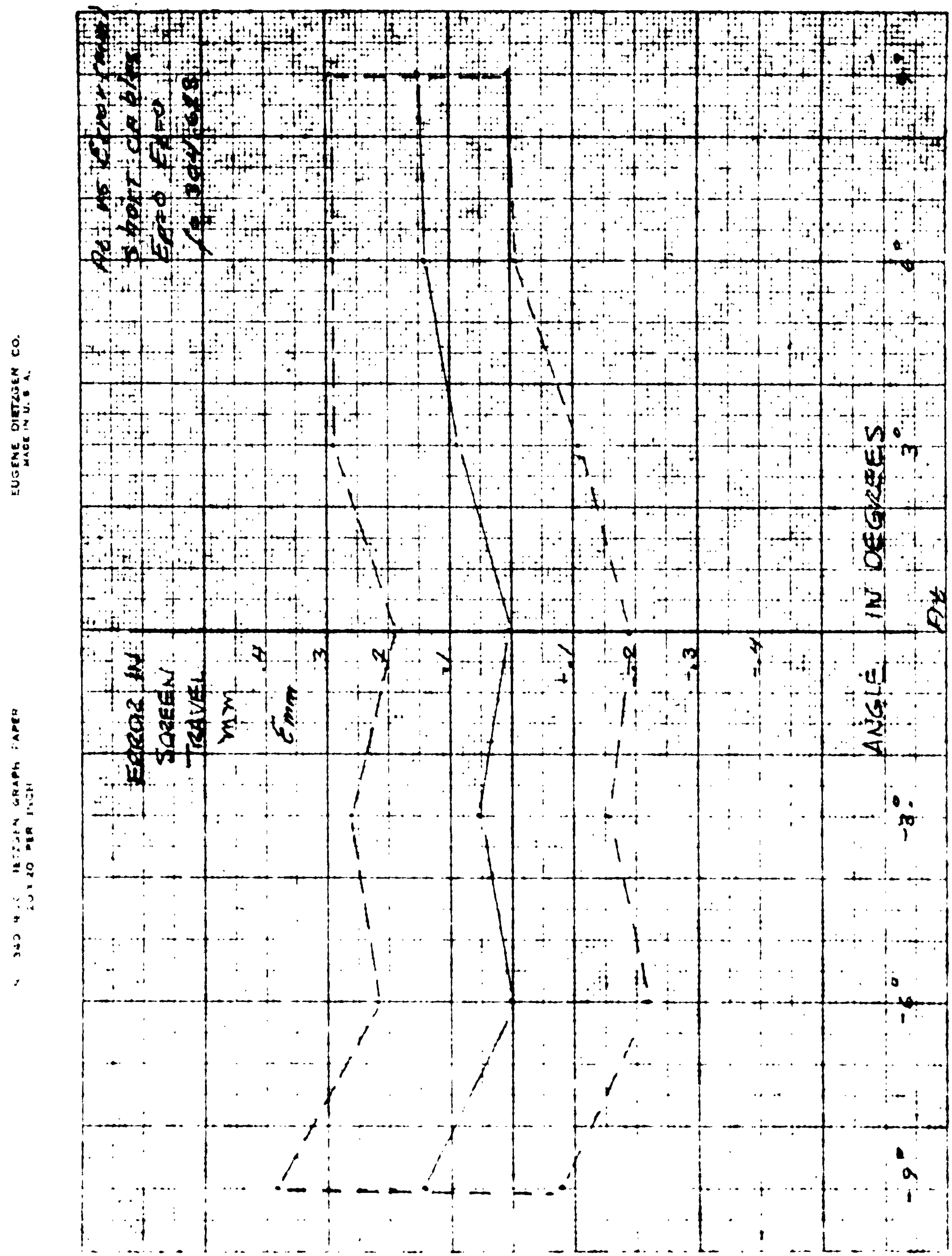

ERROR IN SCREEN TRAVEL
MM
ANGLE IN DEGREES
EUGENE DIETZGEN CO.
MADE IN U.S.A.

FIGURE 28

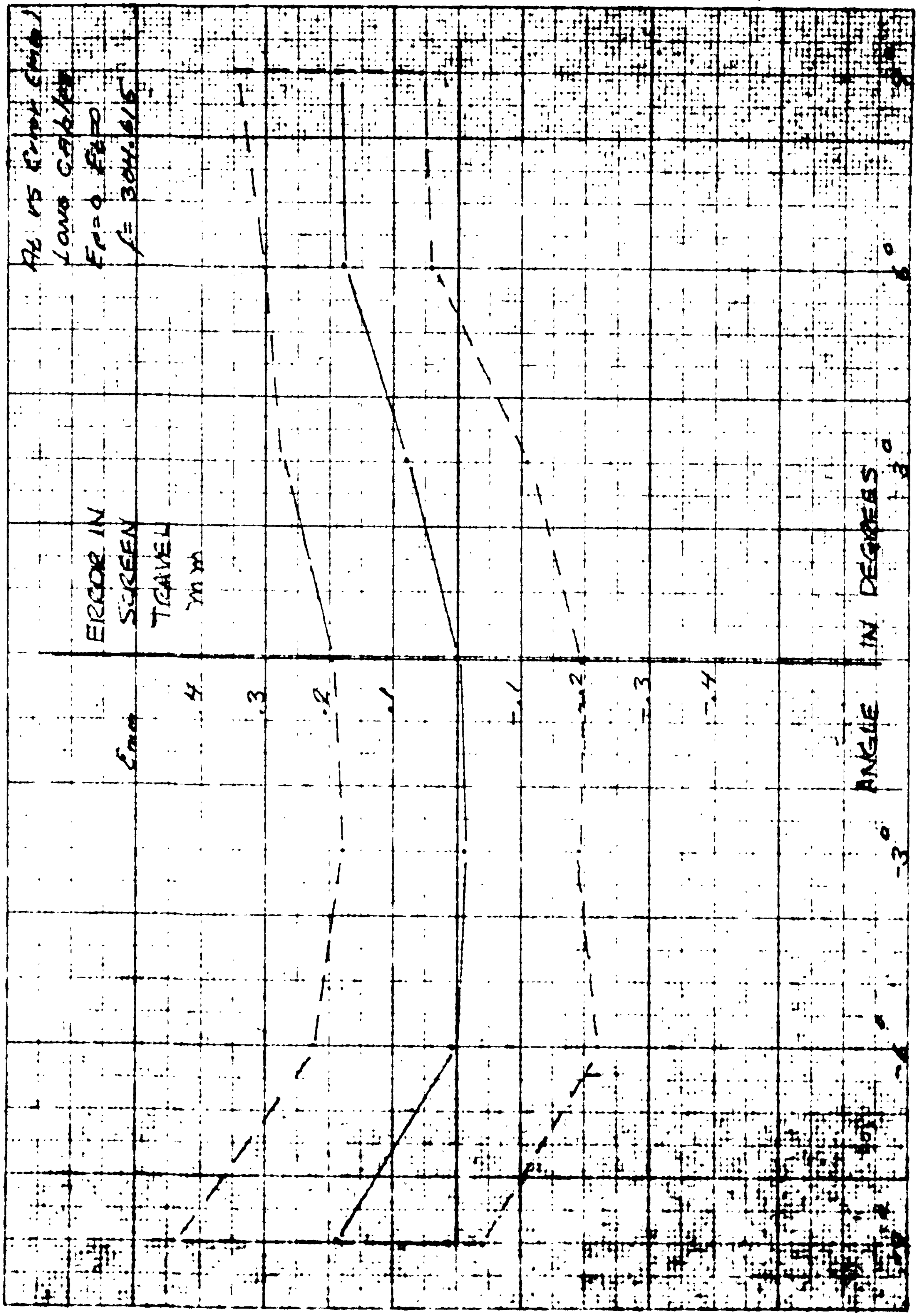



FIGURE 29

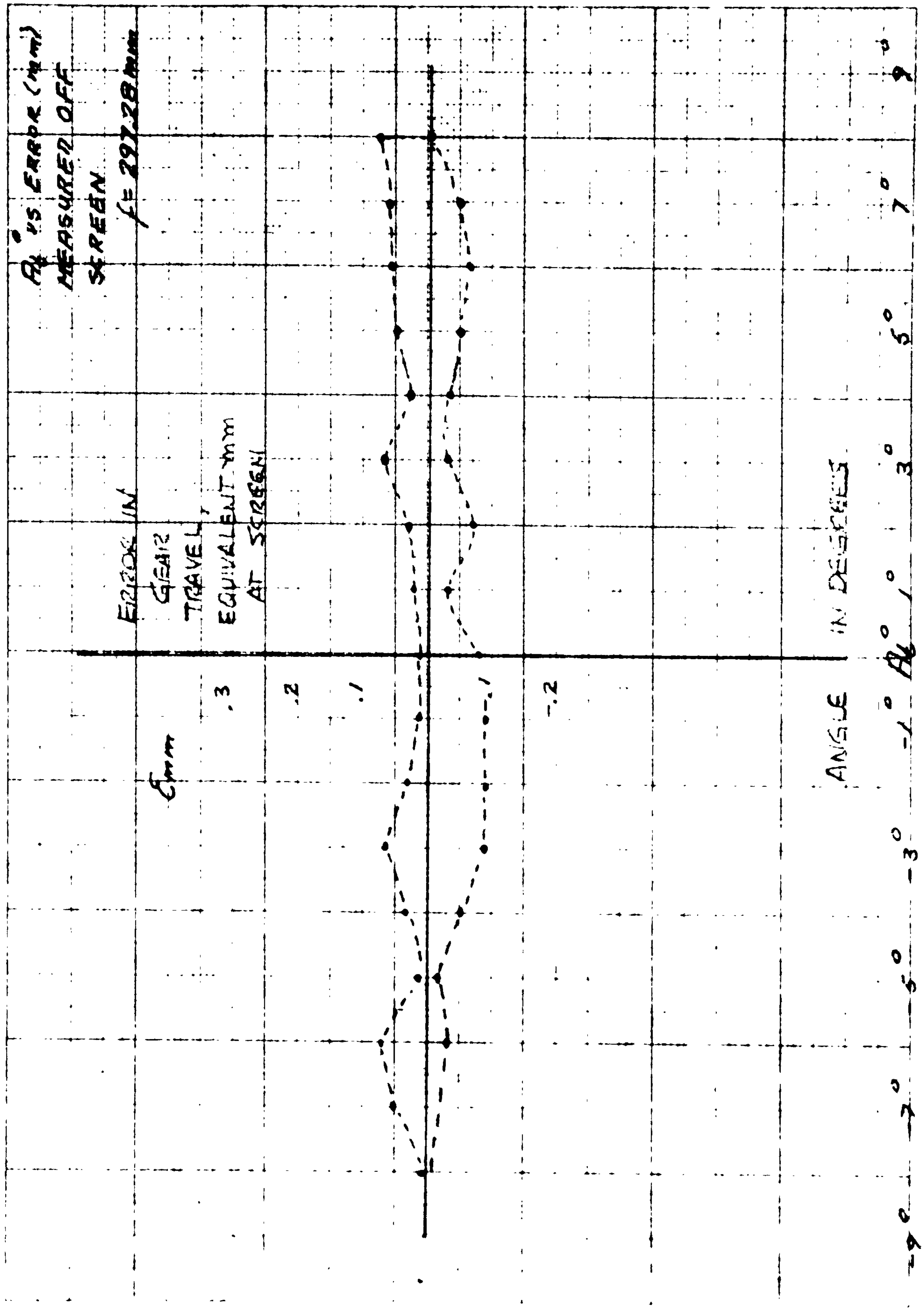

A vs ERROR (mm)
MEASURED OFF
SCREEN
f = 297.28 mm
ERROR IN
GEAR
TRAVEL,
EQUIVALENT mm
AT SCREEN
E mm
.3
.2
.1
-.1
-.2
ANGLE IN DEGREES

FIGURE 3C

vertical error. The results are shown in Figures 31 and 32 as plots of the errors over the face of the photograph plate. Note that the maximum composite resultant error is 1.0 mm. The average error is 0.4 mm.

Some of this error is contributed by the screens themselves since the slit edges, where position measurements were made, are not straight. A measure of the errors contributed by the slit edges is shown in Figures 33 and 34.

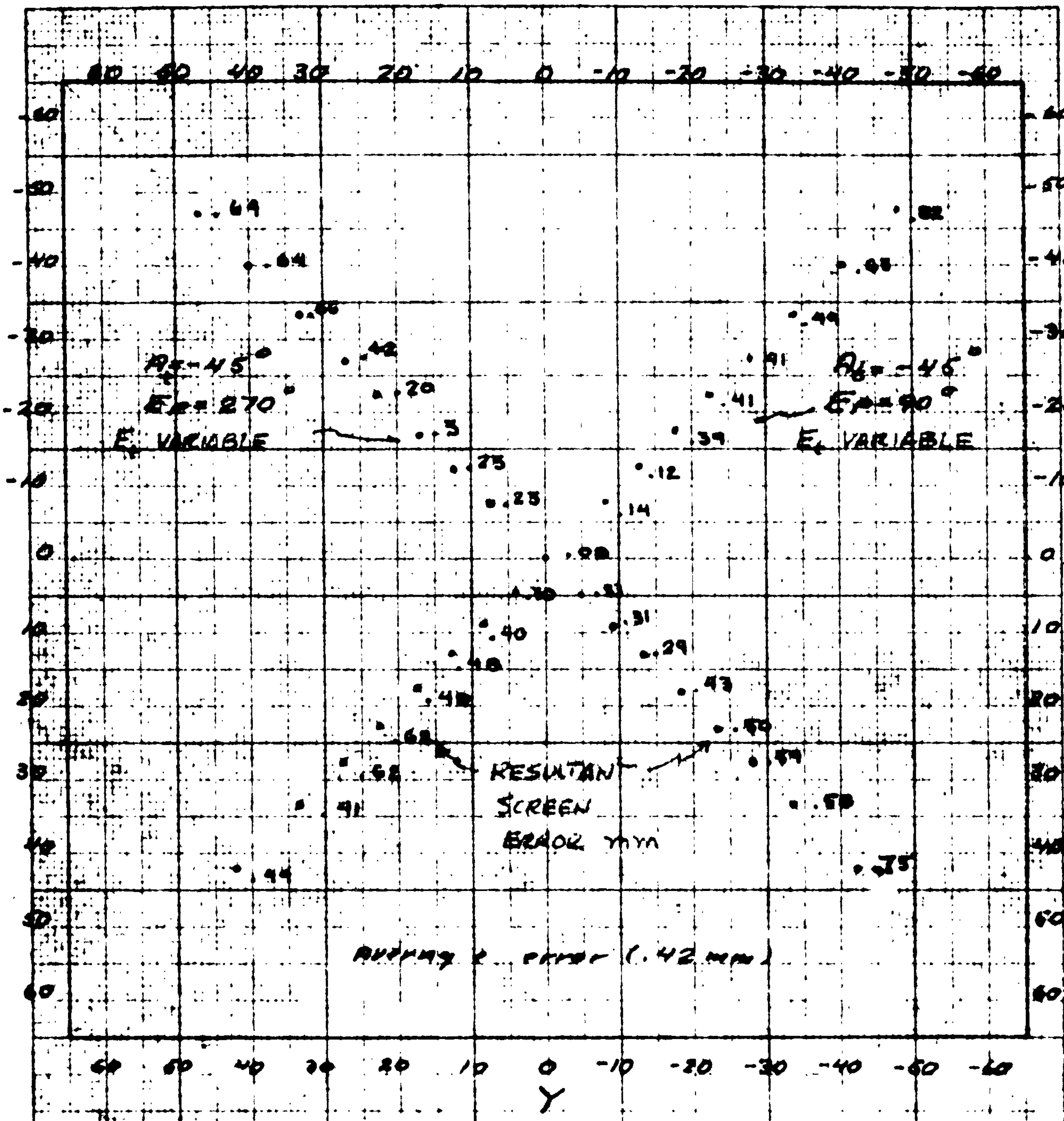
## V. CONCLUSIONS AND RECOMMENDATIONS

The electromechanical Skyscreen Computer System described in this report has proved to be a significant development in the field of analog computation. By means of ultra-precise components and careful attention to circuit trimming, resulting accuracies approach normal limits of analog systems. The Skyscreen System is relatively simple to adjust and operate in field use. Predicted reliability and life are outstanding because of the use throughout of all solid-state electronic circuits. All units are designed for operation in ambient temperatures up to 140°F.

In the development of the Skyscreen Computer experience has been gained which should lead to the improvement in design, adjustment and performance of future models. Specific recommendations are as follows:

(1) Provide a 60-400 cycle frequency changer with better regulation and less harmonic voltage. (5 to 10% voltage and frequency regulation and harmonics)

(2) Redesign the vertical channel attenuator to eliminate the need for a tapped transformer which introduces phase distortion




FOCAL LENGTH SPECIFIED 68.000
FOCAL LENGTH MEASURED 68.087
PARA POSITION 146.45

RESULTANT SCREEN ERRORS - TEST 1

FIGURE 31

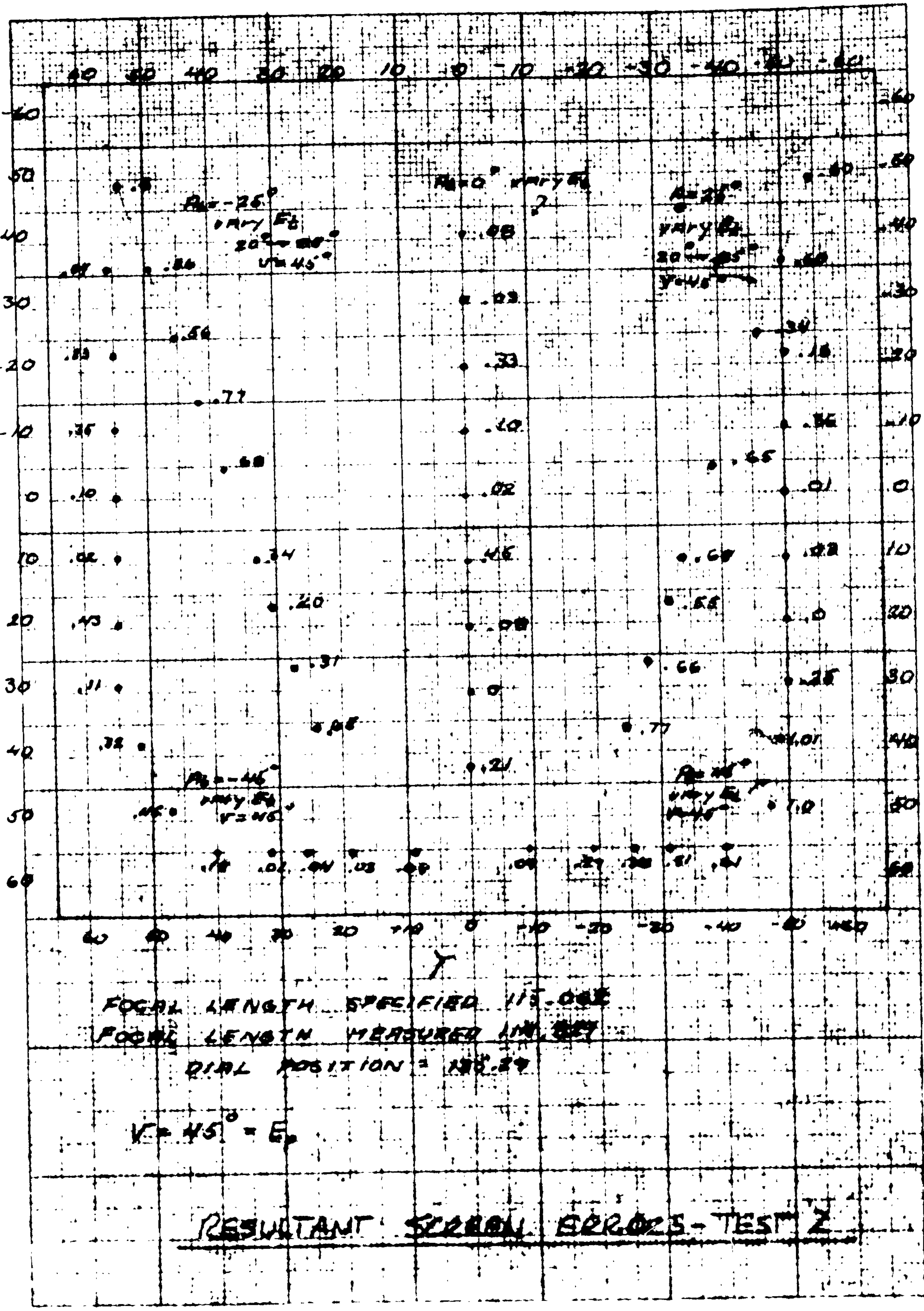

X
Y
FOCAL LENGTH SPECIFIED
FOCAL LENGTH MEASURED
DIAL POSITION =
RESULTANT SCREEN ERRORS - TEST 2

FIGURE 32

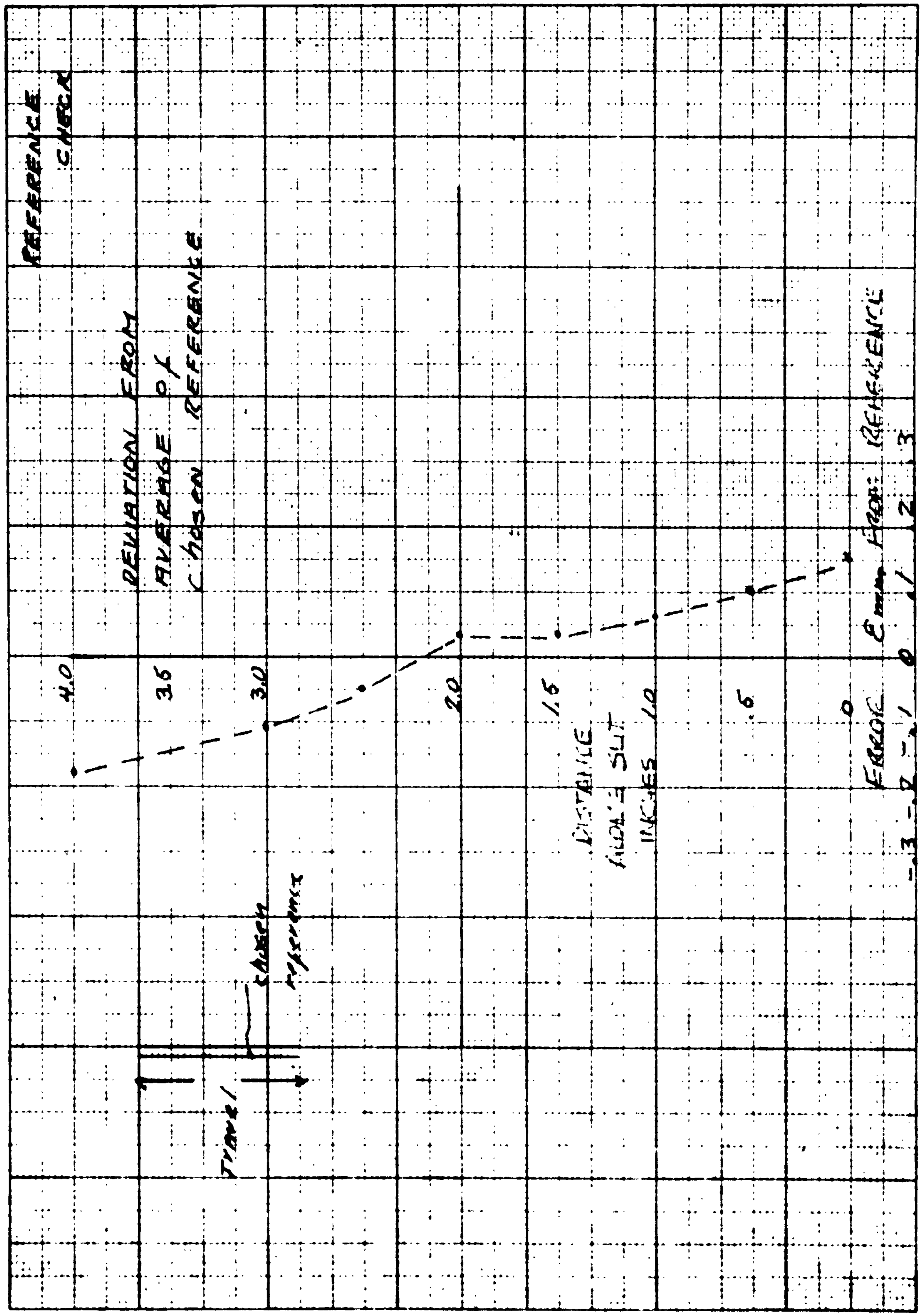

REFERENCE CHECK
DEVIATION FROM AVERAGE of Chosen REFERENCE
4.0
3.5
3.0
2.0
1.5
1.0
.5
0
DISTANCE ALONG SLIT INCHES
ERROR
-.3 -.2 -.1 0 .1 .2 .3
Travel
Chosen reference

FIGURE 33

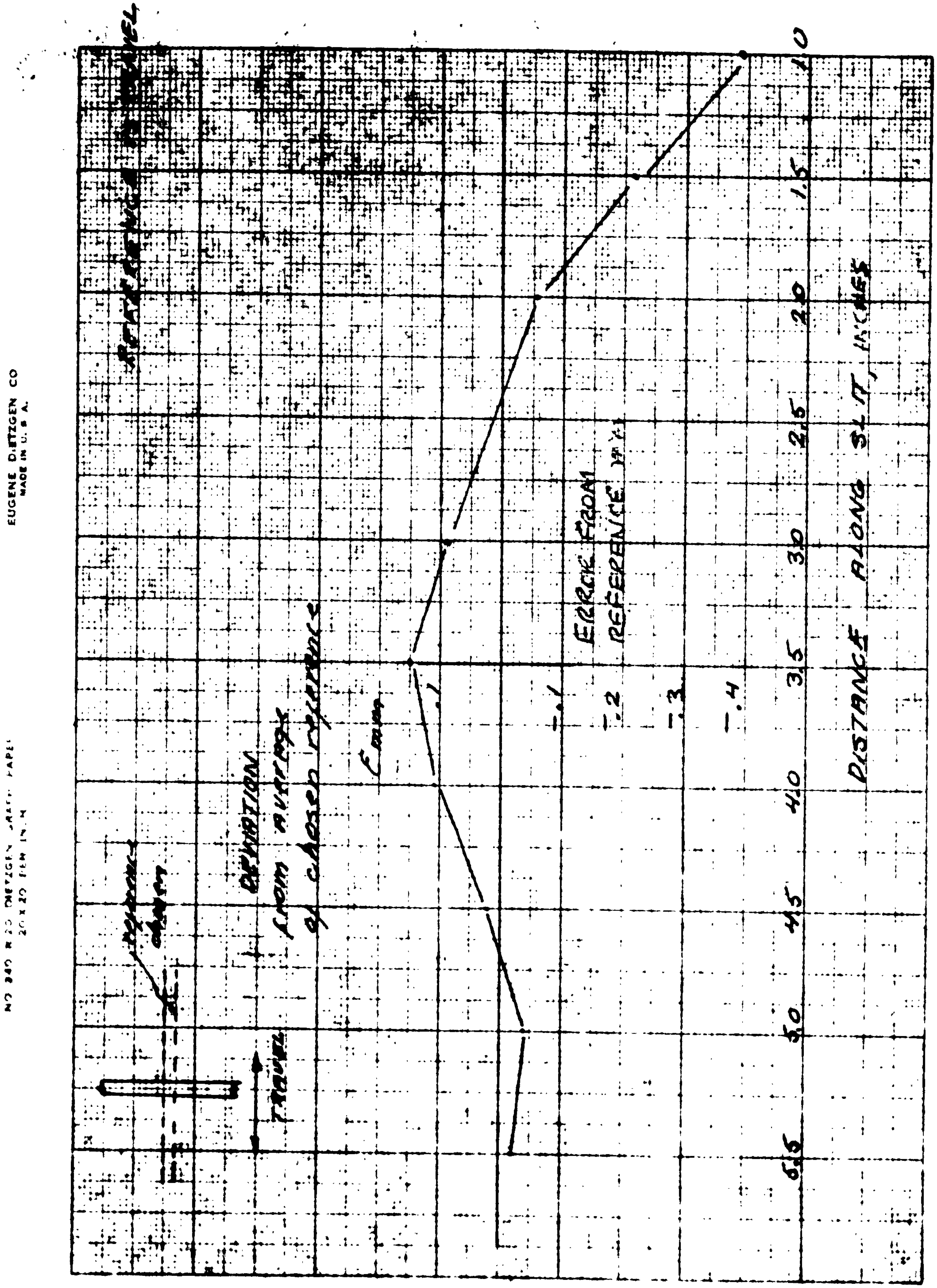

EUGENE DIETZGEN CO
MADE IN U.S.A.
DISTANCE ALONG SLIT, INCHES
ERROR FROM REFERENCE
DEVIATION FROM AVERAGE OF CLOSED REFERENCE
TRAVEL
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
.1
-.1
-.2
-.3
-.4

FIGURE 34

and makes alignment more difficult.

(3) Procure an improved solid-state, gain-controlled servo preamplifier with better stability for improved reproducibility.

(4) Provide more travel between electrical and mechanical limits to avoid striking the mechanical stops.

(5) Redesign manual input panel for better optical and mechanical stability.

(6) Include a digital readout of actual computed focal length with internal reference to avoid the need for attenuator calibration.

(7) Redesign computer rack layout to reduce physical size.

The prototype Skyscreen Computer is now ready for field evaluation. Because of the high cost of ultra-precise components and the difficulties of adjusting for presently specified accuracies, it is strongly suggested that the requirements for the application be carefully reviewed. Significant savings are possible with reduced accuracy specifications.

Anthony Marmarou
Research Engineer

Richard H. Field
Technical Associate

Approved by:

Charles A. Belsterling, Manager
Power and Control Laboratory

C. W. Hargens
Technical Director

Francis L. Jackson
Director of Laboratories

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The Franklin Institute Laboratories, Philadelphia 3, Penna.

"DEVELOPMENT OF A SKYSCREEN COMPUTER"
Anthony Marmarou, Richard H. Field, Charles A. Belsterling

Report F-A2435-01, June 1, 1960 to July 12, 1962
22 pp, 34 Figs.

Ballistic Research Laboratories Contract No. DA-36-034-509-ORD-3241-RD

This report describes the functional requirements, development and test of a new electromechanical analog computer. Its purpose is to position blanking screens in a missile-tracking phototheodolite camera to avoid overexposure of the photographic plate. Azimuth and elevation information are continuously varying inputs from a tracking instrument. The Skyscreen Computer solves the trigonometric equations necessary to transform the spherical coordinates of the target with respect to the tracking instrument into rectilinear coordinates of the focal plane in the phototheodolite.

The Skyscreen Computer System was developed successfully using ultra-precise electromechanical devices, all solid-state electronic circuits and high-quality mechanical components. Laboratory tests show that the System positions the aperture in the camera screens with an average error of 0.4 mm and a maximum error of 1.0 mm. These results indicate an overall average accuracy of one part in 320 which approaches the reasonable limit of a complex analog system.

The Skyscreen Computer is now ready for evaluation in field use.

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