A FLYING SPOT SCANNER SYSTEM

by

S. A. Underwood
D. H. Williams
P. Costa
J. K. Aggarwal
Department of Electrical Engineering
The University of Texas at Austin
Austin, Texas 78712

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Electronics Research Center
The University of Texas at Austin
Austin, Texas 78712

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ABSTRACT

A Flying Spot Scanner (FSS) system has been designed and constructed to digitize color images from 35 mm transparencies. This system features random access operation and can output a maximum of 8 bits of intensity information with a resolution of 20 lines/mm for each of the red, blue, and green channels. Each transparency may be digitized into a maximum of 4096 x 4096 points with a cycle time of 200 μsec/point. A flexible software system permits histogram and color triangle distributions to be outputted along with the color intensity, color hue, and color purity information.

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I. INTRODUCTION

The following paper describes the design and operation of a Flying Spot Scanner (FSS) system which digitizes color images from standard 35 mm transparencies. The FSS technique was initially selected over alternate methods because it offered the unique combination of good speed, good resolution and excellent flexibility. Other digitizing methods (i.e., photodensitometers, dissector cameras) are available which are equal or superior in performance for one or two of these attributes, but none give the balanced overall performance which uniquely makes the FSS a valuable research tool.

Our scanner has the following features: For flexibility, random access operation is available so that all or part of a transparency may be scanned without obtaining a large amount of unwanted information. For speed, the red, blue,and green intensities are digitized simultaneously with each of the three channels outputting a maximum of 8 bits of intensity information. Resolution is 20 lines/mm and the largest 38 mm square format may be digitized into a maximum array of 4096 x 4096 points with a nominal cycle time of 200 μsec/point.

The scanner consists of three main parts: the optics, the electronics, and the software. An XDS 930 digital computer provides the software instructions and also stores the output information.

The optical system images a spot of light from a precision cathode ray tube (CRT) onto a 35 mm transparency. As the spot of light is positioned on the film at a preset number of discrete points, the spot is transmitted through the transparency according to the density and color of the film at each location. The resulting light signal is optically changed into its red, blue, and green primary components and imaged upon three photomultipliers (PMT) which transform the light information into electronic signals.

The electronic system provides deflection information to the CRT and controls the scanner operation so that the proper chain of events occur in the correct sequence. Also, the PMT signals, proportioned to the red, blue and green outputs, are processed and sent to XDS 930 where they are stored. The software has overall command of the scanner to permit flexible operation. Software controls the random access operation which allows scanning of all or only part of the transparency. In addition, standard processing packages are integrated with the digitized output so that useful information such as histogram and chromaticity distributions are calculated as data is obtained. The color information may be outputted as a picture on the computer line printer or a storage display or simply stored on magnetic tape. All in all, the unique combination of good resolution, speed and very flexible software makes this system a very powerful tool for color digital image processing.

II. OPTICS

The optical system images the CRT spot upon the transparency and then separates the resulting signal into the three red, blue,and green components to obtain the color information. Figure 1 shows a general diagram for the optical system.

a. Imaging and Sampling Optics

A Gould-Beta-Data precision CRT with P-24 spectral response generates a light spot that is nominally 1.5 mils in diameter. The spot is demagnified by a factor of 1.65 by the 150 mm f1.3 objective lens assembly and imaged upon the transparency. This increases the maximum resolution of the system by reducing the spot size at the film plane by a factor of 1.65 down to 0.91 mils. It also increases the distance that the CRT must be deflected so that 35 mm is the largest format utilized.

The objective lens is a prepackaged assembly of four color corrected lenses with an adjustable aperture. It causes no measurable spatial distortion and outputs a strong signal due to the large aperture which is set at f4.0. Larger aperture settings cause light to be lost off the edges of the following lenses.

Figure 2 shows the imaging of the spot and sampling optics. Sampling is necessary because the CRT phosphor is spatially inhomogeneous causing the spot intensity to vary from point to point on the face of the CRT. To correct for this variation, the spot is sampled before it reaches the film plane, so that processing occurs only after the spot intensity has reached a preset level.

The spot is sampled by aiming a photomultiplier assembly directly at the face of the CRT. This method is used instead of the more standard method of placing a beam splitter at the focal point of the main objective lens since the large size of the objective lens and beam splitter caused

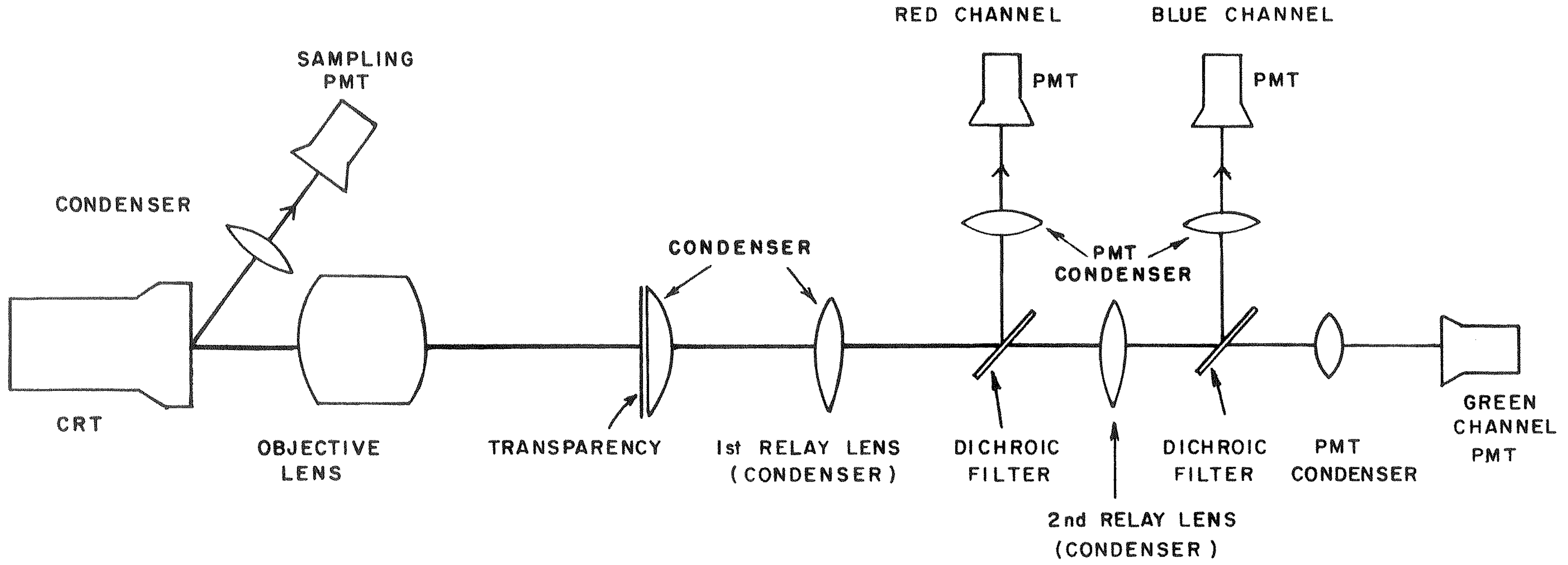


Figure 1. Scanner Optical System

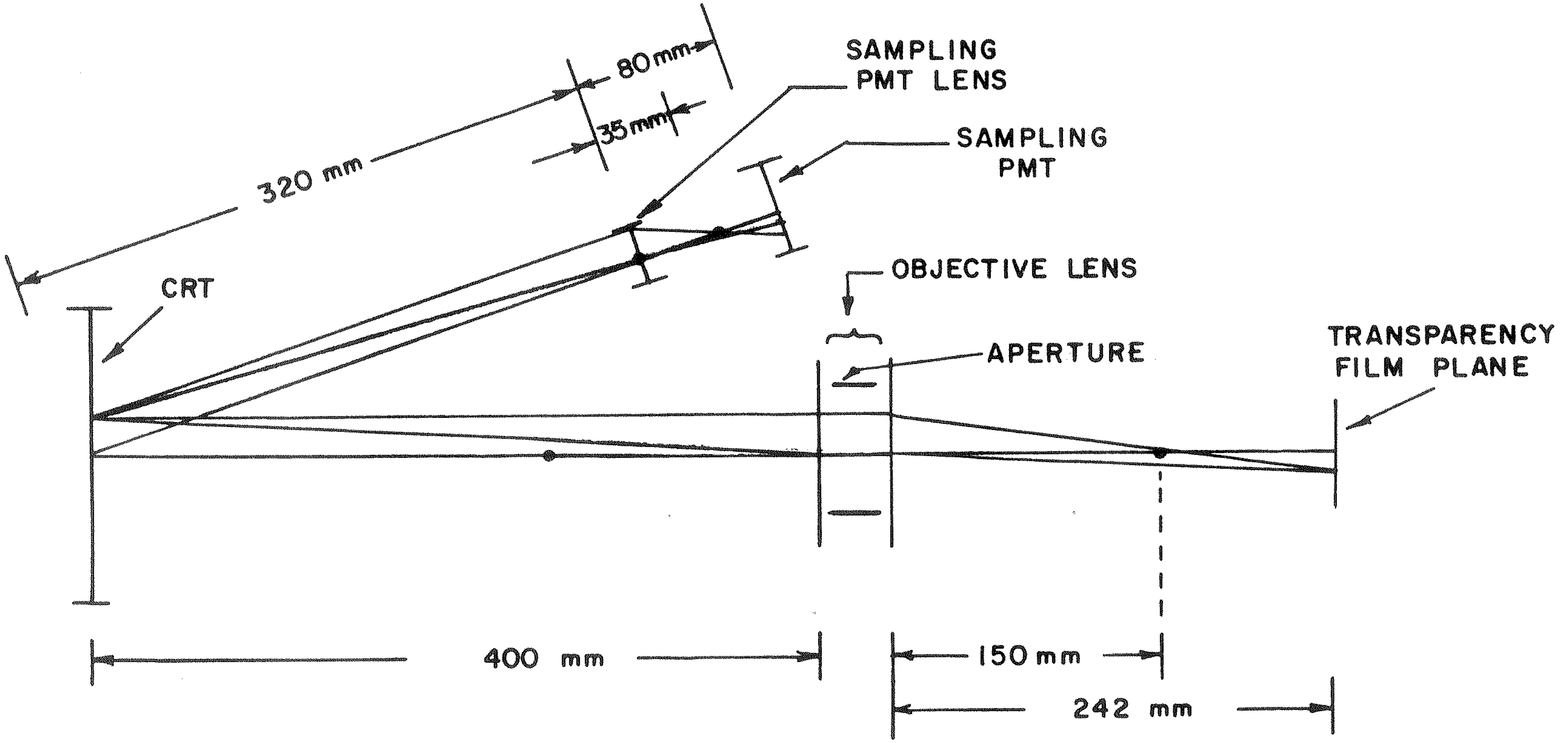


Figure 2. Imaging and Sampling Optics

poor results. The sample optics consists of a Takumar f2.0 35 mm camera lens with an adjustable aperture which is mounted directly on the photomultiplier assembly.

Note (Fig. 2) that the light spot is defocused at the sampling PMT image plane. This makes the signal insensitive to local imperfections on the face of the PMT that would otherwise tend to cause noise if the spot were sharply focused. Also, the intensity of the CRT is not constant since the sampling PMT is offset and not equidistant from all points on the face of the CRT. To correct for this a correction factor in the software proportional to R_0^2 / R_1^2 is used to correct the output intensities. R_0 is the distance from the CRT origin to the PMT while R_1 is the distance from a given point on the CRT to the PMT.

b. Color Separation and PMT Optics

After the spot is imaged on the transparency, the lens system shown in Fig. 3 is used to catch the light and separate it into the three primary red, blue, and green components. Characteristics of the lens are shown in Table 1. Since no images are being formed, relatively inexpensive Pyrex lens can be used without degrading the performance of the system.

Lens L2 is a plano-convex type and is located at the film plane to catch the light diffracted by the transparency image. The light still diverges as it leaves lens L2, but the first relay lens, L3, is positioned to gather all of the light and reconverge it so that the light can be imaged entirely on the red dichroic filter. The filter is positioned so that the dichroic filter, the second relay lens, L4, and the red PMT condenser, L6, can be of reasonable size without losing any light.

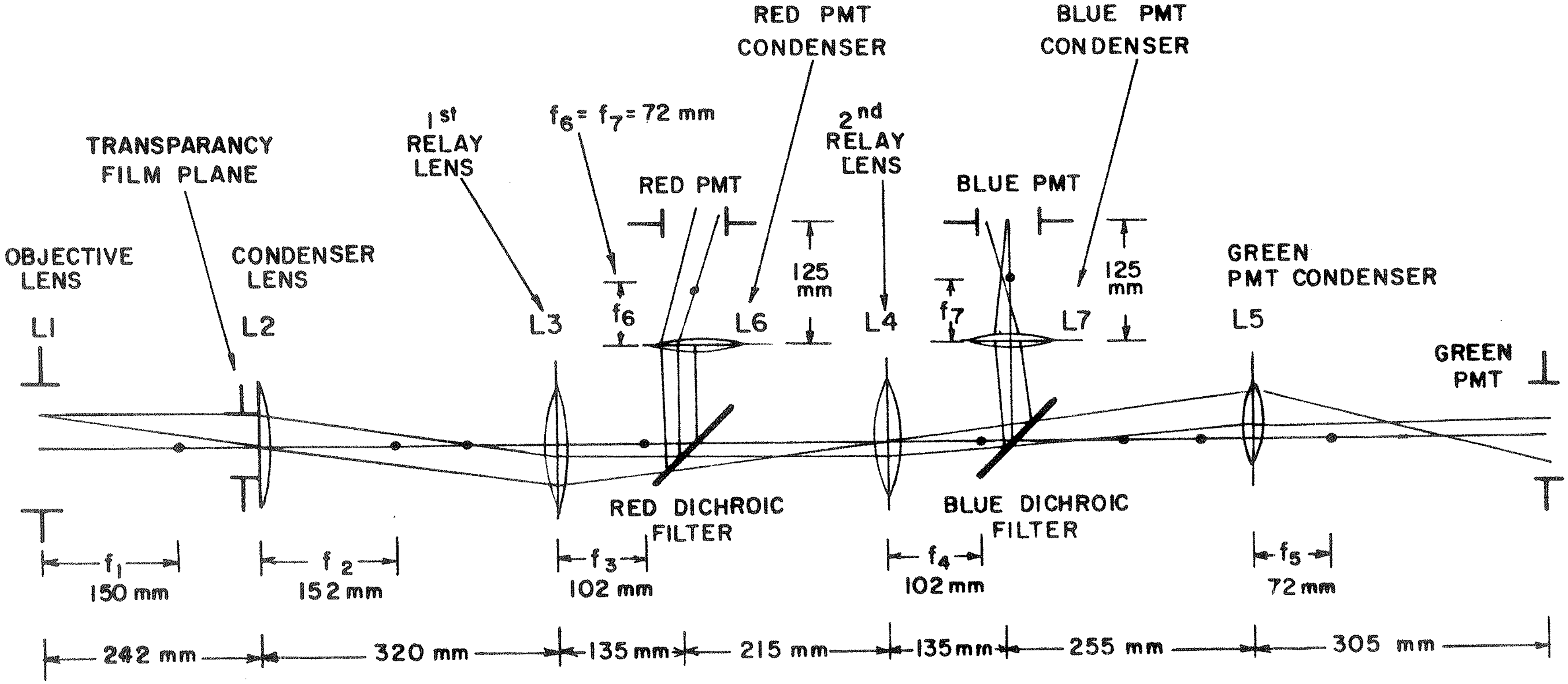


Figure 3. Color Separation Optics

TABLE 1. LENS CHARACTERISTICS

LENS	TYPE	DIAMETER (mm)	FOCAL LENGTH (mm)
L1	Color Corrected System W/Stop	115 max	150
L2	Plano Convex	115	152
L3	Double Convex	127	102
L4	Double Convex	127	102
L5	Plano Convex	75	72
L6	Double Convex	75	72
L7	Double Convex	75	72

The red dichroic filter reflects red light (above 5800 Å) through the red condenser, L6, into the red PMT, and transmits blue-green light (below 5800 Å) to the second relay lens. The red light is imaged by the red PMT condenser into a defocused circle at the face of the PMT.

The now diverging blue-green light is reconverged by the second relay lens and is then imaged as a defocused elipse on the blue dichroic filter. This dichroic filter reflects blue light (below 5000 Å) into the blue PMT condenser, L7, and transmits the remaining green light (between 5000 Å and 5800 Å) to the green PMT condenser, L5.

Again the dichroic filter is placed so that the remaining condenser lenses (L5 and L7) can be of reasonable size without losing any light. The blue light is imaged by the blue PMT condenser as a defocused circle on the face of the blue PMT and the green light is imaged in a similar manner on the face of the green PMT.

The photomultipliers are two inch end window type (EMI 9958B) with S20 spectral response. Each PMT assembly contains an electronic shutter and an adjustable aperture. The PMT's have a peak quantum efficiency of 21.6 percent at 400 nm which drops to 2.5 percent at 700 nm. Combined with a blue-white CRT spot, this causes the system to give a stronger response in the blue end of the spectrum.

III. ELECTRONICS

The electronics system controls the FSS operation and processes the signals flowing in and out of the scanner so that they are of the proper form and occur in the proper sequence during each cycle. Figure 4 gives a block diagram of the entire system.

The cycle starts when the scanner receives digital deflection information from the XDS 930 computer. This information is converted into two analog voltage signals that drive the X and Y deflection amplifiers of the CRT. The CRT then unblanks, causing intensity information to be imaged on the photomultipliers. The photomultipliers, output electronic signals proportional to the light intensities incident upon their face. These signals are then amplified and integrated by identical analog channels, which are gated by the control logic.

Integration decreases noise and provides a signal proportional to light energy. The outputs of the color channels are then fed into sample and hold (S&H) circuits, which sample when the CRT is on. The output of the CRT sampling integrator is fed into a comparator which fires when it reaches a preset level. This causes the control logic to blank the CRT, switch the S&H circuits into the hold mode and start the A/D conversion of the three color channels. When the A/D conversion is completed in all three channels, the scanner sends the XDS 930 computer a signal which signifies that the information is ready for storage. Upon accepting and storing the data, the computer sends the scanner a signal which resets the scanner for a new cycle. The computer then sends new deflection information and the cycle begins again. This process is repeated until the desired scanning format has been covered.

a. Analog Processing

The analog processing circuitry is shown in Fig. 5. The PMT circuit is first amplified by A1 which has a V_{out}/I_{in} gain of $-R_2$. This

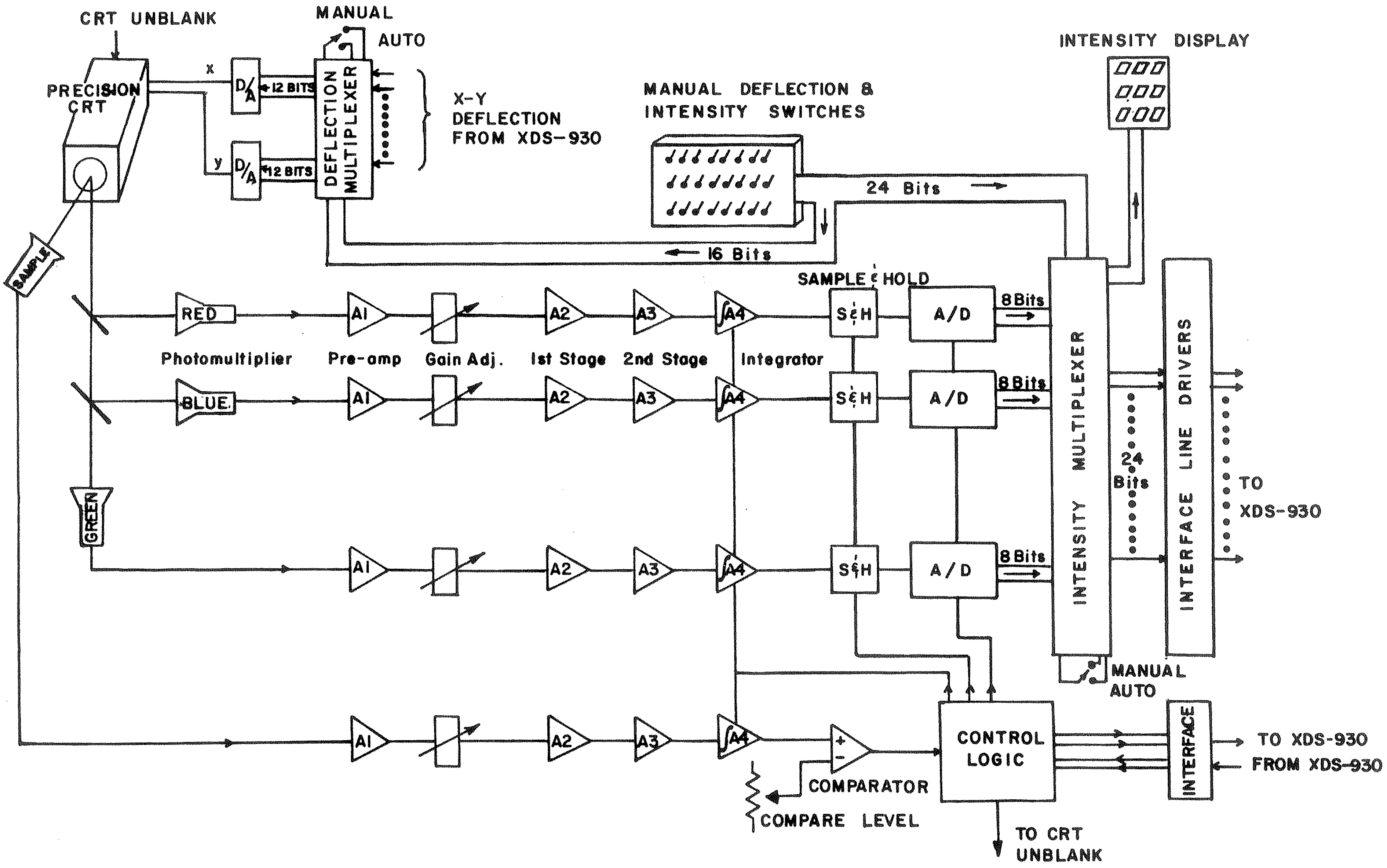


Figure 4. Scanner Electronics System

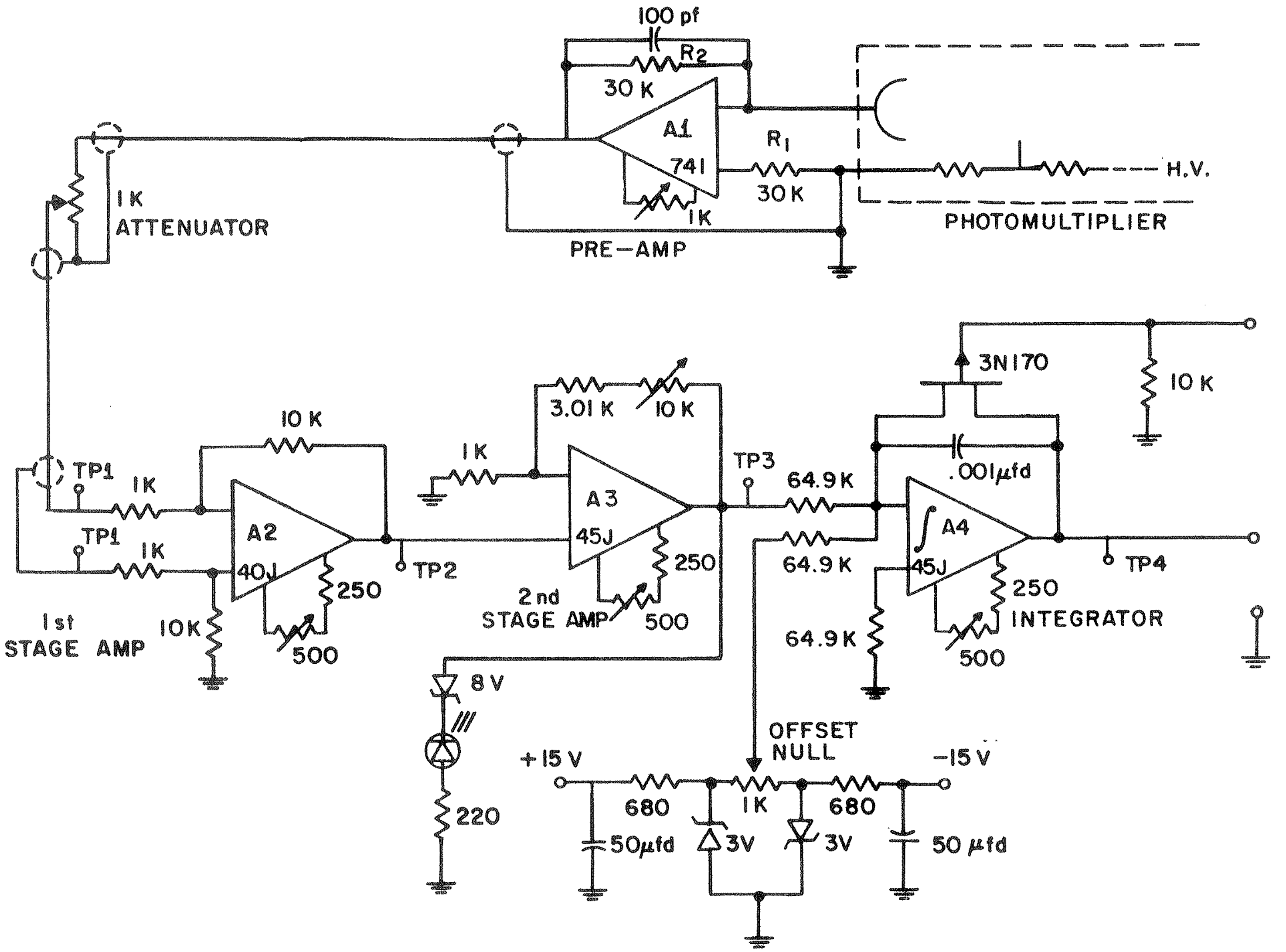


Figure 5. Analog Circuitry

provides a low impedance driver for the 93 ohm coaxial cable from the PMT to the electronics chassis. A 100 ohm ten-turn potentiometer is used for external gain adjustment. A1 is a μ741 operational amplifier and is powered by two 6-volt batteries for ground and noise isolation.

The coaxial shield is isolated from chassis ground after A1 so that amplifier A2 requires a differential input. A2 provides 20db of gain for the sampled signal and is a fast slew-rate, low noise operational amplifier (Analog 45J). Amplifier A3 is another 45J op-amp connected in a non-inverting configuration and provides an additional 30db of gain. The output of A3 is a negative pulse that represents light intensity.

A measure of the light energy is provided by integrating the output of A3. Amplifier A4 is initialized by the N-channel FET. The control logic provides a +13 signal to the FET gate during the non-sample period which keeps the integrating capacitor (.001 uf) discharged ($r_{ds(on)} <$ 200 ohms). During the sampling period, the input to the FET is held at 0 volts by the control logic and a diode, which compensates for the V_{CEon} of the control logic amplifier; and the FET becomes a high impedance path ($r_{ds(off)} >$ 1000 megohms). The integrator has a ramp output with a maximum amplitude of +13 volts. A4 is an Analog 40J operational amplifier which has a high impedance FET input. A ± 3 volt input bias can be applied to the input of the integrator by the offset null potentiometer. This bias can be used to compensate for the photomultiplier dark current and as a threshold for intensity measurements.

The input of the sampling integrator goes to the comparator circuit, which is shown in Fig. 6. This signal is divided by a factor of 3 to reduce its maximum value below 5 volts and compared with a preset 0 - 5V DC signal that is selected by a ten turn potentiometer. The LMT 116 comparator provides a +5V output signal as long as the integrator signal is below the preset voltage. When this voltage is exceeded, the comparator drops to 0 volts within 40 nsec, triggering the 74121 monostable

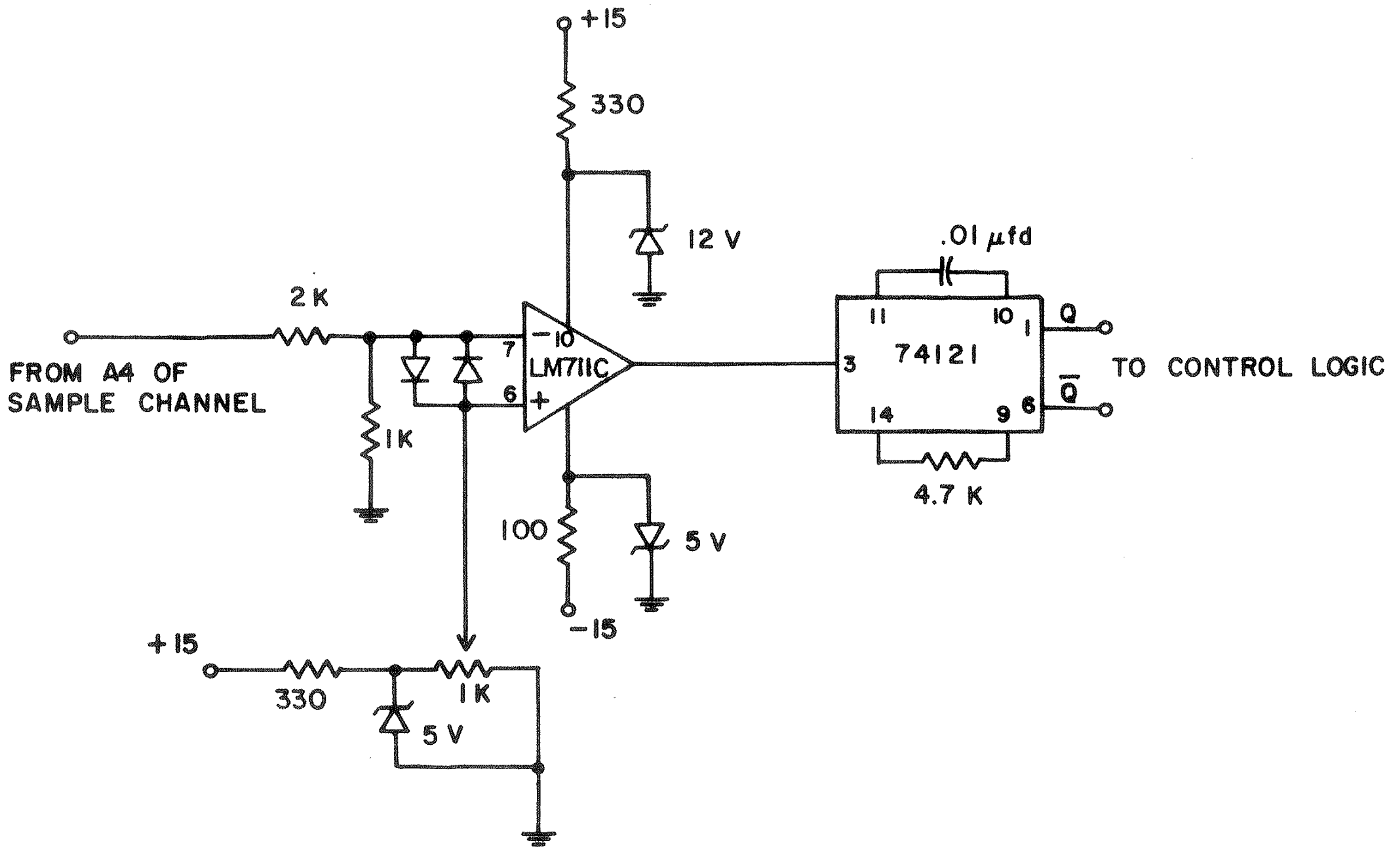


Figure 6. Comparator Circuit

with the falling edge. This causes the monostable to output a 1 μsec pulse which signals the control logic that the preset amount of light energy has been produced by the CRT.

In the meantime, the sample and hold (S&H) circuits on the output of the three color integrators have been sampling the signal while the CRT is unblanked. When the 1 μsec pulse is received, the control logic blanks the CRT and switches the S&H circuits to the HOLD mode. This latches the three color signals for A/D conversion. Typical analog channel waveforms are shown in Fig. 7.

b. Control Logic

The purpose of the control logic is to regulate the chain of events associated with the different system functions, as well as to provide an efficient communication link from the system to the XDS-930 digital computer. The logic was designed so that the system produces all of the critical commands, communicating with the computer only at the start and finish of a cycle, and when data is to be transmitted. The cycling time, the time it takes for one intensity point to be processed and stored in the computer, is determined by the system itself and can be varied over a wide range. Typically, the cycle time for one point is 200 μsec. The control logic circuit diagram is shown in Fig. 8.

The main system control is provided by the Sample and Hold, Unblank, A/D and Gating flip-flops. The SKS-1 and SKS-2 flip-flops provide ready commands to the 930 computer. The monostable multivibrators and the logic gates are necessary to provide the proper timing sequences between commands and functions and to provide a protection pulse for the CRT. This function is necessary in order to insure that the CRT is blanked after a certain time in case the system malfunctions and the CRT is not blanked by the normal chain of events. Continual unblanking of a fixed spot can damage the phosphor and must be avoided.

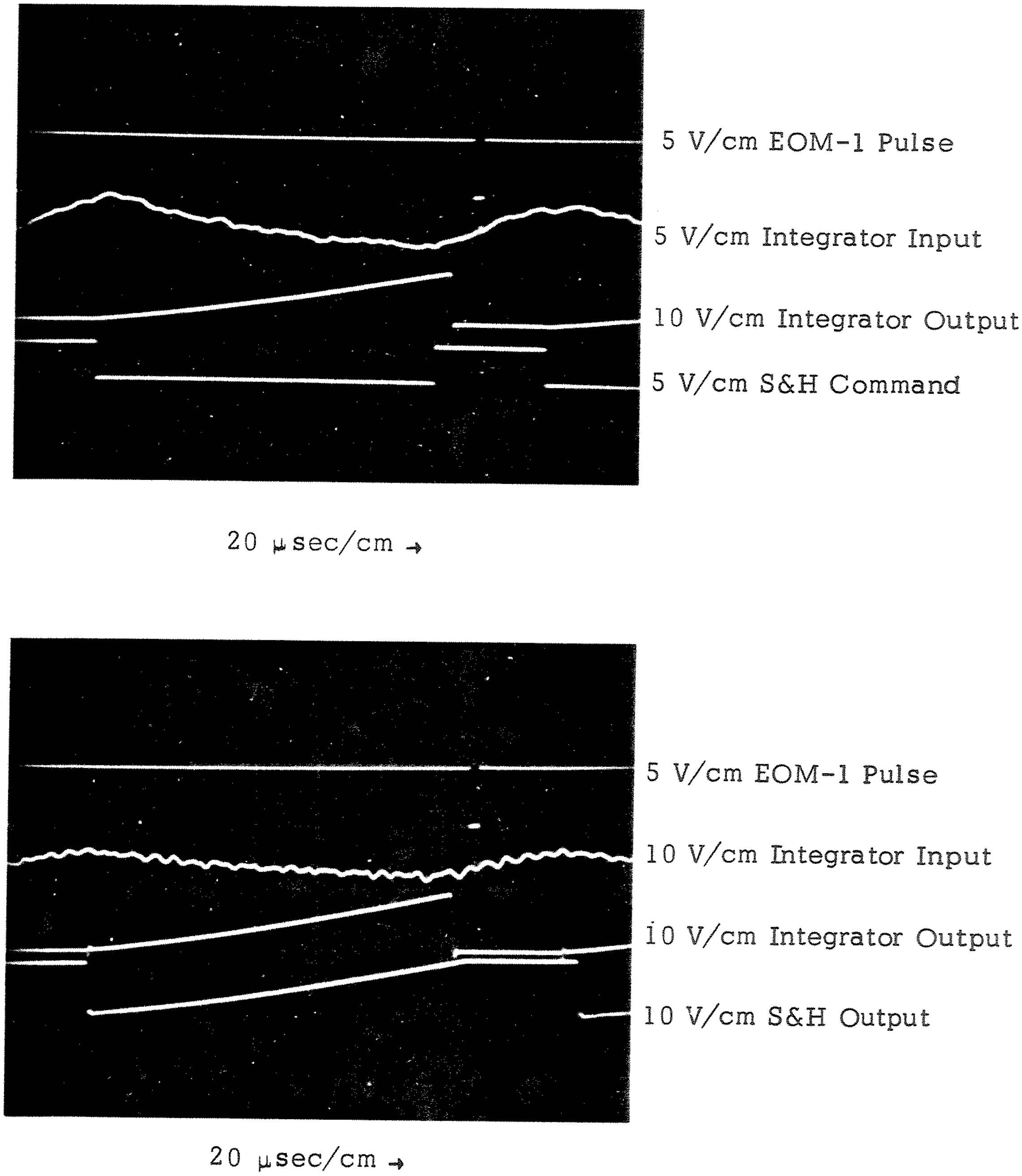


Figure 7. Analog Channel Waveforms

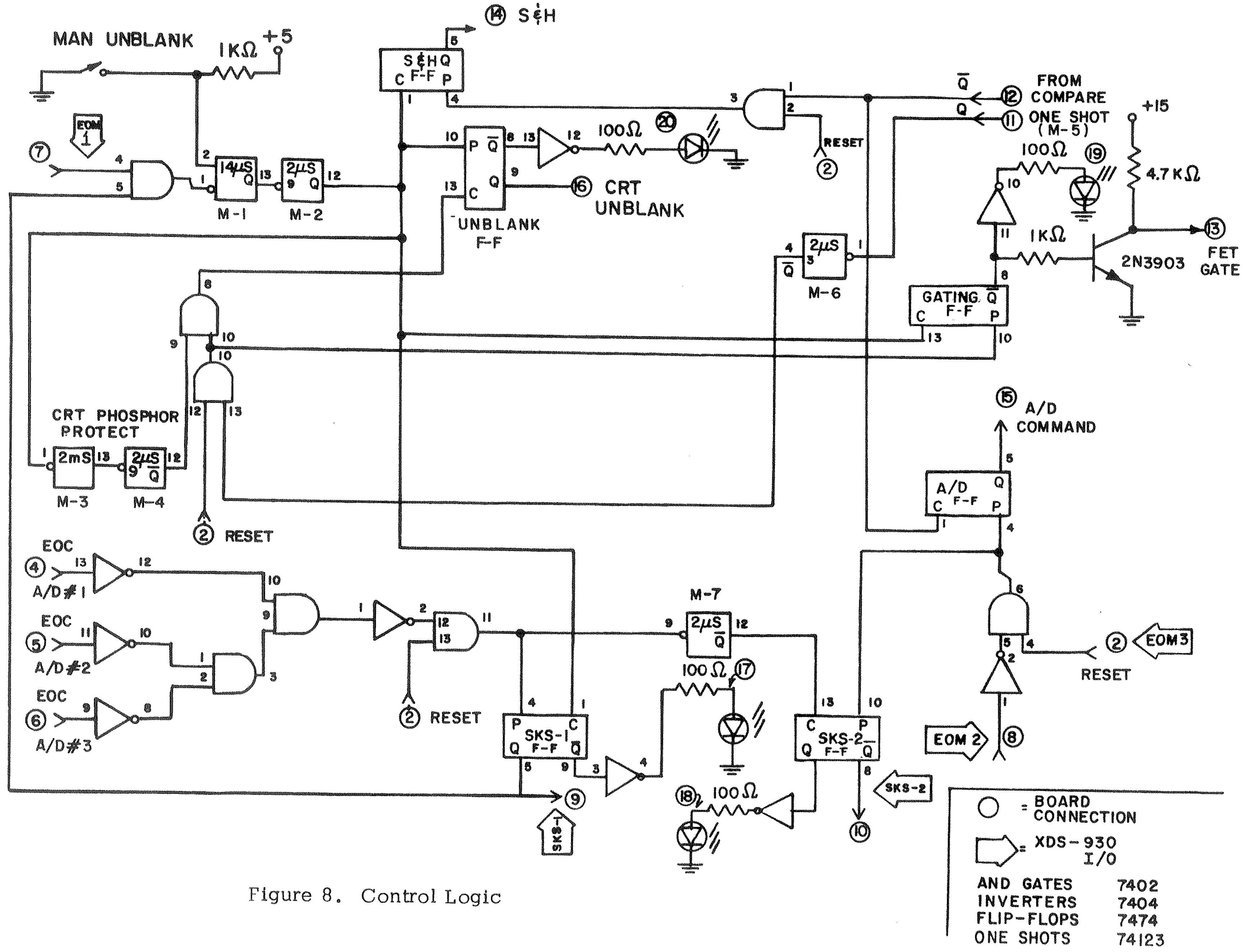


Figure 8. Control Logic

The control sequence for digitizing one point (Fig. 9) starts when the system receives a reset pulse at time t_{reset}, which is controlled by either a manual switch or by computer command. The reset pulse has the following effect:

1. The SKS-1 flip-flop is set HIGH, which indicates to the computer that the system is ready to accept deflection information.
2. The UNBLANKING flip-flop is set LOW to insure that the CRT is blanked.
3. The S&H flip-flop is set HIGH. This prevents the S&H modules from sampling while there is no input.
4. The GATING flip-flop is set HIGH, keeping the integrator stage of the analog processing channels and the comparator in the reset state.
5. The A/D flip-flop is set HIGH, which commands the A/D circuit to the reset state (not converting).
6. The SKS-2 flip-flop output $\bar{Q}$ is set LOW, which indicates to the computer that the system has not processed information.

The system will stay in the RESET state until the computer sends an EOM-1 pulse, signifying that it is sending binary deflection information simultaneously. Since the CRT deflection circuitry takes a finite time to position the spot properly, (the CRT settling time to position the spot anywhere inside a 4.25" circle is 10.0 μsec), a delay monostable (M-1) is adjusted to delay the 2 μsec UNBLANK trigger pulse (M-2) by approximately 14 μsec. This insures that the spot has been deflected to the proper position before sampling occurs.

The UNBLANK trigger pulse initiates the following operations:

1. The UNBLANK flip-flop is set HIGH, which, when fed to the inverting limiter amplifier A1, (Fig. 10) provides a -3V pulse to the CRT, thereby unblanking it.

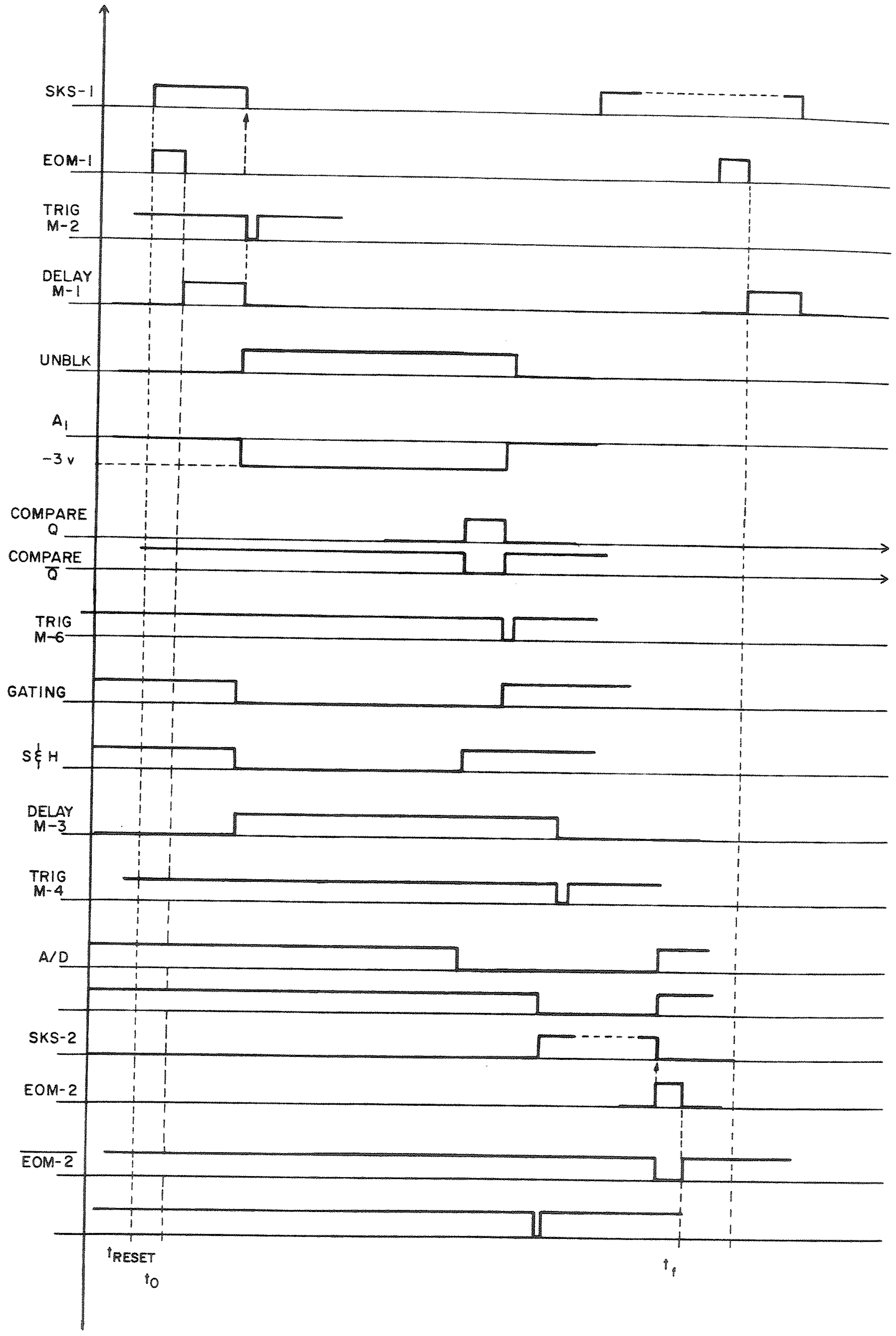


Figure 9. Control Logic Timing Diagram

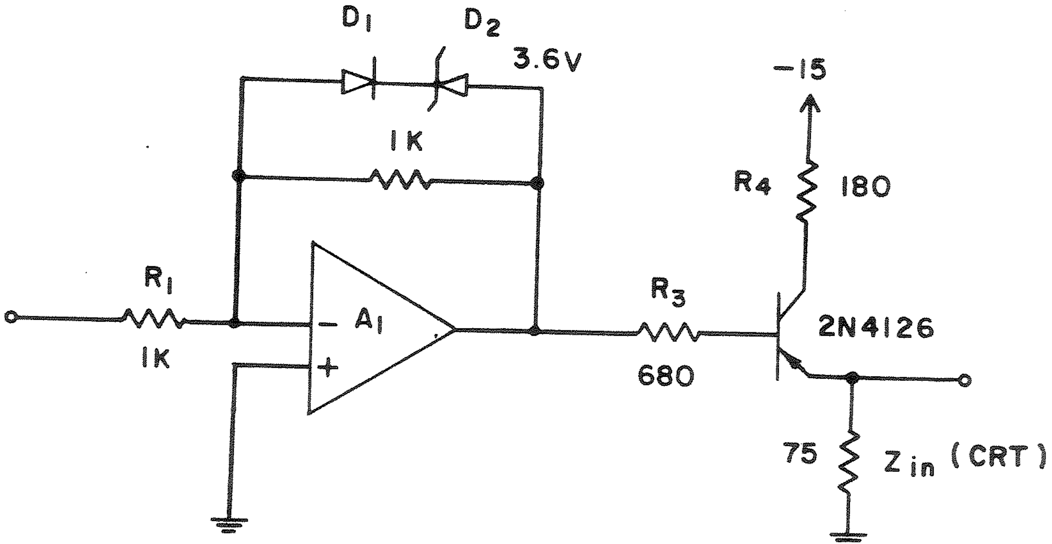


Figure 10. CRT Unblanking Pulse Limiter

2. The S&H flip-flop is set LOW, setting the S&H circuit to the SAMPLE state.

3. The GATING flip-flop is set LOW, which enables the comparator and analog processing to start.

4. The phosphor protect monostable (M-3) is started.

At this time, the system is in a processing state and awaits the comparator signal (sampling channel) to stop processing. When the comparator changes state, it triggers the compare monostable M-5 which outputs a 2 μsec pulse. This pulse causes the following events to occur:

1. The S&H flip-flop is set HIGH, causing the sample and hold modules to hold the processed color information.

2. The A/D flip-flop is set LOW, causing the three A/D modules to start converting the information held in the S&H modules.

3. The trailing edge of the pulse from M-5 triggers monostable M-6.

The 2 μsec pulse from M-6 triggers the following operations:

1. The UNBLANK flip-flop is set LOW, blanking the CRT.

2. The GATING flip-flop is set HIGH, resetting the four integrators in the analog channels.

The 2 μsec delay pulse from monostable M-5 insures that the integrators are not reset while the S&H circuits are still sampling.

The End of Conversion (EOC) outputs from the three A/D converters are inputted to an OR gate. When all three of the EOC signals change to LOW, signaling end of A/D conversion, the OR output changes to LOW. This triggers the following events:

1. The SKS-1 flip-flop is set HIGH, resetting the scanner to accept deflection information.

2. Monostable M-7 is triggered, which in turn sets the SKS-2 flip-flop $\bar{Q}$ output HIGH. This signifies to the computer that the

color information is ready to be stored.

When the computer has stored the information, it sends an EOM-2 pulse to the scanner, indicating that the color information has been received and stored. The EOM-2 pulse resets the SKS-2 $\bar{Q}$ output LOW (information not ready for storage) and the A/D flip-flop HIGH (reset).

At this time, (t_f) the control logic is completely reset to its original state (t_{reset}), (see Fig. 9), and awaits an EOM-1 pulse from the computer to restart the cycle.

If the proper chain of events do not occur in the scanner, backup protection circuits are activated. Normally, the scanner takes 200 μsec to process one intensity point of information. At the same time that monostable M-2 triggers the CRT UNBLANK flip-flop, it also triggers the 2 msec phosphor protect monostable M-3. If the proper chain of events does not occur, so that the scanner does not cycle again in 2 msec, then the falling edge from the output of M-3 will trigger M-4, which in turn will set the UNBLANK flip-flop to LOW, blanking the CRT.

The software also monitors the scanner operation, so that if the SKS-2 flip-flop $\bar{Q}$ output does not go HIGH within 7 msec, then the computer sends an EOM-3 pulse which resets the scanner. After one second, an EOM-1 pulse is then sent, restarting another cycle.

The UNBLANKING flip-flop is not capable of driving the CRT directly, because the CRT input requires a -3v pulse to unblank; therefore, a limiter-driver stage is needed to perform this function. Figure 10 shows the circuit designed for this purpose. Since the logic output pulse is a +5v level, the limiter stage does not need to provide gain. Thus, R_1 is set at 1kohm to avoid loading the logic output, and R_2 is also chosen as 1kohm. The slope of the limiting network, with the zener D_2 is determined by

$$\text{slope} = \frac{r_z + r_f}{R_1}$$

where r_z is the zener resistance and r_f is the diode forward resistance. This slope is fairly low and will provide fairly flat zener regulation. The limit at the output is set by the zener voltage and the forward voltage drop of the diode. This output, however, cannot be used to drive the CRT, since it would need to provide a current: $I = \frac{3v}{75\Omega} = 40ma$. An emitter follower is used to provide the needed current. Resistor R_3 is used to limit the input base current, while R_4 is used to limit the current through the transistor so as not to exceed its power limitation.

c. Multiplex and Display Network

The multiplex network serves a variety of purposes. It allows a digital readout of intensity information directly from the A/D converters as points are being sampled on the transparency. It also allows a binary sequence to be manually inserted to three color channels going to the XDS-930. Thus, the interface can be checked for errors or malfunctions by inserting a digital word in the manual register and reading the information received by the computer on the computer scope terminal. The multiplex network also serves either to manually deflect the CRT spot to any point on the CRT or to use the computer deflection input to position the spot. Figure 11 shows the intensity multiplex circuit which is identical for each of the red, blue and green color channels, while Fig. 12 shows the circuit that is used for both the X and Y deflection channels. Open-collector NAND gates are used to obtain the wired-OR function. By selecting either AUTO or MANUAL on the selection switch, one of the two gates for each bit is disabled while the other gate is enabled and has as an output the inverse of the input. The output of the three intensity multiplex circuits go to the interface logic, as well as to the display logic. The display logic is composed of decoder-drivers, which convert binary to a seven-segment display. By separating the 8-bit word, as shown in Fig. 13, the display readout is converted to octal.

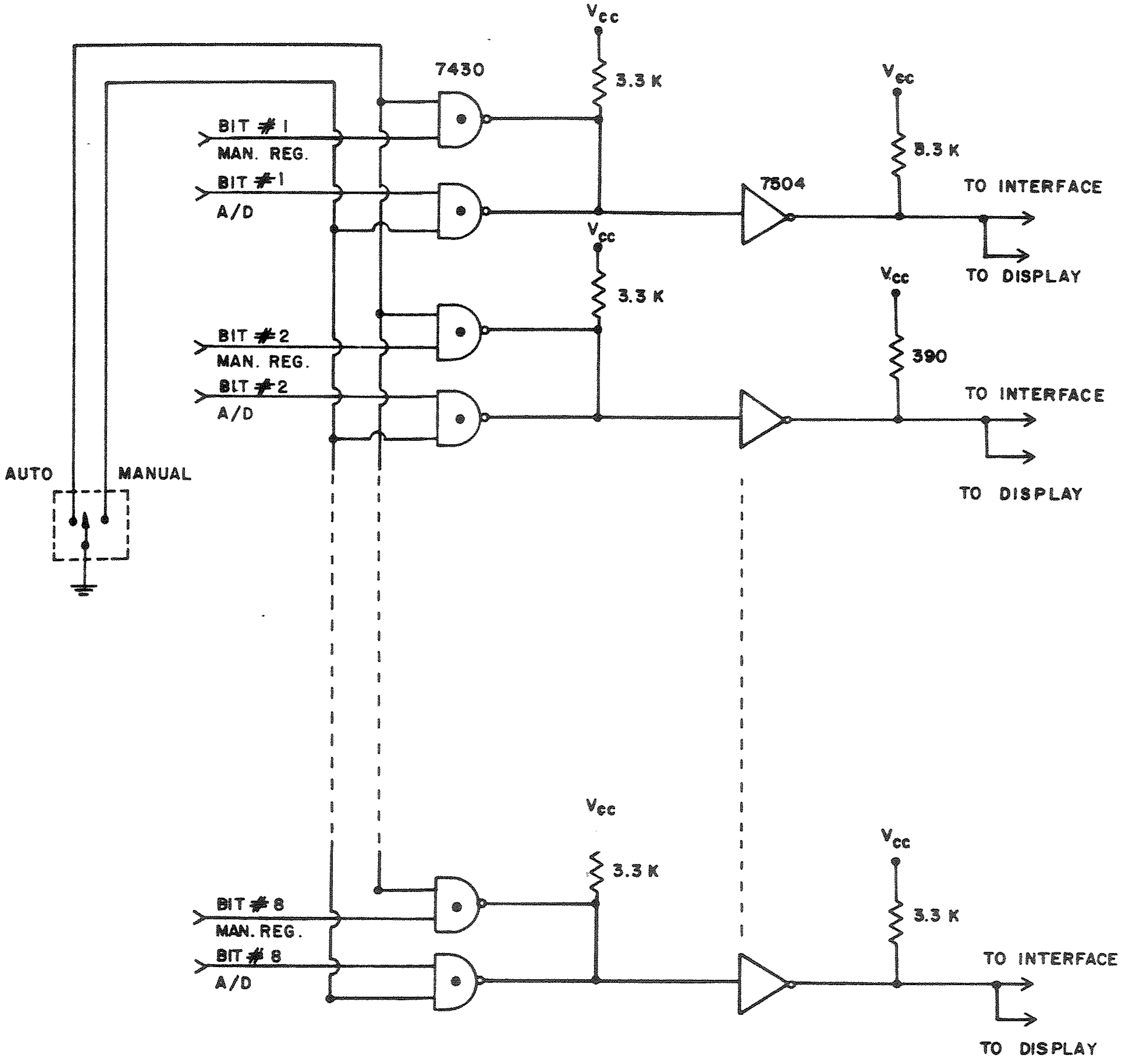


Figure 11. Intensity Multiplex Circuit

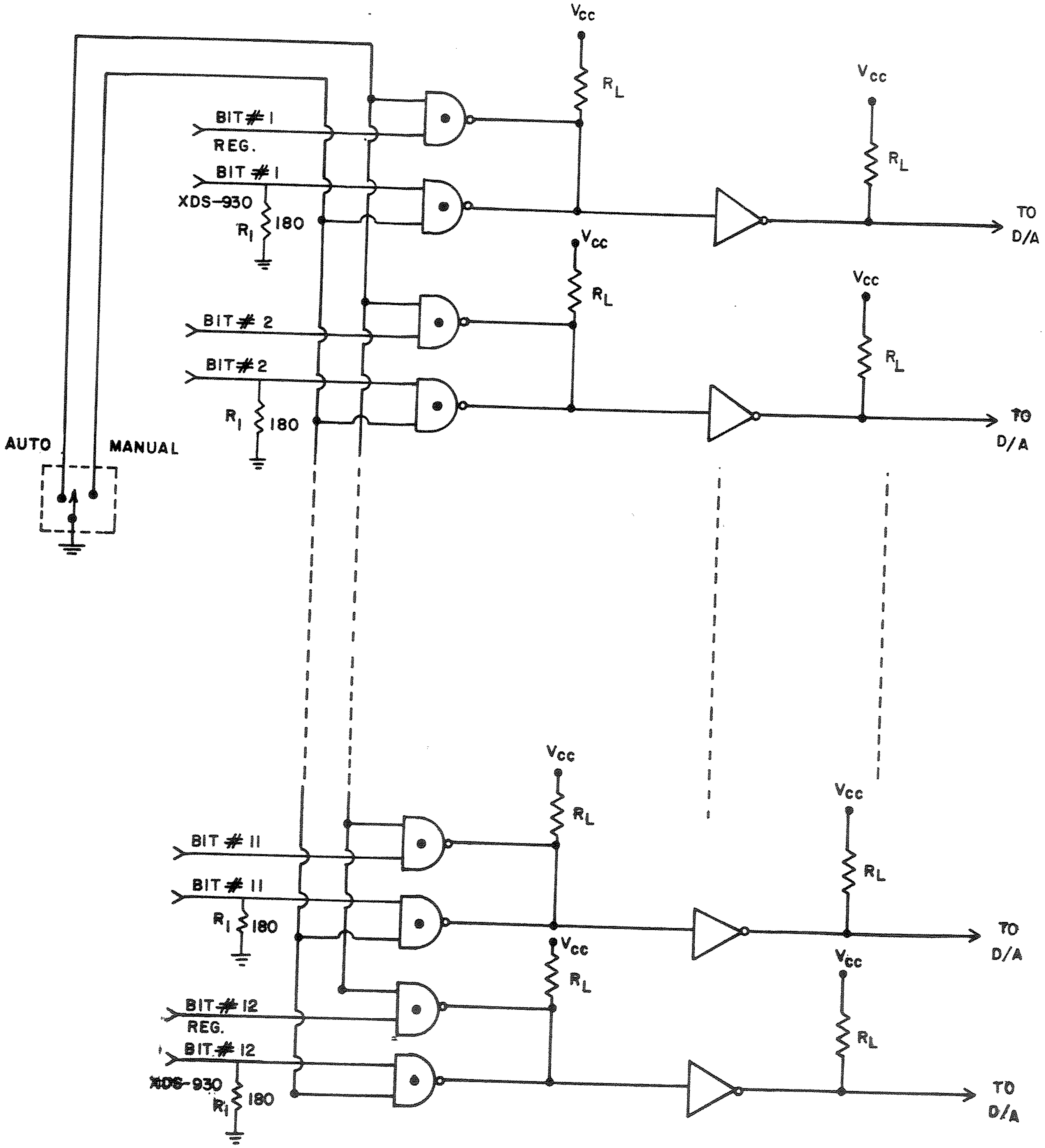


Figure 12. Deflection Multiplex Circuit

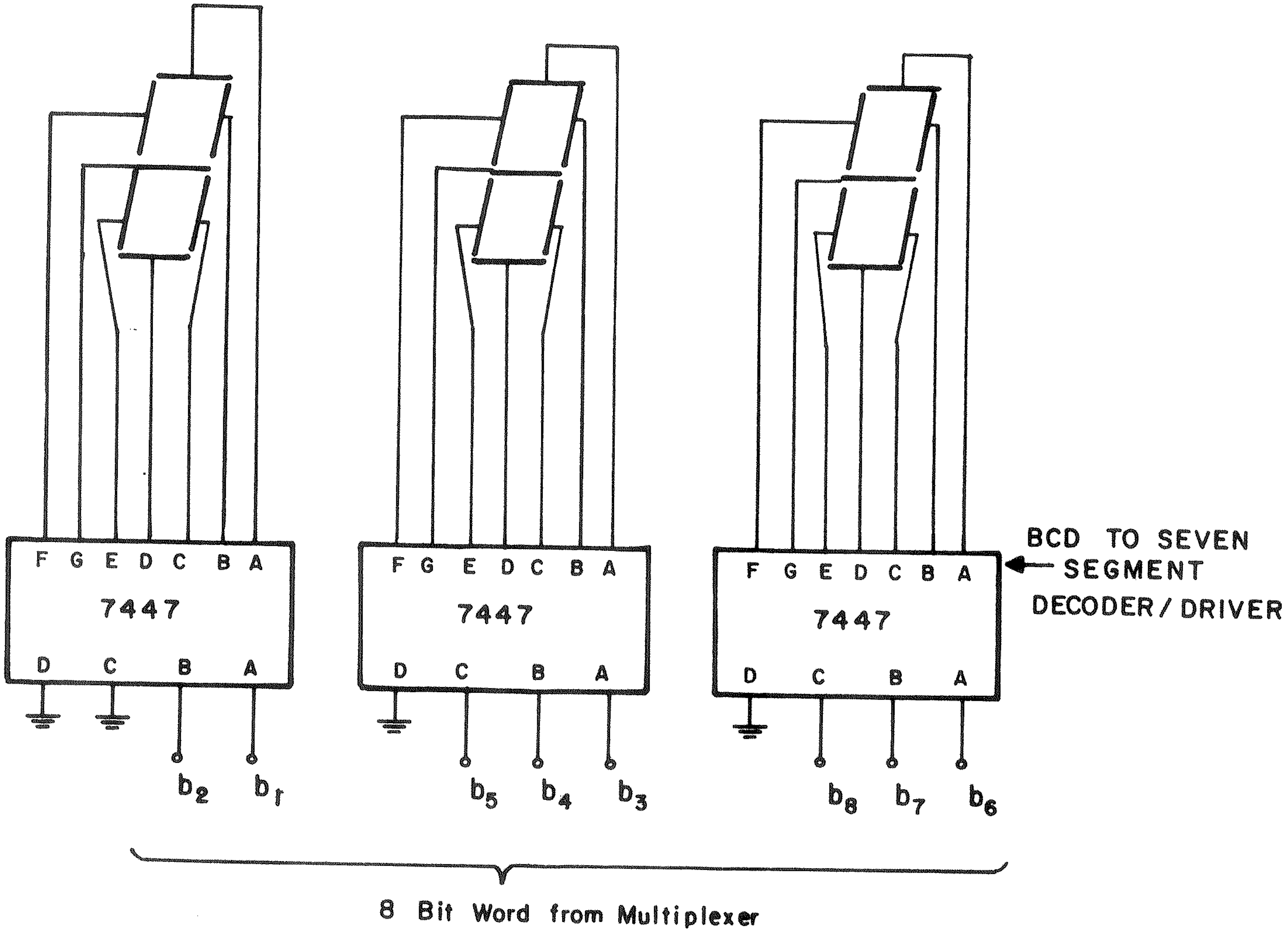


Figure 13. Display Readout

The output of the two deflection multiplex circuits drive the D/A converters, which send the X and Y deflection signals to the CRT.

d. Interface

Since the FSS is controlled by the XDS-930 digital computer, the digitized intensity channels, the address information, and the command signals must be relayed back and forth between the scanner and the computer. The data transmission is done in parallel, with 24 intensity bits being sent to the computer, corresponding to the three 8-bit color channel outputs and 24 deflection bits (two 12-bit address words corresponding to X and Y deflections) being received by the FSS.

The digital output of the FSS is sent to the computer, as shown in Fig. 14. The 7416 inverting drivers are used to drive the XDS-930 PIN lines. The choice of pullup resistor was chosen so as to limit the current though the 7416, and the terminating resistor was chosen experimentally to furnish a clean pulse to the XDS-930.

The EOM control signals cannot be sent to the FSS directly by the XDS-930 without being buffered. Figure 15 shows the driver-receiver network. The 2N3903 transistor is used to impedance match the 50 ohm line, and to invert and reduce the 8 volt EOM pulse from the computer down to 5 volts, so that it is compatible with the TTL 7404 inverters. The two inverters then shape the pulse before it is sent to the scanner control logic.

The digital signal containing the deflection information is strong enough to be sent directly to the scanner without a driver. A resistor divider at the input of the multiplex network then decreases the 8-volt pulse amplitude down to 4 volts, so that it is compatible with the following TTL logic.

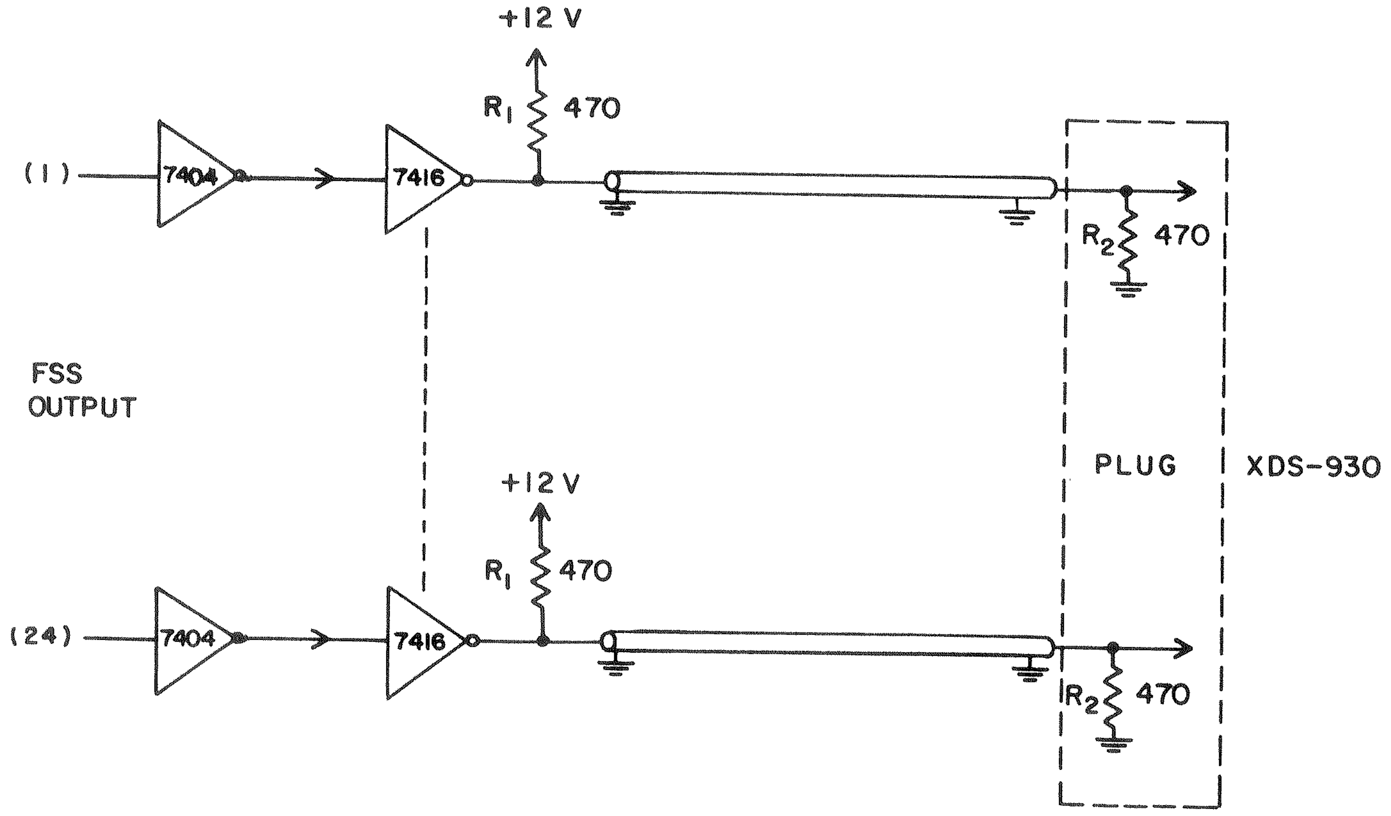


Figure 14. Output Drivers

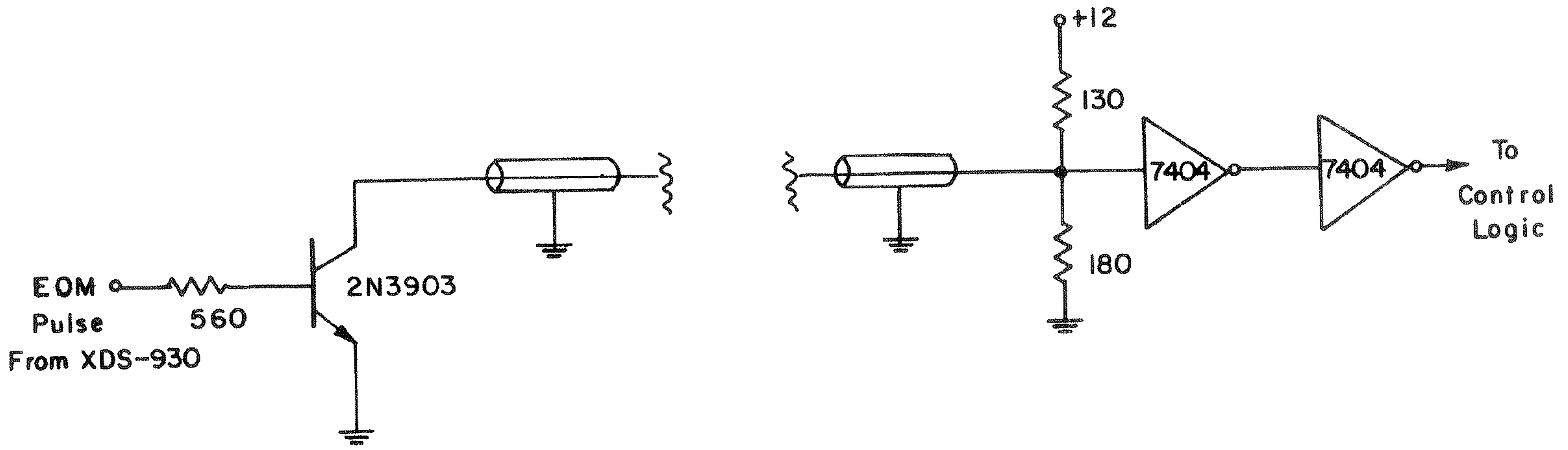


Figure 15. EOM Signal Interface

IV. SOFTWARE

In contrast to the scanner hardware which provides direct control, the scanner software contained in the XDS-930 computer provides overall direction and allows interactive operation of the FSS. The software controls the scanning format through deflection information for the scanner and also provides preprocessing of the output to enhance the operational flexibility. Software also corrects for the intensity error caused by the sampling PMT being offset to one side of the CRT. The scanner program is written in XDS-930 assembly language.

a. Measurement and Control

The basic program for measuring the intensity at an arbitrary point (X,Y) is shown below.

```
                                                ARACHNID VERS 02.72.00
LDA     Y
RSH     12
LDA     X
LSH     12
STA     BUF          (BUF) = X-Y
LDX     =-100
SKS     034200       CHECK IF THE SCANNER IS READY (SKS1)
BRU     $+3
BRX     $-2
BRU     ERROR        ERROR EXIT - SCANNER DOES NOT RESPOND
EOM     030071
POT     BUF          TRANSMIT X-Y COORDINATE TO THE SCANNER
EOM     030004,2     SEND EOM1 PULSE TO THE SCANNER
LDX     =-1000
SKS     034100       CHECK IF THE INTENSITY IS READY (SKS2)
BRU     $+3
BRX     $-2
BRU     ERROR        ERROR EXIT - SCANNER DOES NOT RESPOND
EOM     030061
PIN     BUF          (BUF) = 3 INTENSITY VALUES
EOM     030005,2     SEND EOM2 PULSE TO THE SCANNER
```

Each sampling point in a standard 35 mm format is assigned an address from 0 to 4095 in both the X and Y directions. These points may be addressed individually or in any format that has constant sampling distance in the X and Y directions. The X and Y sampling distances do not have to be identical, however. Addressing in this manner allows the scanner to have random access so that all or any part of the transparency may be digitized without storing a large amount of unwanted information.

b. Processing

Software is available to output information from the scanner as shown in Table 2.

TABLE 2. SCANNER PROCESSING OPTIONS

Process	Output	Output Unit
Single Scan	Color Channel Intensities	Scan Converter
	Intensity Histograms	Line Printer Computer Scope
Continuous Scan	Color Channel Intensities	Scan Converter
Intensity Number Printout	Color Channel Intensities	Line Printer
Gray Level	Color Channel Intensities (Overprint)	Line Printer
Color Purity	Color Purity	Line Printer (2D) Storage Scope (3D&2D) Calcomp Plotter (3D)
Color Triangle	Color Triangle Distribution	Storage Scope Calcomp Plotter
Tape Storage	Color Channel Intensities Intensity Histograms	Magnetic Tape
Color Intensity	Color Channel Intensities	Storage Scope (3D&2D) Calcomp Plotter (3D)

By scanning the format once, a histogram can be produced of the number of points occuring at each intensity level. This allows the user to check the color balance of the three channels or to determine the dominant intensity levels in the format. The color balance can be adjusted by scanning a neutral density filter and setting the color channel gains, using the histogram outputs. Continuous scanning is useful for system testing and for examining particular transparency features.

Intensity numbers or gray level printouts can be outputted on the line printer. These methods are impractical for large formats, but are otherwise useful in identifying patterns in the transparency. The numerical values are in I3 format (0-256) while the gray level output is an overprint that has eight gray levels. The color intensity option outputs the same information on the lineprinter or either the storage scope or the calcomp plotter in the form of a 3D perspective.

The color purity and the color triangle options give a measure of the actual color information contained in the transparency. Purity (saturation) is determined by the amount of white that is mixed with a pure color, and thus is one indicator of color variation. The color triangle distribution gives an overview of the color hues contained in the scanned format. This information is useful for setting threshold levels for color boundaries (usually done at the next level of processing), and also for determining the color response of the FSS system. System color response will be discussed later in the section on testing and calibration.

The tape storage output allows the three color channel intensities to be stored, along with their histograms, on magnetic tape. This information can then be processed further using either the XDS 930 or a CDC 6600 computer.

These processing and output options allow the FSS to be operated in a very flexible manner. With the random access feature, interesting areas in the format can be examined and tested in detail without the necessity of storing a large amount of unwanted information.

c. Sampling PMT Correction

Software is used to correct for the variation that is caused by the sampling photomultiplier not being equidistant from all points on the face of the CRT. (See Fig. 16). For a point source of light, intensity decreases by $1/R^2$ as the distance from the point source increases by R. As a result, for points that are equally bright on the face of the scanner CRT, a point on the right side will appear brighter to the sampling PMT than a point on the left side. Software is used to compensate for this intensity variation. An origin was arbitrarily chosen (Fig. 16) on the right side of the CRT, and all other points on the CRT were then referenced to this point.

At the sampling PMT, we have:

$$\frac{I_1}{I_0} = \frac{R_0^2}{R_1^2}$$

Where I_0 is the intensity at the sampling PMT from a point at P_0.
I_1 is the intensity at the sampling PMT from a point at an arbitrary location P_1.
R_0 is the distance from the sampling PMT to point P_0.
R_1 is the distance from the sampling PMT to point P_1.

The sampling PMT allows the CRT to stay on until the signal at the sampling PMT reaches a preset level (say I_0). As a result, to the three color PMT's, which are positioned so that light essentially travels an equal distance from all points of the CRT, the intensity from point P_1 will be brighter by a factor of R_1^2/R_0^2 than the intensity from point P_0. To compensate for this variation, the three color intensities at each point scanned are multiplied by R_0^2/R_1^2 to normalize them with respect to the intensities at point P_0. Since all distances are known, the actual equation implemented in software is

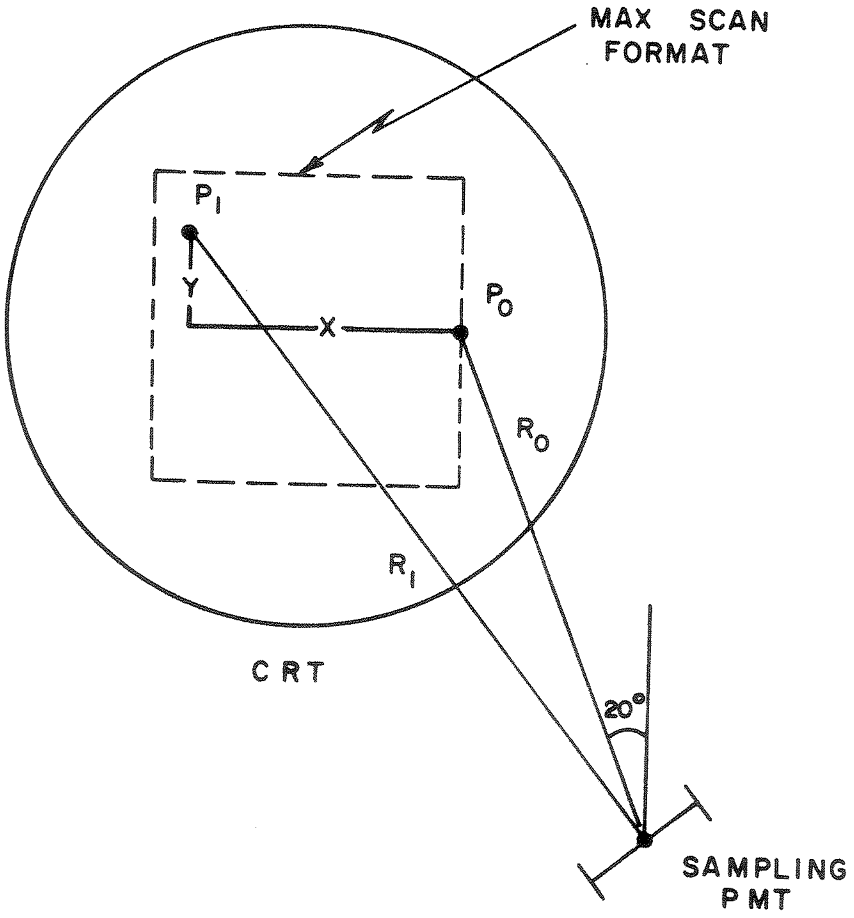


Figure 16. Sampling Compensation

$$I_A = \left(\frac{102,400}{(109+x)^2+y^2+90,519} \right) I_1$$

Where I_A is the actual intensity processed or stored.

I_1 is the intensity measured at point P_1.

X and Y are the distances in mm shown in Fig. 16.

Note that $R_0^2 = 102,400\ \text{mm}^2$.

V. TESTING AND CALIBRATION

To accurately determine the response of the scanner system, test runs were made to check resolution, color response, and noise.

a. Resolution

To obtain the resolution of the system, Ronchi rulings (150 lines/in and 300 lines/in) were photographed using Kodak high contrast copy film, to obtain a set of resolution grids that were of higher spatial frequencies than the original rulings. These grids were then checked with a microscope to determine their true spatial frequency. Each grid was approximately 15 mm square (in the center of a black background) and consisted of alternating black and white lines of a constant spatial frequency. The convention was used that a grid having 12 black and 12 white lines in each millimeter was classified as having a spatial frequency of 12 lines/mm.

To test the resolution, scanner runs were made using different grids. A spatial frequency was considered to be resolved if the scanner could distinguish a grid of that spatial frequency. Using this method, it was found that the scanner could resolve a grid of 20 lines/mm but not one of 28 lines/mm. Gray level printouts of these results are shown in Figs. 17 and 18 for one color channel. Note that the other two color channels gave similar results.

Theoretically, the light spot size at the film plane is 1.5 mils/1.65 = .91 mils; where 1.5 mils is the spot size at the CRT and 1.65 is the demagnification of the spot by the objective lens. Since .91 mils = 23.1 μm, in each millimeter, $1/23.1(10^{-3}) = 43.3$ spots can set side by side without overlapping. Assuming one spot per black line and one spot per white line, then the theoretical scanner resolution is approximately $43.3/2 = 21.7$ lines/mm. This value agrees quite well with the experimental results.

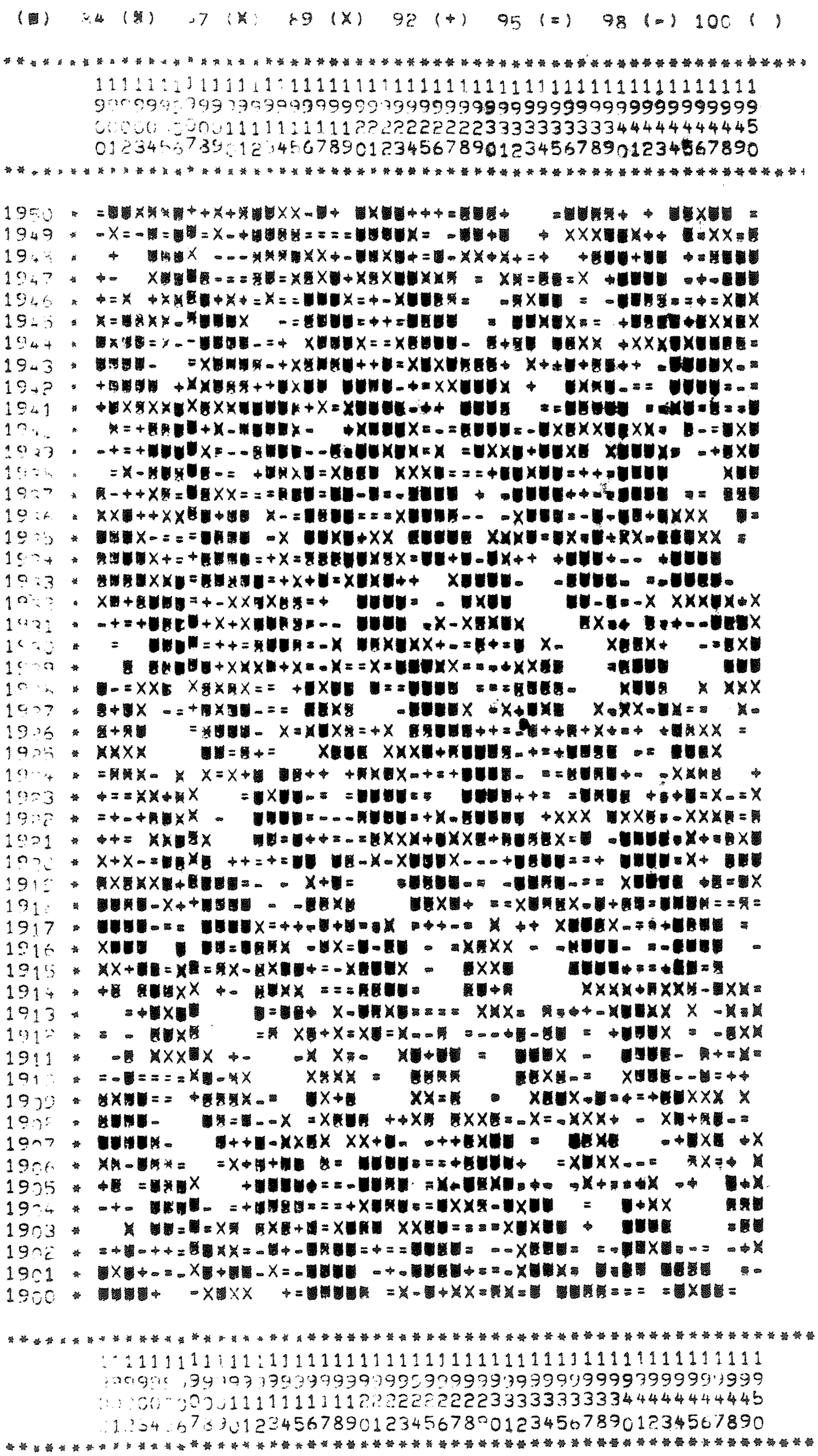


Figure 17. 20 Lines/mm

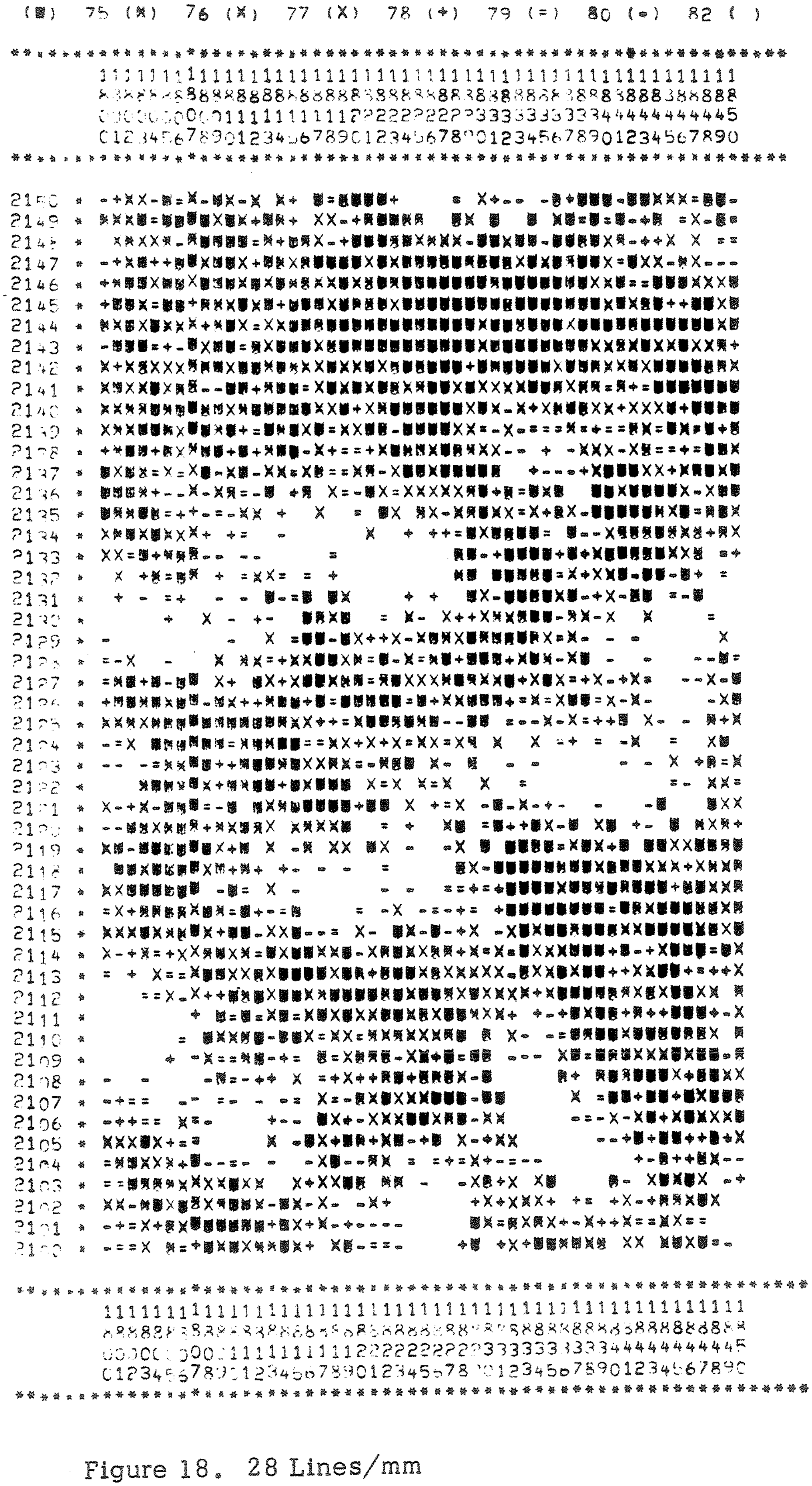


Figure 18. 28 Lines/mm

b. Color Response

The expected color response of the scanner is shown in Fig. 19, along with the CRT phospher spectral response in Fig. 20 and the PMT spectral response in Fig. 21. The peak in the CRT response at 5100 Å causes the CRT light spot to appear blue-white instead of white. The decreasing response of the PMT at higher wavelengths is the primary reason that the expected response in Fig. 19 decreases toward the red end of the spectrum. Ideally, the CRT should act as a white light source, radiating equal light energy over the entire visible spectrum, and the photomultiplier should detect these intensities equally over the same range.

There are two effects of the scanner not responding in the ideal manner. First, all colors will not have an equal scanner response for equal intensities. As an example, reds will give a weaker response (in intensity) than blues. Secondly, the scanner will not "perceive" colors in the same way as humans. Thus some colors that appear to be distinctly different to the average person (i.e. green and yellow) will be perceived to be nearly the same by the FSS.

The perceived color of a scanned point is determined by the ratio of the red, blue, and green channels, and not by the absolute intensities. As an example, red is determined by the strength of the red output in comparison to the green and blue outputs. If the red and blue outputs are strong in relation to the green output, the scanner sees magenta. If all three outputs are nearly equal, the scanner perceives white. Thus a strong signal in the red channel alone does not guarantee that the scanner is actually observing red in the transparency.

To calibrate the scanner color response, a CIE chromaticity diagram was constructed. The scanner color response was set by adjusting the overall gain of each color channel while scanning a No. 6 neutral

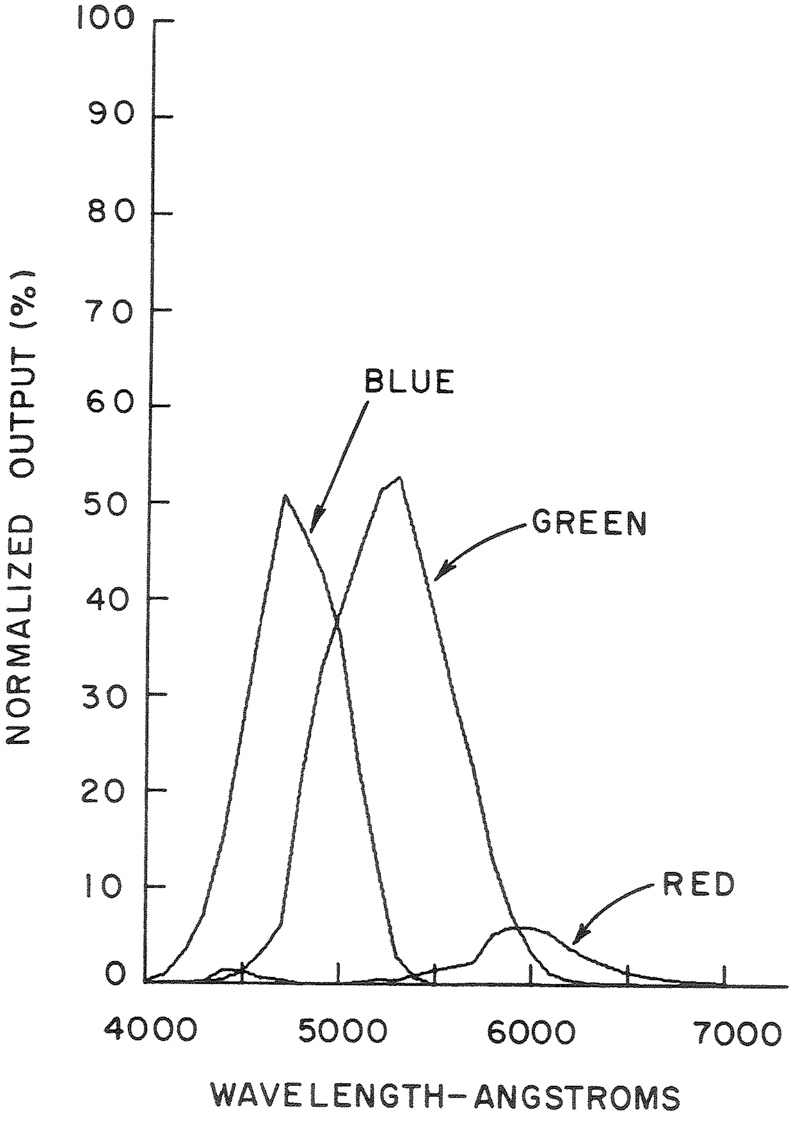


Figure 19. Expected Color Response

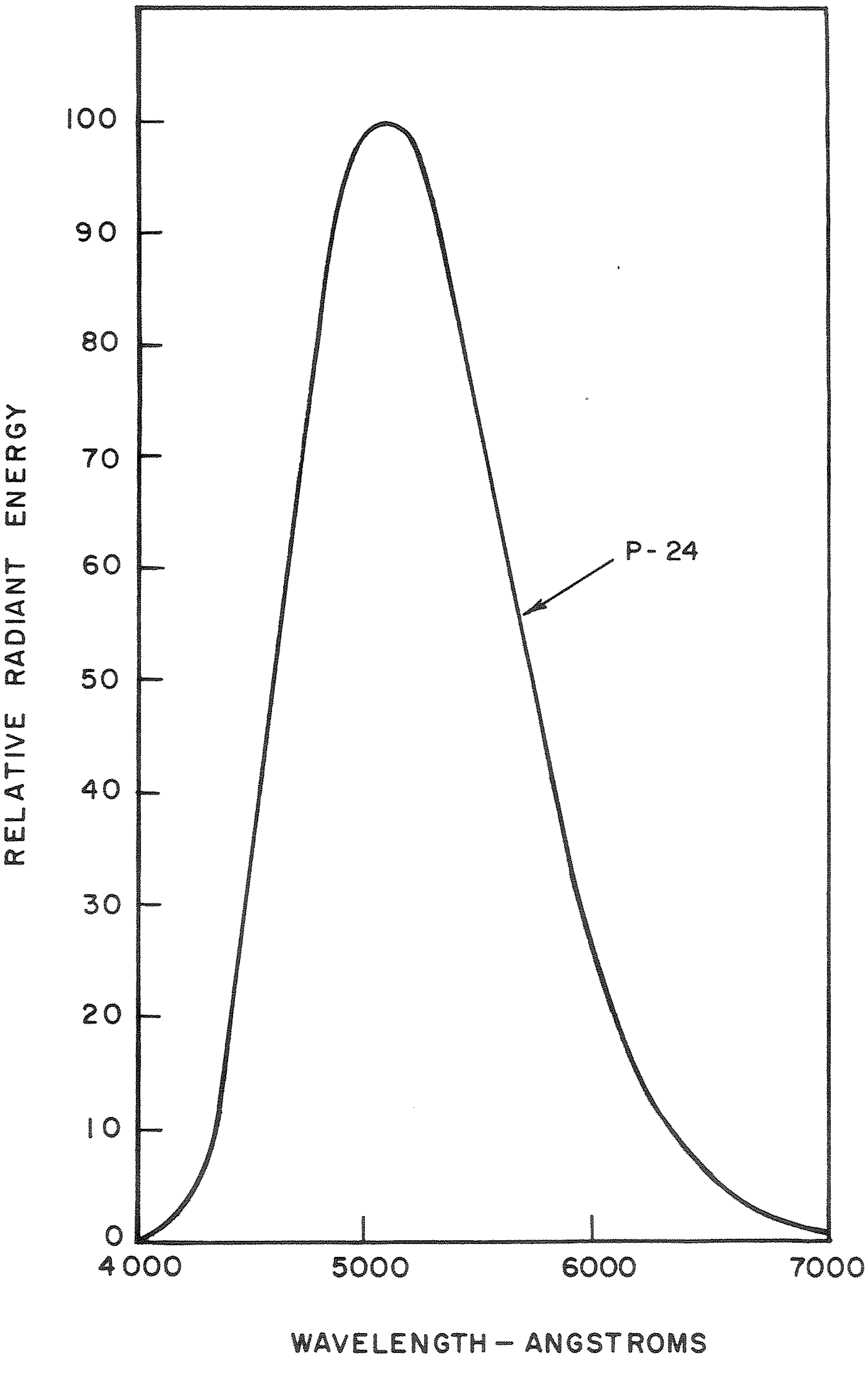


Figure 20. CRT Spectral Response

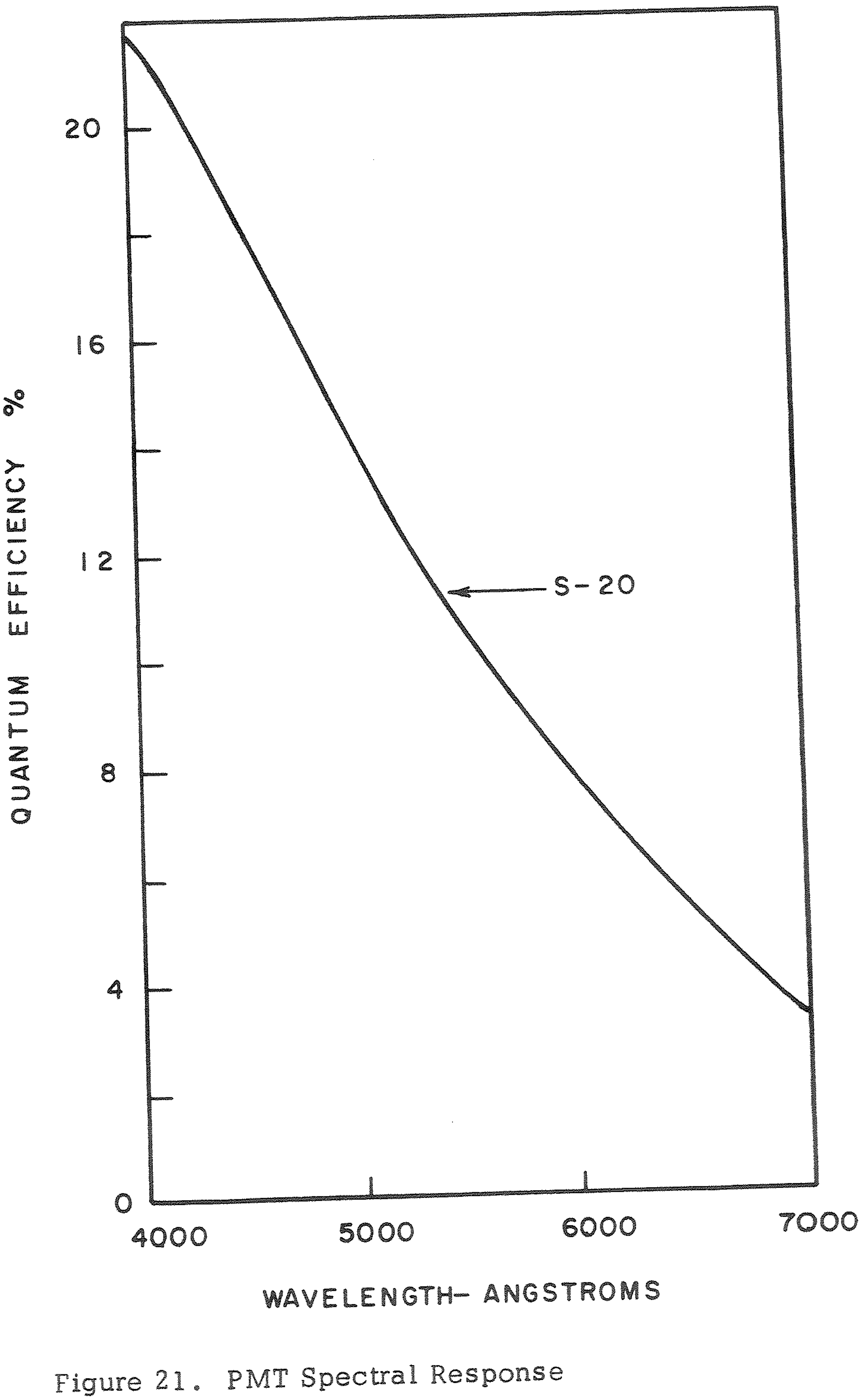


Figure 21. PMT Spectral Response

density filter (20% transmittance). Eleven selected Kodak Wratten filters were then scanned, and their coordinates plotted on the chromaticity diagram. They were then compared with the expected values which were calculated on a CDC 6600 computer, using the response of the scanner, and response curves of the Wratten filters.

The scanner coordinates are calculated by normalizing the outputs of the red, blue,and green channels. X then gives a measure of the red response, Y gives a measure of the green response and Z, which is not plotted directly on the chromaticity diagram, gives a measure of the blue response. Thus, if R, G and B are the scanner red, green,and blue channel outputs respectively, then

$$X = \frac{R}{R+B+G}$$

$$Y = \frac{G}{R+B+G}$$

$$Z = \frac{B}{R+B+G}$$

and

$$X + Y + Z = 1 .$$

Because of the last relationship, it is not necessary to plot the Z value to determine the blue response.

Chromaticity diagrams for three different color channel settings are shown in Figs. 22, 23, and 24. Note that the expected system response is plotted for the visible spectrum (400-700 nm), taking into account the color channel gains. The scanner cannot perceive any colors that lie outside of this curve. Figure 22 shows the results obtained when the color gains were set to the natural response of the system. That is, the neutral density (ND) settings were the average value of each channel taken over the visible spectrum. These results show that the blue

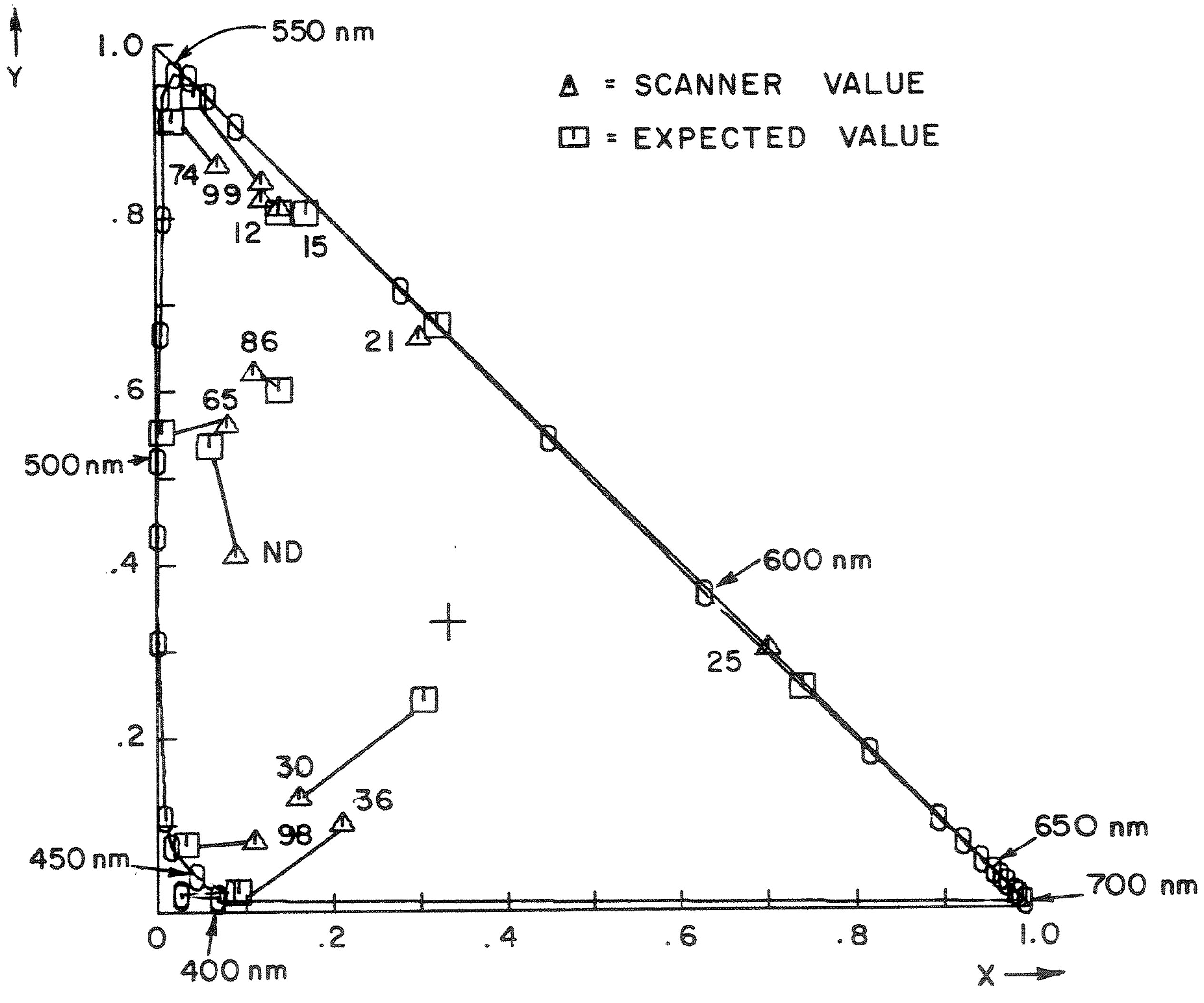


Figure 22. Chromaticity Diagram
ND = .1, .41

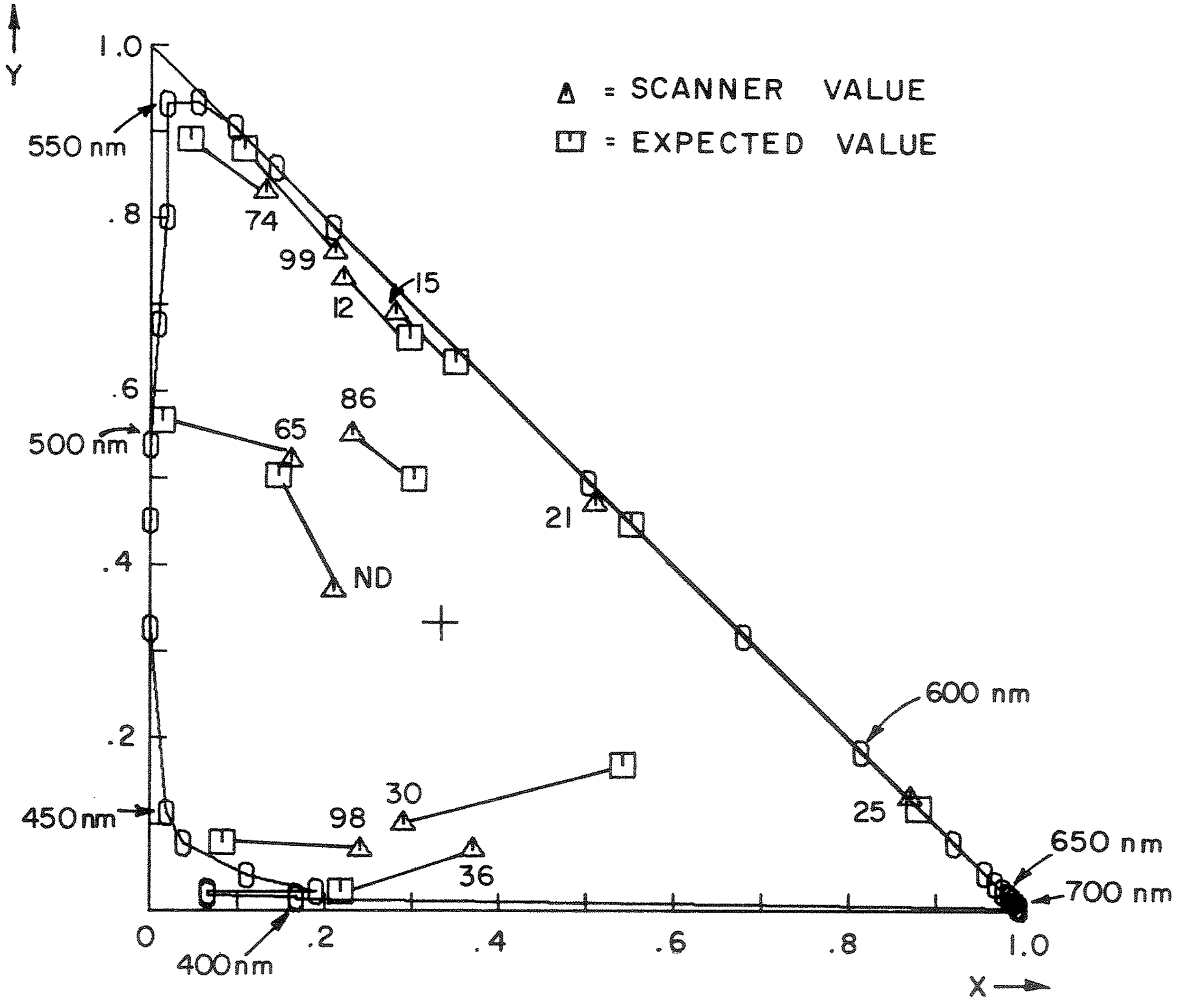


Figure 23. Chromaticity Diagram
ND = .2, .38

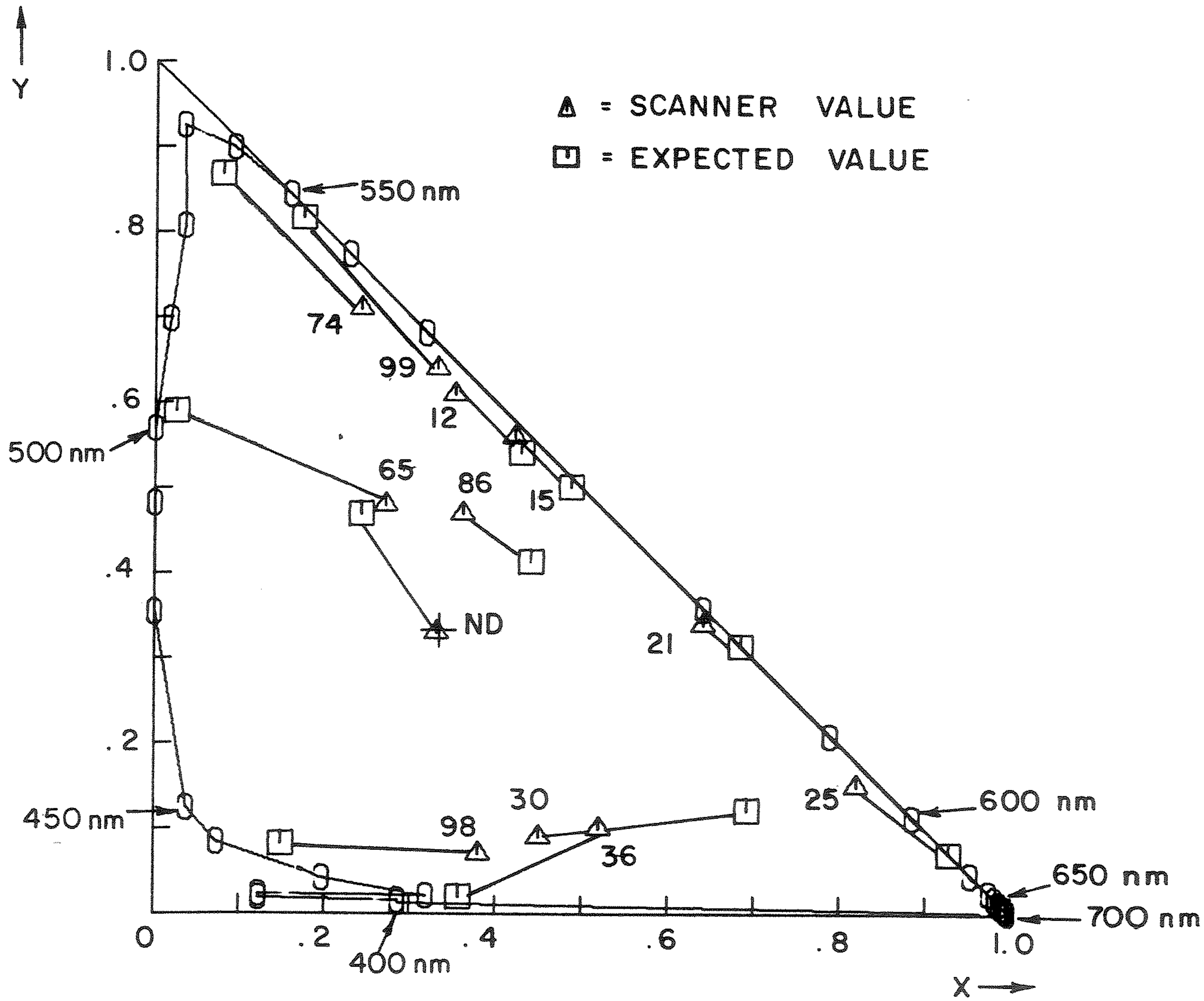


Figure 24. Chromaticity Diagram
ND = .33, .33

response (i.e., #30, #36 and #98 Wratten filters) is somewhat weaker than expected. This apparently is due to the red dichoic filter having a slightly greater leakage of red signal in the lower end of the spectrum than shown in the specs. Also, the scanner cannot differentiate very well between greens (#74, #99) and yellows (#12, #15); this is attributed to the weak red response.

In Fig. 23, the red gain was increased in relation to the blue and green values. These settings appeared to give the best color response, since the filters seem to be spread more evenly on the chromaticity diagram. The weaker blue response remains, however, and there is more scatter from the expected values than in the previous example.

Figure 24 shows the results obtained when the three color gains are set equally. This setting is more unsatisfactory than the previous examples, because of the bunching together of different color filters, denoting an uneven color response. Also increasing the red gain has shifted the response in the red direction, denoting increased red leakage in the lower end of the spectrum.

The color results show that the scanner can perceive and differentiate colors, but not exactly in the same manner that humans perceive them.

c. Noise Measurements

The FSS, being a complex combination of electronic circuitry and optical equipment, contains a certain amount of inherent noise. There are many sources, both electronic and optical, which contribute noise to the system, but the largest contribution appears to come from the photomultipliers. The photomultipliers work using an avalanche effect, which injects high frequency noise into the analog processing channels, and in turn injects a random noise component into the output. This scatters the scanner output values, and in the case of a single intensity transparency, causes a gaussian shaped output rather than the desired sharp spike. The scanner software partially compensates for this noise by sampling each intensity point four times and averaging the four values, before scanning at a new location. In spite of this, a small amount of noise remains.

To determine the magnitude of the scanner noise, Kodak Wratten filters were scanned, which gave low, medium and high intensity outputs in each of the color channels. The mean square error for each channel was then calculated using:

$$\mathrm{MSE} = \frac{1}{M} \sum_{n=1}^{M} (x_n - x_0)^2$$

Where M is the total number of sample points.
x_n is an intensity value.
x_0 is the mean intensity.

This value was normalized to obtain a percentage noise:

$$\%\ \mathrm{Noise} = \frac{\sqrt{\mathrm{MSE}}}{x_0} \times 100$$

These results are given in Table 3, and show that any color intensity can be expected to be accurate within 5%.

TABLE 3. NOISE MEASUREMENTS

	Percent Noise		
	Low Intensity	Medium Intensity	High Intensity
Red	4.06%	1.60%	1.67%
Green	3.43%	1.84%	3.00%
Blue	4.08%	1.81%	1.51%

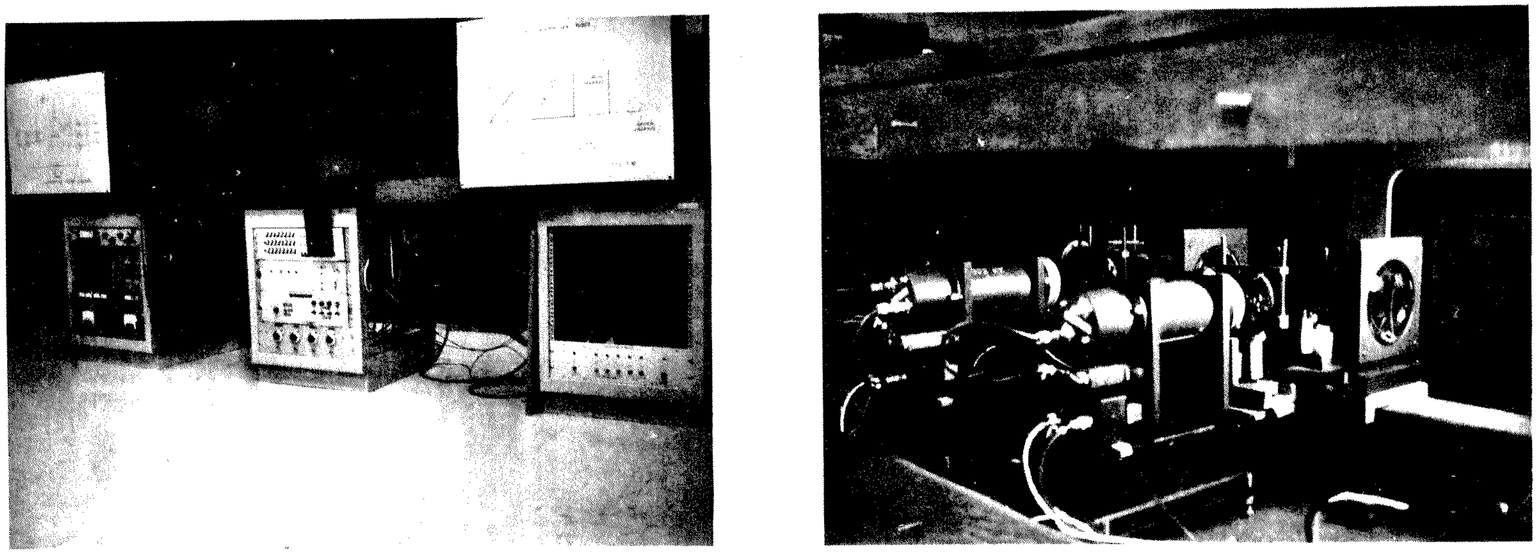
VI. RESULTS AND CONCLUSIONS

Figure 25 shows the final operational configuration of the scanner. Figure 26 is a color print of an infrared transparency that has been digitized. This scene contains a low level aerial view of soybean fields and grapefruit groves located in the Rio Grande Valley of Texas. Scenes of this type are being investigated to determine whether small insect or disease infestations can be detected using digital picture processing methods. These infestations are manifested by small changes in the infrared color reflected by the plant foliage.

Figures 27, 28 and 29 show the output of the FSS color channels for the scene in Fig. 26. Note that the lighter-colored information, such as the roads and the white houses, have the highest intensities in each of the red, blue,and green channels, while the darker red and green information have lower intensities. This results from the lighter colors having a higher transmittance, even though they contain less red or blue or green "color".

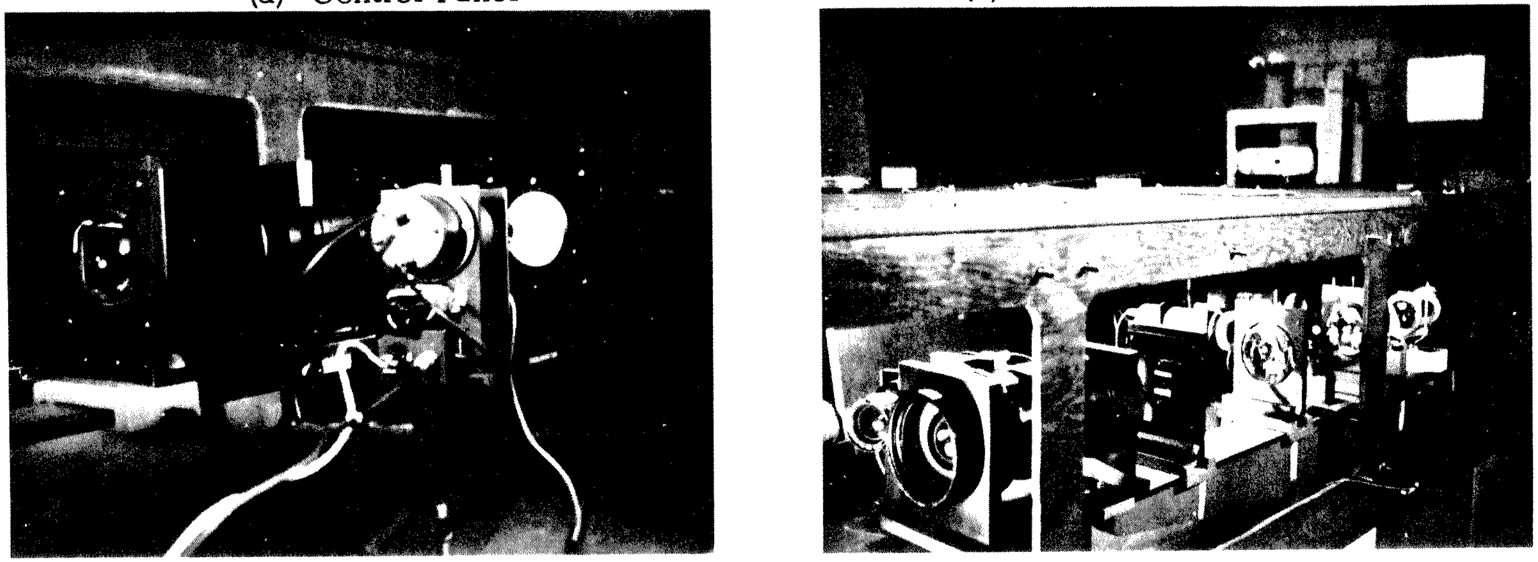
Figures 30 and 31 show the scene after it has been processed for color purity (saturation). In this case, the X, Y and Z color coordinates were calculated for each intensity point, and then thresholding was used to separate the red from the green (and yellow) hues. A measure of purity was obtained by taking the square of the distance of the color coordinates for each intensity point from the color coordinates for white. Purity was then plotted versus the location in the scene. Note that the roads and white houses form valleys, since they have low color content. Also, the red amplitudes are larger than the greens, since the red colors are brighter and more saturated. No blue is shown since there is no blue color in this particular scene.

Figures 32, 33 and 34 show the scanner color channel outputs for the portion of the tree grove outlined in Fig. 26. Figures 35 and 36 show the red and green colors contained in this scene. Note that the red



(a) Control Panel

(b) Red and Blue PMTS



(c) Sampling and Imaging Optics

(d) Optical System

Figure 25. Selected Scanner Views

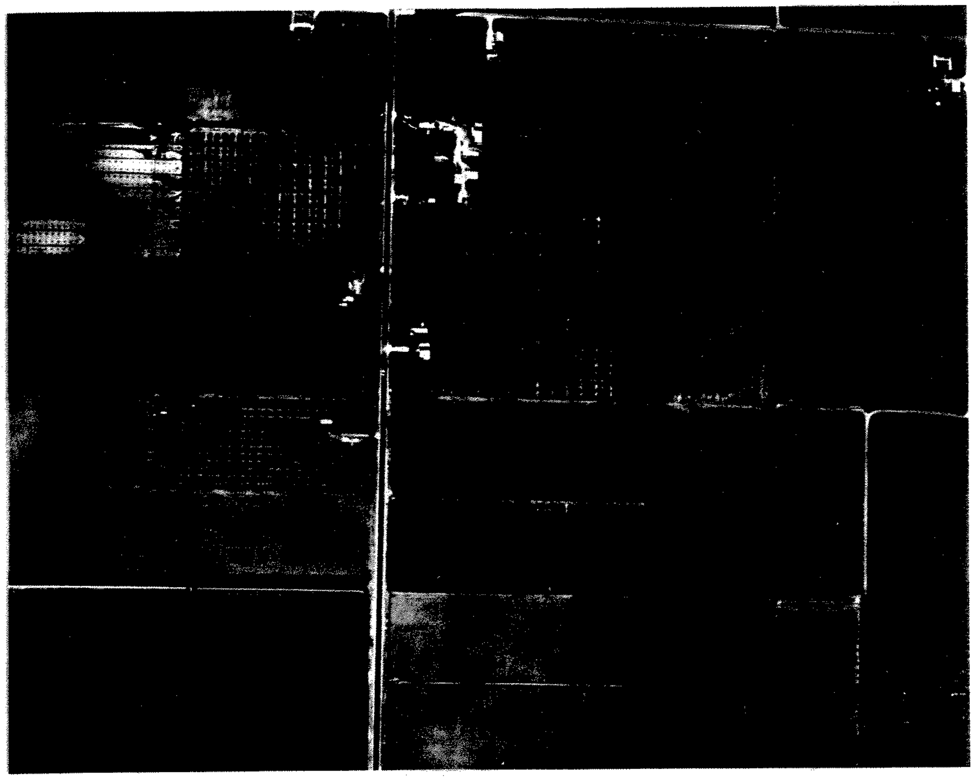


Figure 26. Color Picture of Fields

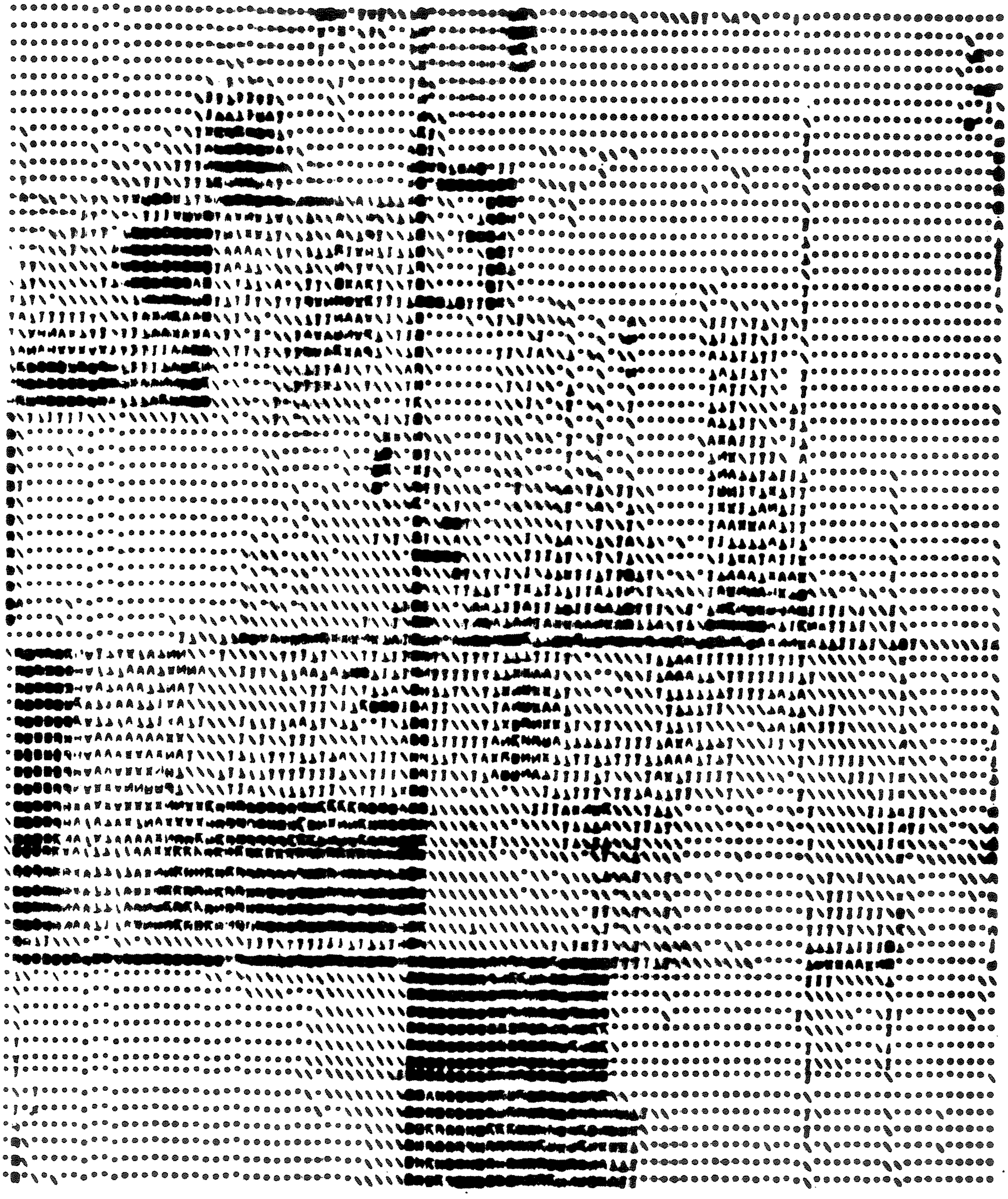


Figure 27. Red Channel

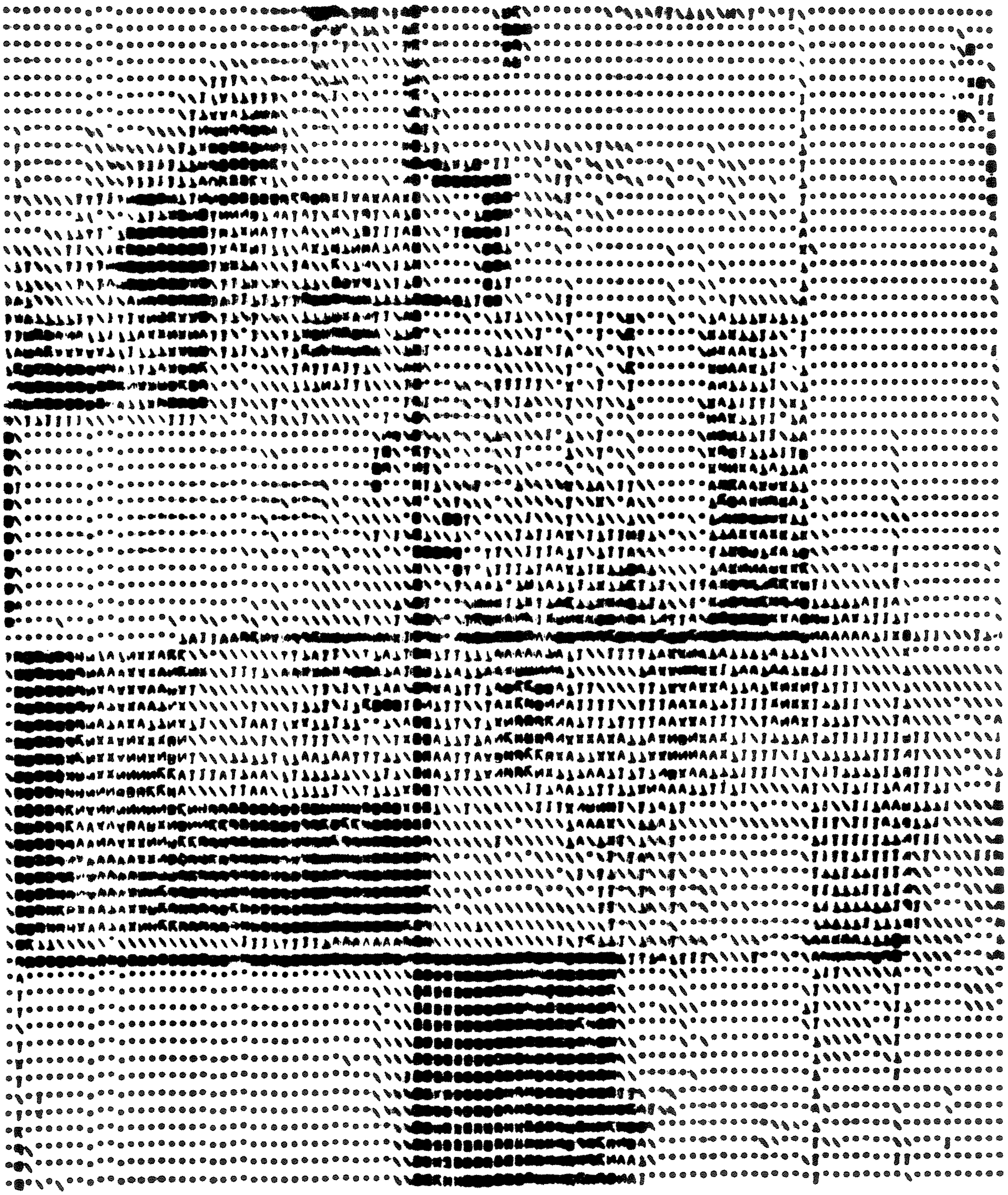


Figure 28. Green Channel

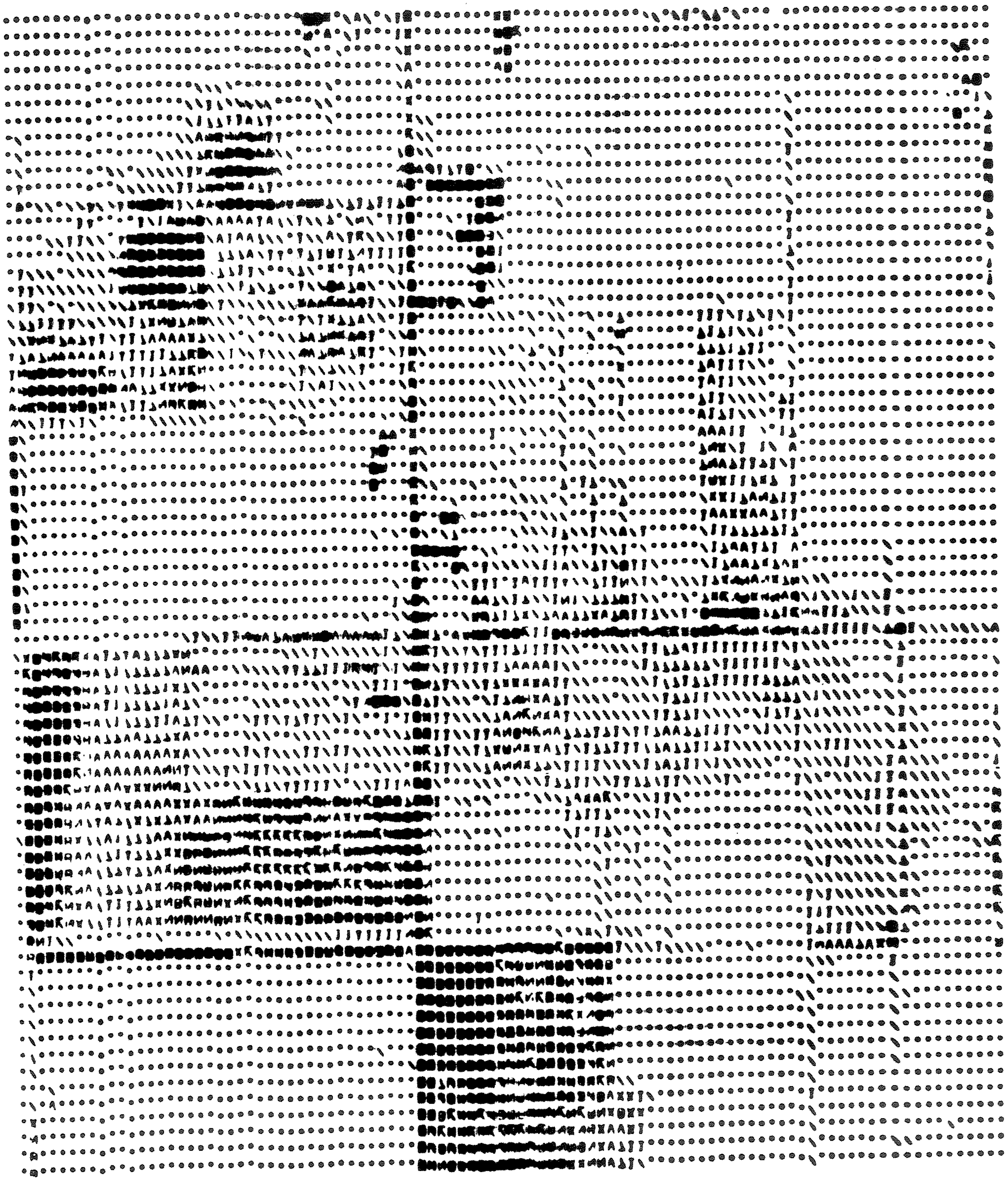


Figure 29. Blue Channel

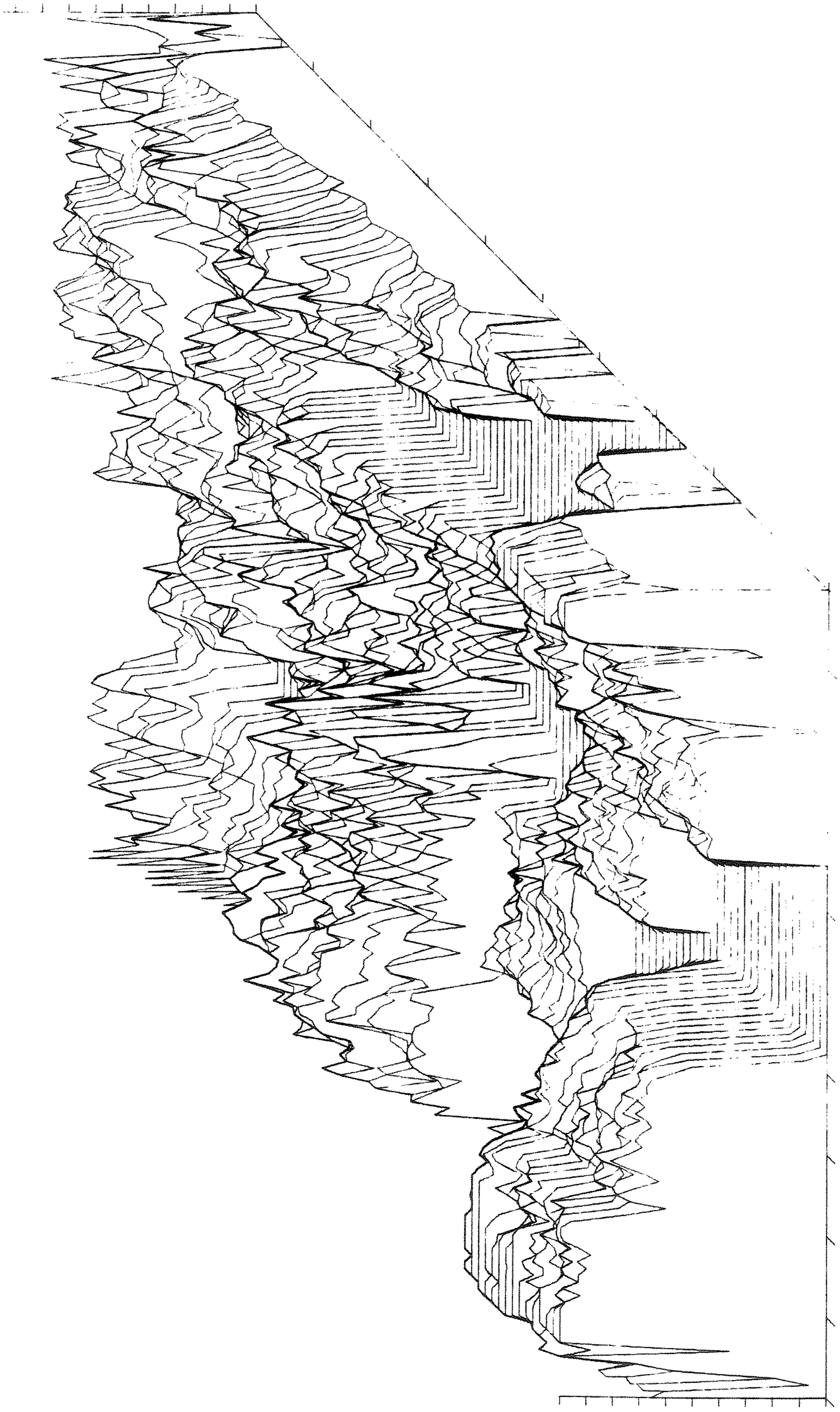


Figure 30. Red Color

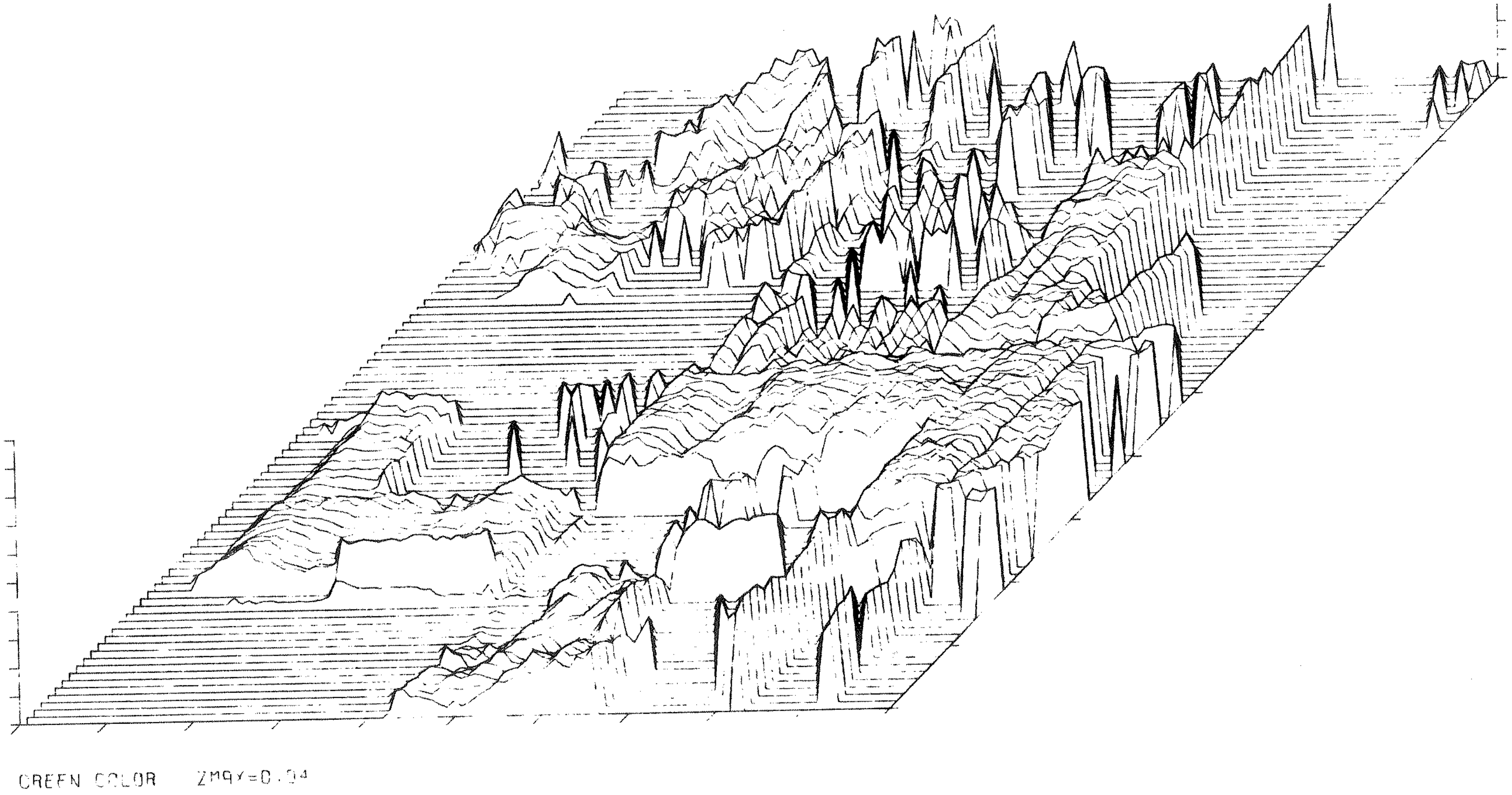


Figure 31. Green Color

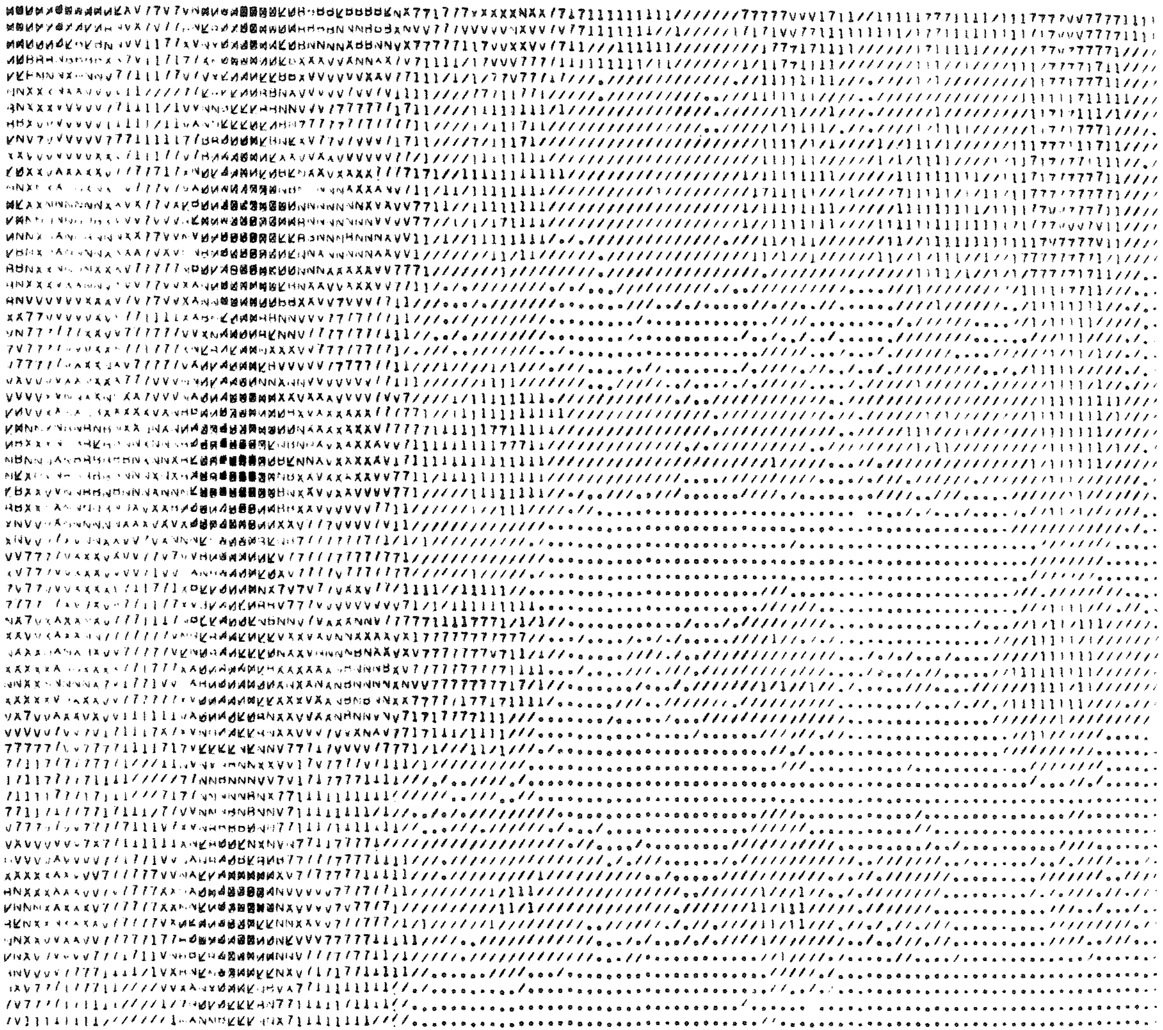


Figure 32. Red Channel

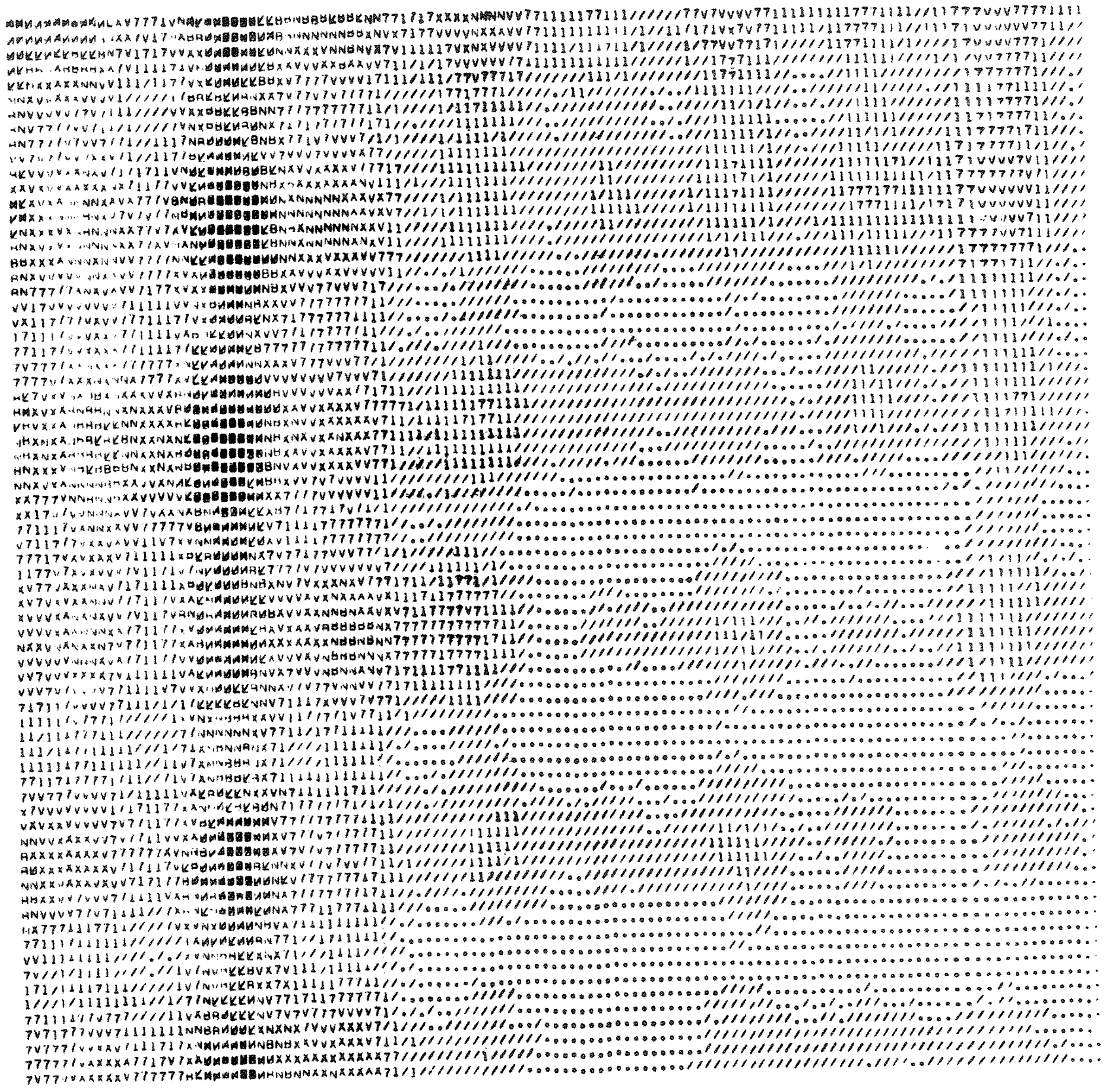


Figure 33. Green Channel

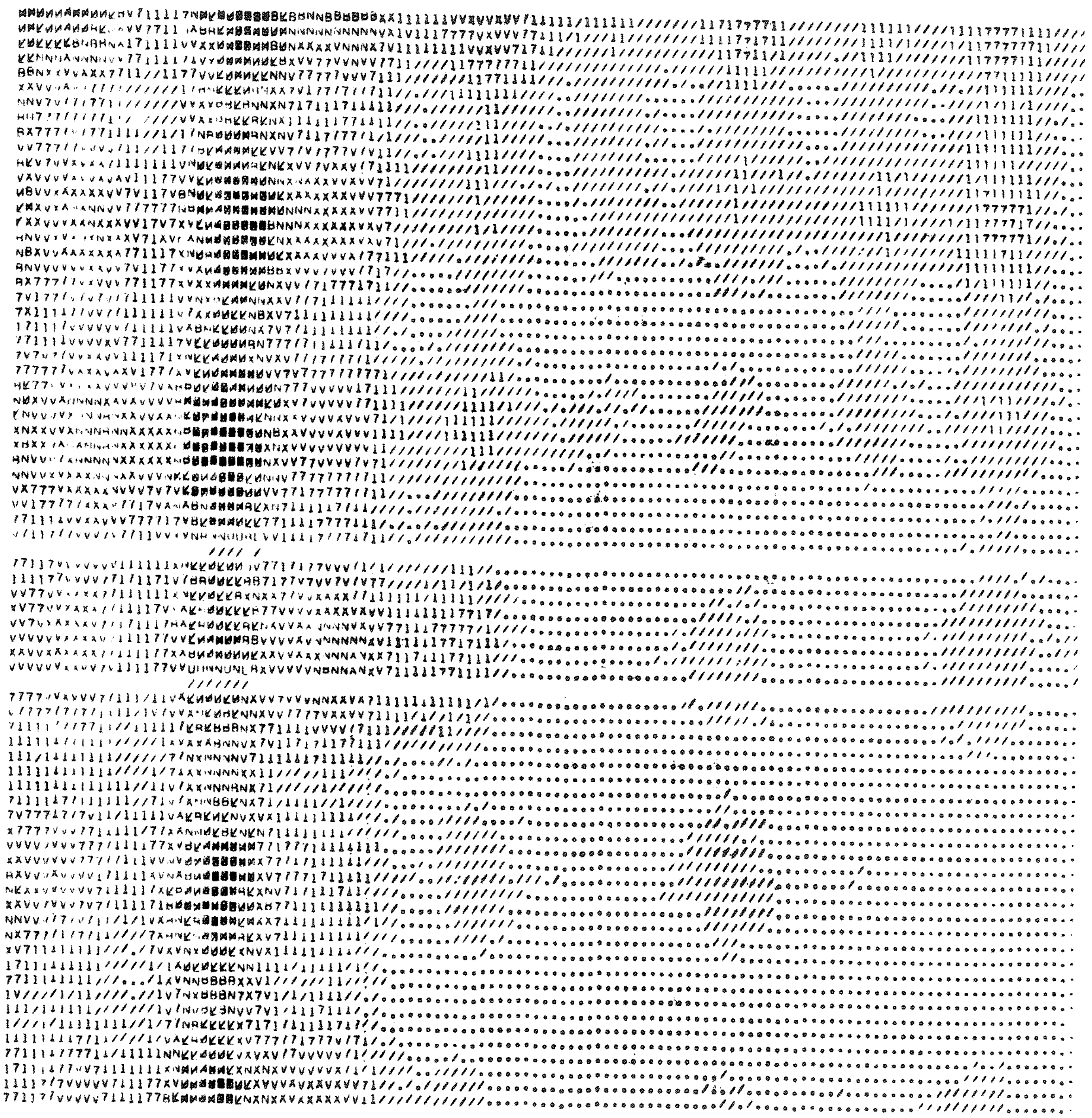


Figure 34. Blue Channel

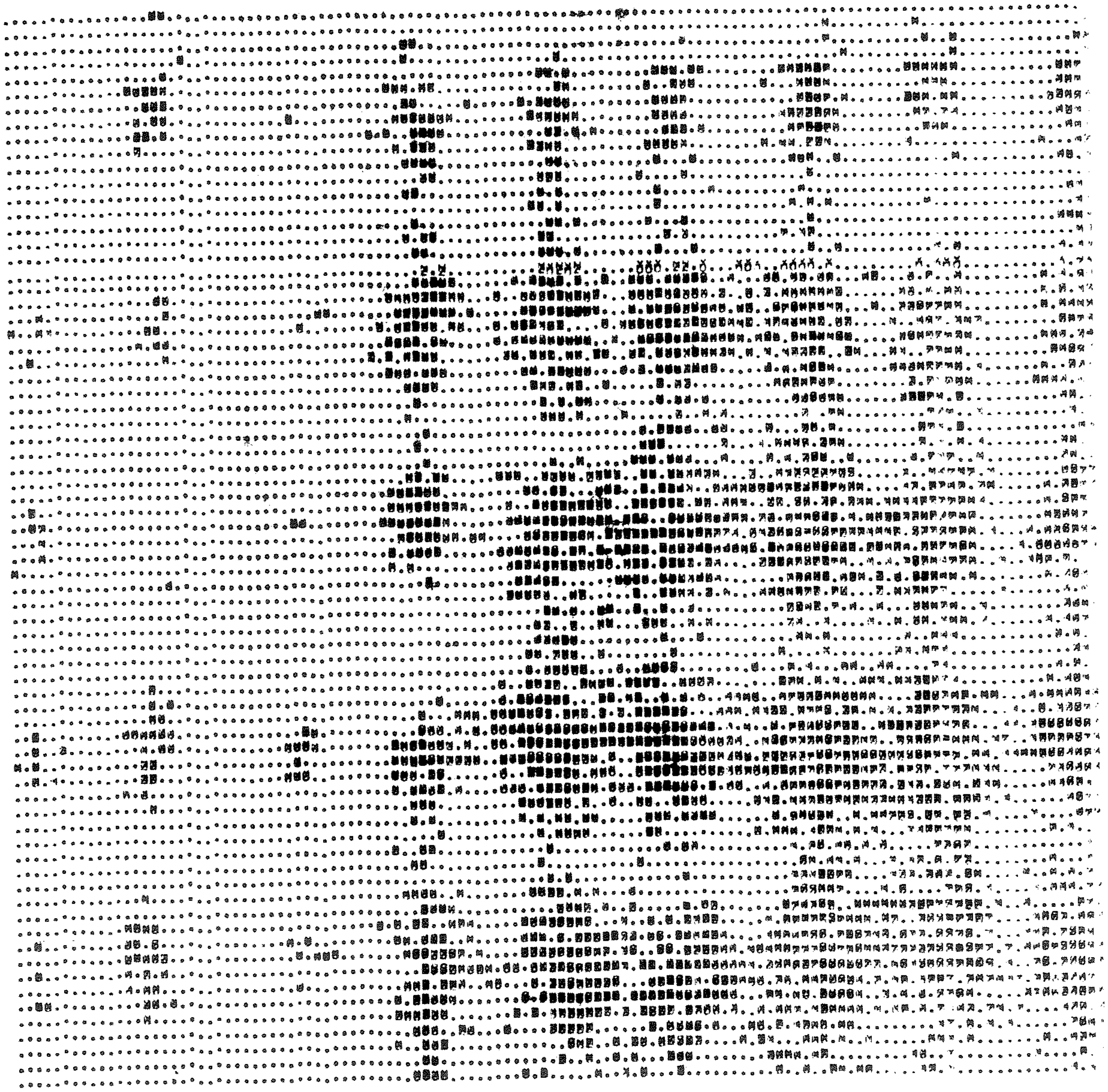


Figure 35. Red Color

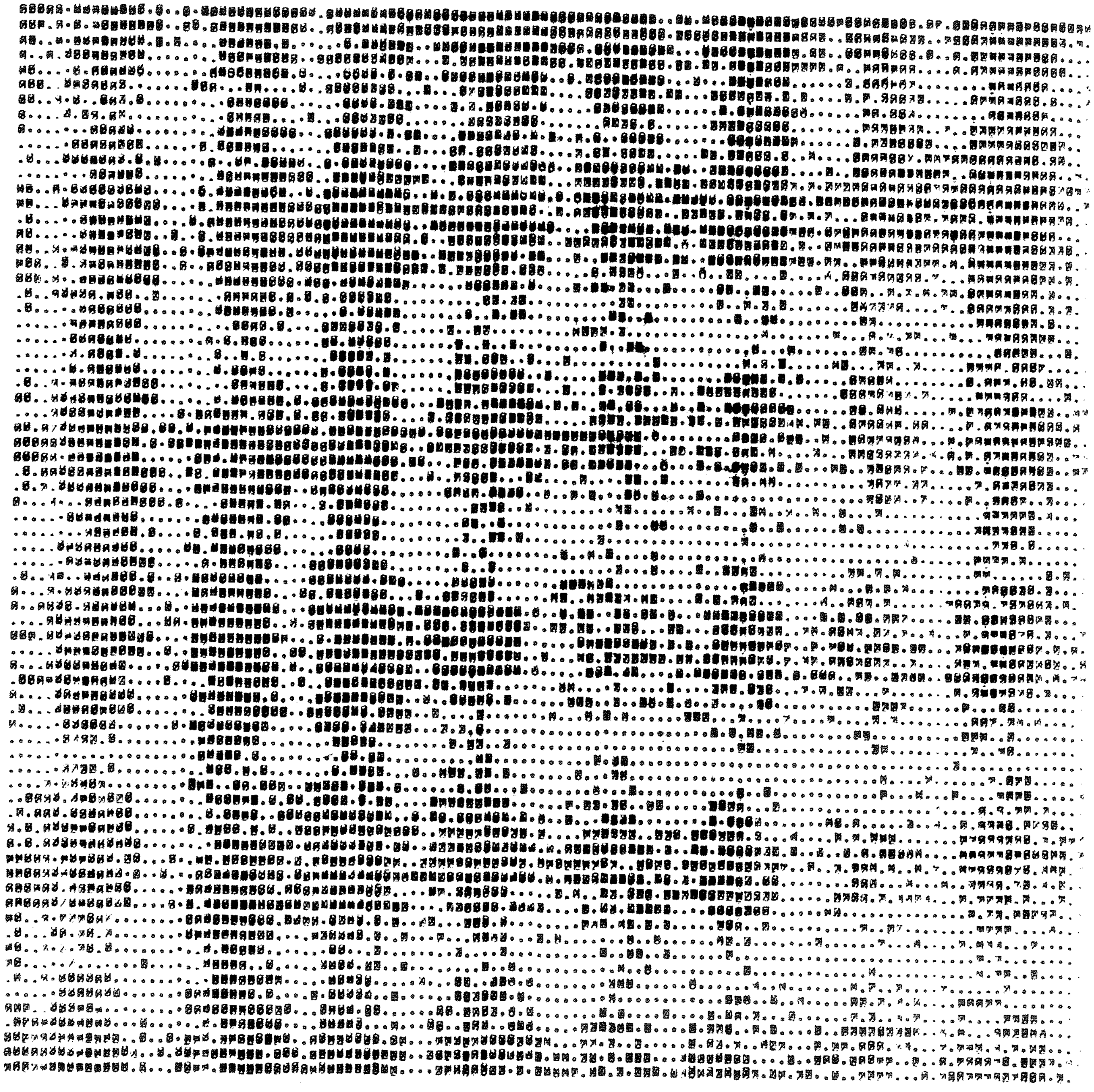


Figure 36. Green (and Yellow) Color

decreases and the green (and yellow) increases as we go right to left. This is consistent with the original scene in Fig. 26, since the red is darker on the left and lighter on the right, where the tree rows thin somewhat. It also indicates that the FSS can detect small color variations. Also, while the color channel outputs are rather nondescript, the color outputs clearly show the pattern of the individual trees, illustrating that color adds information. Note that the scanner resolution is quite satisfactory for this type of processing.

The results illustrate the capabilities of the FSS. Color variations can be detected, and objects can be digitized with good resolution. These features, together with random access operation and a comprehensive software processing package, make the FSS a powerful research tool for color digital picture processing.

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