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PENETRON LAND COLOR DISPLAY SYSTEM (PENTECOST) AND SOME OBSERVATIONS CONCERNING COLOR PERCEPTION

by

G. Panigrahi

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This work examines the human color vision mechanism in light of Dr. E. H. Land's two-color experiments on color vision. The problem of color perception in machines is looked into. Some of the two-color experiments are described. But the main emphasis has been on the building of a two-color television display system based on the two-color projection experiments.

The Penetron Electronic Color System (PENTECOST) is a two-primary color television system intended to examine the scope and the limitations of using the Land two-primary scheme for high resolution color information displays. It employs a penetration type cathode ray tube (Penetron) having red and white layers of phosphors that are sequentially excited every alternate field to display the red and green record of a scene taken synchronously through the red-green color filter-wheel. The Penetron tube as a color display tube is evaluated and the different switching and registration circuits are described. The camera system with the lead-oxide vidicon (Plumbicon) pick-up tube, the color filter-wheel, and the associated synchronizing circuits are also described. The use of an electronically controlled solid state filter like Gadolinium Molybdate instead of the color wheel is considered.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Professor W. J. Poppelbaum for suggesting this thesis topic and for his continued guidance and support. He is also grateful to Professor W. J. Kubitz for his assistance and encouragement during all phases of this project.

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This thesis is dedicated to the memory of Gautam and Bhagawan who are no more.

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1. INTRODUCTION

The human visual system has certain inherent peculiarities that can be taken advantage of to reduce the amount of data necessary to transmit a color picture. Dr. E. H. Land's experiments with two-primary color projections[1-4] demonstrate the extraordinary ability of the human visual system to perceive object colors of all hues, even though the visual system receives color information from only two primaries. These experiments indicate how important a role brain mechanisms play in color perception. The Circuit and Hardware Systems Research Group of the Department of Computer Sciences at the University of Illinois has been involved in uncommon methods of Information Processing. We became interested in Dr. Land's experiments for two reasons; one was the prospect of reducing the transmission bandwith of picture signals and the other was to understand the visual information processing in the human brain. Dr. W. J. Poppelbaum proposed to construct a two-primary closed-circuit television system called 'PENTECOST' for Penetron Electronic Color System, based upon Dr. Land's experiments. It was noted at the outset that the Land system reproduces color pictures of low saturation (such as would be encountered in transmission of pictures of human faces, etc.) very well and so could be quite suited for video transmission. An additional goal of the project was to investigate some aspects of the color vision processing capabilities of the human retina-cortical system, coined "Retinex' by Dr. Land. Understanding the basis of the human visual system, we could probably draw some analogy for the efficient organization of an intelligent machine using color information for its visual perception.

Several technological advances in display devices were taken advantage of in building PENTECOST. One was the Penetration Cathode Ray

Tube (Penetron) which became commercially available at this time. The other was the prospect of having an electrically controlled color filter which became possible through recent advances with ferroelectric ceramics and ferroelectric-ferroelastic materials.

The organization of the thesis can be conveniently divided into two parts. The first part consists of Sections 2.0 - 4.0 and considers the problem of color vision and investigates the human visual system and then speculates on congnitive machines that could have color vision. The second part of the thesis, Sections 5.0 - 10.0, relates to the organization and actual construction of the PENTECOST system.

2. COLOR PERCEPTION IN HUMANS

2.1 The Human Visual System

The human visual system represents the utmost sophistication in the organization of the nervous system. The nervous system, as such, can be divided into the peripheral system, the central nervous system (CNS), and the autonomic system. The peripheral system includes the sensory inputs and the motor outputs controlling muscular activities. The CNS processes all of the input data and takes action depending upon present and past data. The autonomic system regulates all of the chemical and physiological processes that go on constantly to sustain life.

There are five major sensory data input channels to the CNS. The data gathered by the skin receptors and that concerning the muscle and joint tension and pressures are transmitted via the spinal cord. The other three--visual, aural and gustatory information--are directly transmitted to the lower portions of the brain. Figure 2.1 shows a schematic representation of the human brain and the different information paths to the brain.

Here, we are primarily concerned with the visual information system. At the peripheral end of the visual system, we have the eye which receives the light energy formed as an image of the world it looks upon. Figure 2.2 shows the horizontal cross-section of the eye. Incoming light passes successively through the cornea, aqueous humor, lens and the vitreous humor and finally falls on the retina. The retina contains the principal receptors of the light energy. A cross-section of the retina, shown in Figure 2.3, explains its organization. It basically contains three layers of neuron cells: the receptors consisting of rods and cones, the bipolar cells, and the ganglion cells. The receptors perform photodetection. The bipolar cells interconnect the receptors and

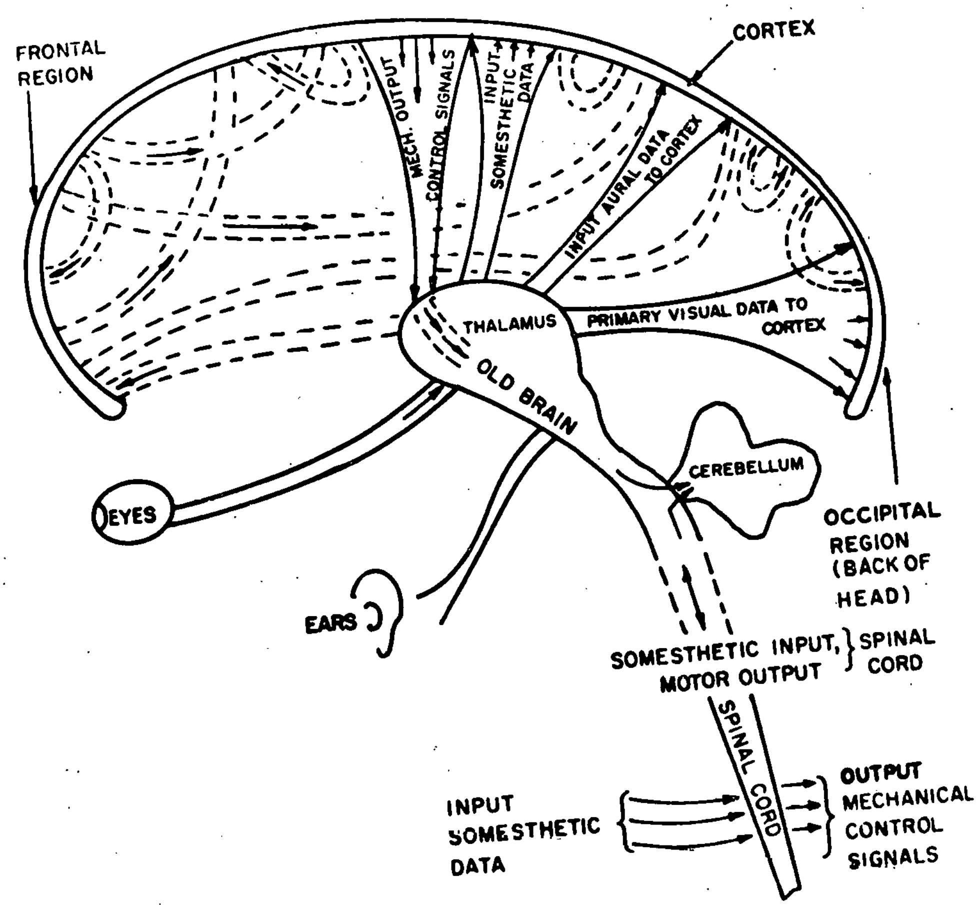


Figure 2.1. Information Flow in Human Brain[8]

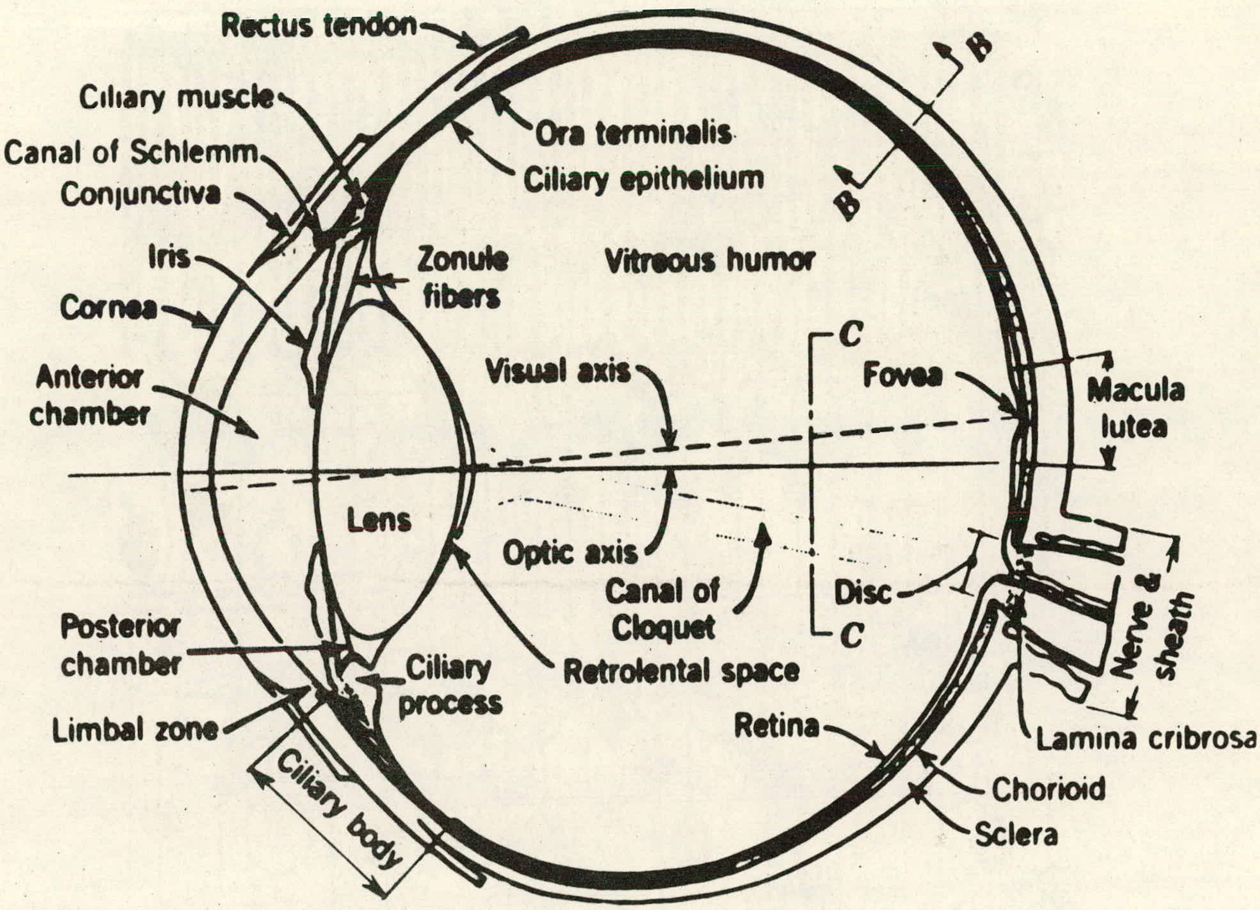


Figure 2.2. Horizontal Cross-Section of the Eye

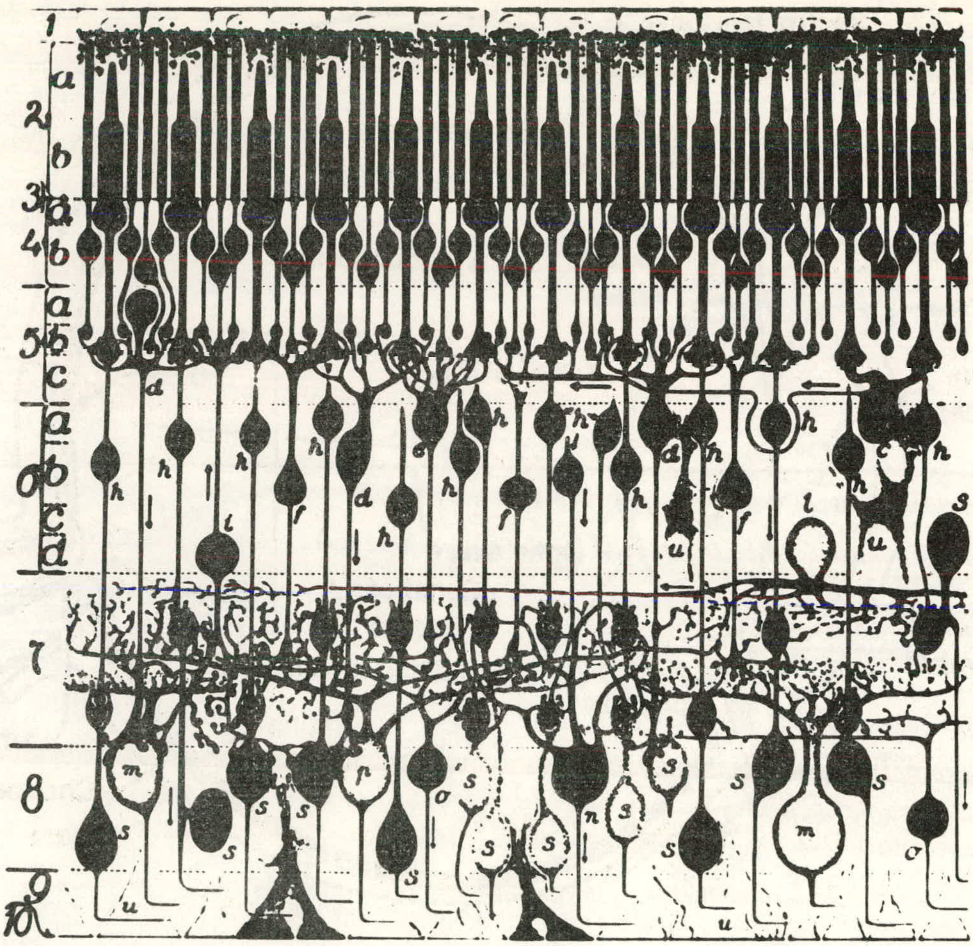


Figure 2.3. Plan of the Retinal Neurons[5]

the ganglion cells in a complex fashion. The ganglion cells form the optic nerve which carries visual information to the occipital cortex by way of laternal geniculate bodies.

There are approximately 150 million rods and 7 million cones in the retina. The rod receptor is of cylindrical shape, about 1 μm in diameter and 50 μm long. It is divided into two sections of approximately equal length, called the inner and outer segments. The outer segment of a cone has the same shape as that of a rod, but the inner segment is broad at the end, and contains a conical section of gradual taper from the outer segment. The cones are responsible for color vision of high acuity; the rods only for achromatic vision of low acuity. There is a great amount of data compression in the retina as is evidenced by the fact that there are only about 1 million optic nerve fibers. The foveal region of the retina contains only cones and there is an optic nerve channel for each cone. As we go from the foveal region to the periphery, the density of the cones decreases but that of the rods increases. At the peripheral portions, the output from hundreds of receptors is combined in some complex manner into a single channel in the optic nerve.

The optic bundle from each eye starts from the blind spot in the back of the eye and travels towards the brain. They intersect at the optic chiasma. The optic bundles are split so that the optic nerve going to the right hemisphere of the brain carries information from left half of each retina and the one going to the left hemisphere carries information from right half of each retina.

The optic nerves terminate in two-dimensional layers in the thalamus called lateral geniculate bodies. This is shown in Figure 2.4. A small amount of processing is performed on the data in the thalamus and

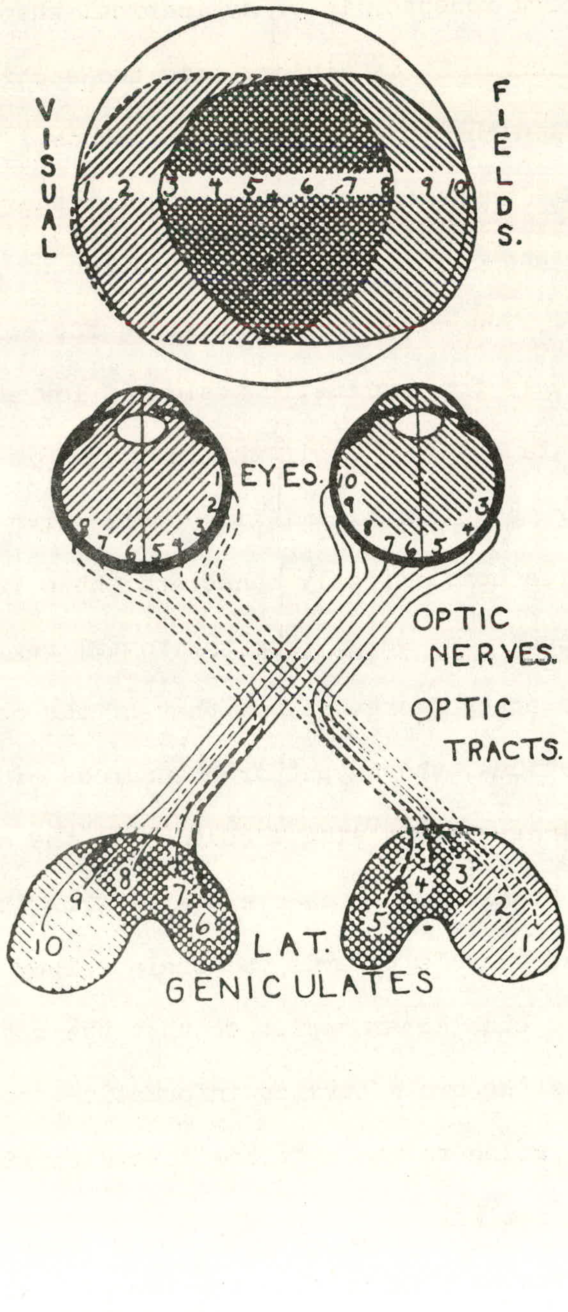


Figure 2.4. Visual Pathways to the Lateral Geniculate Bodies

information is then transmitted to the primary visual area of the cortex (also called 'area 17' or 'area striate') through bundled output axons.

The human brain lying above the thalamus consists of so-called 'gray matter' and 'white matter'. The 'gray matter' or cortex is a sheet of interconnected neurons about 2.5 mm thick but with an area of 2200 cm^2. The 'white matter' consists of the bundles of transmission axons that interconnect the thalamus and the cortex, and the various regions of the cortex.

The visual information reaching the cortex is still in conformal form[5] and takes up about 26 sq.cm. of area in the occipital part of the brain. But this conformality is scrambled[6] after the visual data are processed beyond the input region of the cortex. It is experimentally proved that information flows between the primary visual cortex and the secondary visual cortex[7] (area 18 which surrounds area 17). Visual perception in the brain is the result of some co-relation and cross-corelation between the information in these two cortices.[8]

2.2 Theories of Color Vision

Among the various theories of color vision the Young-Helmholtz theory and the Hering theory are the most widely known. The first one emphasizes the physical aspects of color and the later one is very much response-oriented. In addition, a number of modifications, variations and combinations of these two theories have been proposed over the years.

Young-Helmholtz Theory: Thomas Young proposed a set of three receptors sensitive to 'red', 'green', and 'blue'.[9] Maxwell incorporated these into some experiments and equations.[10] German physicist Helmholtz slightly modified Young's hypothesis[11] and his contribution to a sound scientific explanation was so immense that the theory became known as the Young-Helmholtz theory of color vision. In essence, the theory postulates that there are three kinds of receptors which produce 'red', 'green', and 'blue' responses and that these responses are transmitted to the brain where it is processed to give color perception.

Hering Theory: German physiologist Eward Hering suggested that the eye contains three chemically different substances (Empfangstoffen) which absorb light and interact with a receptor mechanism (seshubstanz) to yield three kinds of opponent responses: white-black, red-green, and blue-yellow.[12] The co-ordinates of color perception according to Hering are shown below in Figure 2.5.

Hering's co-ordinate system has one drawback. Instead of having zero sensation at the origin we experience gray. Wallach modified Hering's theory to include another co-ordinate of luminous-gray sensation that is distinct from white-black sensation. The luminous gray sensation gives an indication of the general lighting in the scene and provides sensations as surface gloss and metallic luster.

Feedback Model of Vision: Biernson[14] proposed a feedback model of achromatic vision which is then generalized to include color vision. His model is based on the Hering Theory but attempts to find a functional basis for it. He developed a functional achromatic model relating to known physiological findings on the structure of the retina[15] and the presence of modulation signals in the receptor output.[16,17] This model, in the form of a feedback-controlled bridge network incorporating time-average feedback, spatial-average feedback and gain control action, is shown in Figure 2.6. The photopigment molecules alternating between bleaching and regenerating states provide the time-average feedback. The time-constant of photopigment

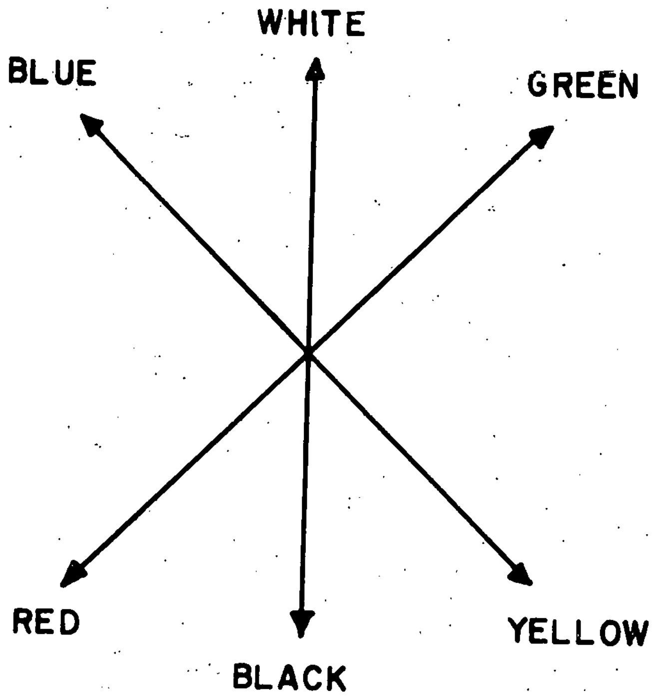


Figure 2.5. Co-ordinates of Color Perception

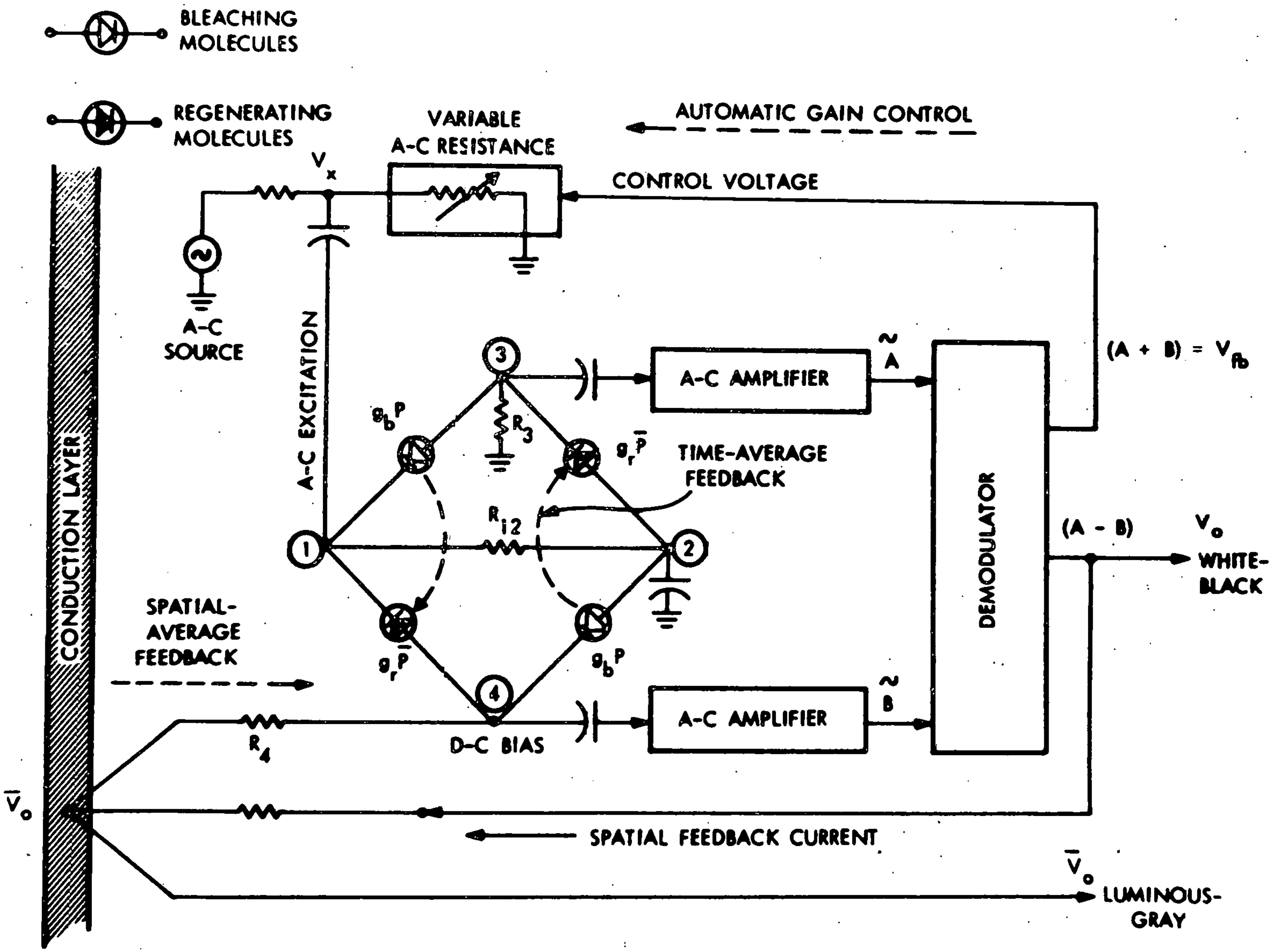


Figure 2.6. Biernson's Model

regeneration is two minutes for cone receptors and ten minutes for rod receptors. Speaking of spatial-average feedback he says,

> "The output voltage, Vo, from the receptor is coupled to the conduction layer of the retina through a high resistance, which feeds a spatial feedback current to the receptors. The currents flowing through the conduction layer establish at each point on the retina a bias voltage, Vb, which represents a weighted spatial average of all the output voltages of all the receptors."

The variable resistance in the feedback path provides for the automatic gain control function. There are two output signals from the network: The white-black signal Vo, and the luminous gray signal $\overline{\text{Vo}}$.

Biernson extends this achromatic model to provide color vision in the following way.

> "Since the outer segment of a retinal cone is only about two wavelengths of visible light in diameter, it acts as a dielectric waveguide, and light can propagate down it only as a summation of a few particular waveguide modes. The modes cause the light energy in the cone to vary with radial distance from the axis, and the radial mode pattern changes in a complex manner with wavelength. These patterns contain considerable spectral information and so are theoretically capable of providing color discrimination. A simple way in which the cone might detect its mode pattern is to employ a scanning process which scans within each disk of the outer segment, starting at the circumference and progressing inward to the axis in the form of a contracting ring. The scan would cause the output voltage from the cone to vary with time, modulating it with a waveform having the shape of the spatial mode pattern. A demodulation process synchronized to the scan could derive the red-green and yellow-blue chromatic signals from the modulation on the cone output signal."

> "It is assumed that the scanning processes in all the cones are synchronized so that all the cone photopigment molecules in the retina at a given value of outersegment radius are sampled at the same instant of time. If the spatial feedback is much faster than the scan, the adaptation processes would operate independently at each value of radius. Hence the cones would adapt to the time-average and spatial-average mode patterns. This would compensate accurately for the spectral characteristics of illumination, so that the mode pattern information carried as a modulation on a cone output voltage would describe the reflectance spectra of the object being sensed. Demodulating this waveform would provide signals representing the color of the object, which are essentially independent of illuminant spectrum."

Biernson's electronic model gains support from the fact that though three kinds of cone spectral responses have been detected it has not yet been possible to detect any three kinds of cones or connections between them. There is also some similarity between the scanning process and the nerve impulse, except the latter have higher amplitude and propagation rates.

2.3 Receptors of Color Vision

Light passes through eight of the retinal layers to the receptor layers where it is absorbed. The first of the light-sensitive pigments to be discovered was rhodopsin. The rhodopsin molecule is made up of opsin and 11-cis retinene. When light is absorbed only retinene is isomerized to produce intermediate products. Rhodopsin is the visual pigment of rod receptors[18,19] and has a difference spectrum that is similar to the 507 nm peak of the scotopic luminosity curve. Rods are not important for color vision and occur only in the extra-foveal regions.

The first two of the pigments responsible for color vision were isolated by Rushton.[20] They are the green-sensitive pigment called erythrolable and the red-sensitive pigment called chlorolabe. The blue pigment cyanolabe was later isolated by Wald.[21] Erythrolabe, chlorolabe, and cyanolabe have peaks at 55 nm, 525 nm, and 450 nm respectively. These pigments are associated with the cones. It is likely that they have the same retinenes but different opsins from that of the rods.[19] The difference spectrum of rhodopsin as well as that of cyanolabe, chlorolabe and erythrolabe are shown in Figure 2.7.

The spectral absorption characteristics overlap to a large extent and it is apparent that there must be some form of encoding to extract the

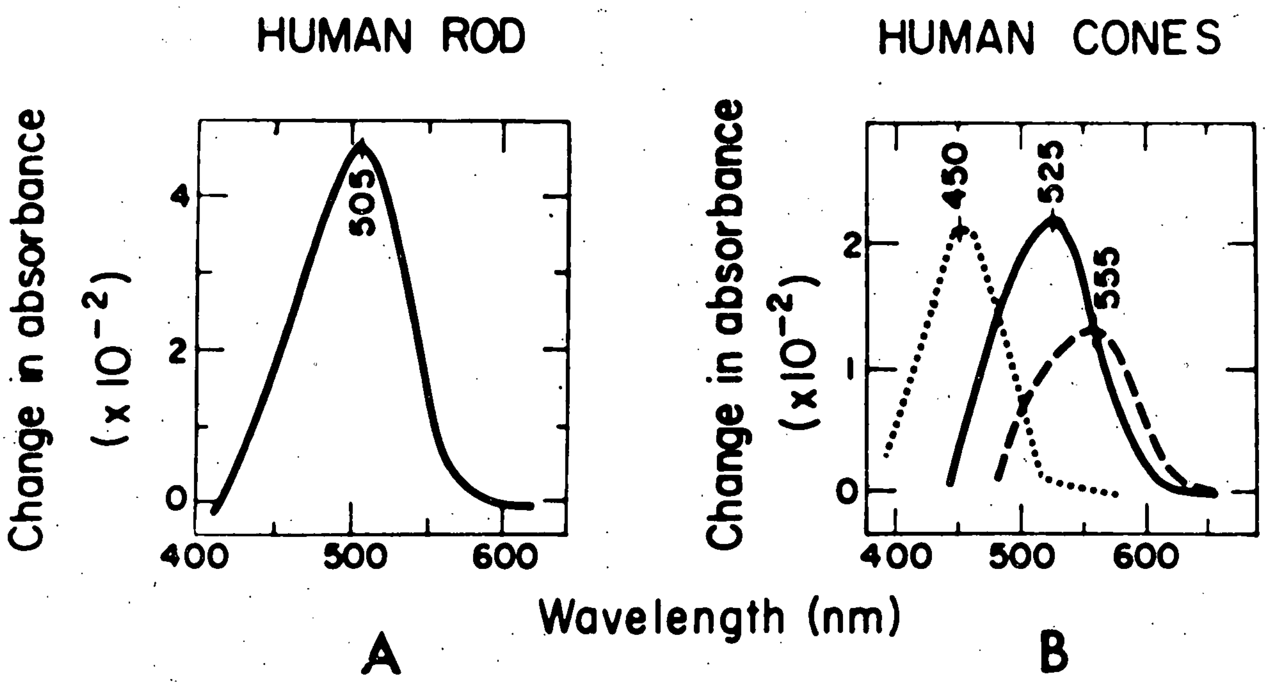


Figure 2.7. Difference Spectra of Rod and Cone Pigments

red, green and blue information. Some indication about the encoding and processing that take place at the receptor level can be obtained from Figure 2.3. The footnote in the figure explains the complex interconnection patterns which signify a complex data processing operation. The centripetal bipolar cells are amplifier-mixers that gather signals from a number of receptors and pass them on to a higher level. These are the horizontal bipolars which interconnect different receptors. The centrigual bipolar cells provide feedback directly from higher brain centers carried through afferent fibers.

2.4 Representation of Color

We will discuss in this section how color is represented in the trichromatic theory of color vision. According to trichromatic theory, colors are fully characterized by three parameters. Hence, it is usual to represent them in three-dimensional space. In one method, where they are represented by brightness, hue, and saturation, the z-axis represents brightness, the angle represents hue and the radius r represents the saturation. The notion of brightness, hue, and saturation is psychological in nature. In psychophysical studies color is usually represented by red, green and blue components. The psychophysical color vector Q can be represented in a three-dimensional space as

$$\vec{Q} = R\vec{R} + G\vec{G} + B\vec{B}$$

where R, G, B are the amounts of fixed primaries $\vec{R}$, $\vec{G}$, $\vec{B}$ that are required to match color $\vec{Q}$. R, G, B are called the tristimulus values. The chromaticity co-ordinates corresponding to these tristimulus values are defined by the equations

$$r = R/(R+G+B),$$

$$g = G/(R+G+B),$$

$$b = B/(R+G+B).$$

In colorimetry an ideal observer's color-matching functions are defined by specifying three independent functions of wavelength. The 1931 CIE defined two linearly related standard observer's color-matching functions. The RGB system employs reference monochromatic primaries of wavelengths 700, 546.1, and 435.8 nm with the white lying in the centre of the diagram. One of the drawbacks of the RGB system is that one of the chromaticity co-ordinates is always negative for spectral colors and this complicates the calculations. The 1931 CIE adopted another transformed trichromatic system, the XYZ system with primaries X, Y, Z that are based on the primaries R. G. B. The X, Y, Z primaries are chosen to have the following properties.

1. The Tristimulus value Y is equal to the luminous flux. X and Z points represent zero luminous flux.
2. The triangle XYZ is formed by the sides XY and YZ that are tangents to the spectrum locus.
3. The white source, W, is at the centre of the diagram as in the RGB system.

The XYZ triangle completely encloses the spectrum locus and the purple line, and hence the chromaticity co-ordinates corresponding to the tristimulus values X, Y, Z of any real color are always positive. The XYZ chromaticity diagram is shown in Figure 2.8. It shows how the color solid is constructed and labels names for different regions in the chromaticity diagram. The chromaticity co-ordinates of the CIE standard sources A, B, C are shown along with the equi-energy white.

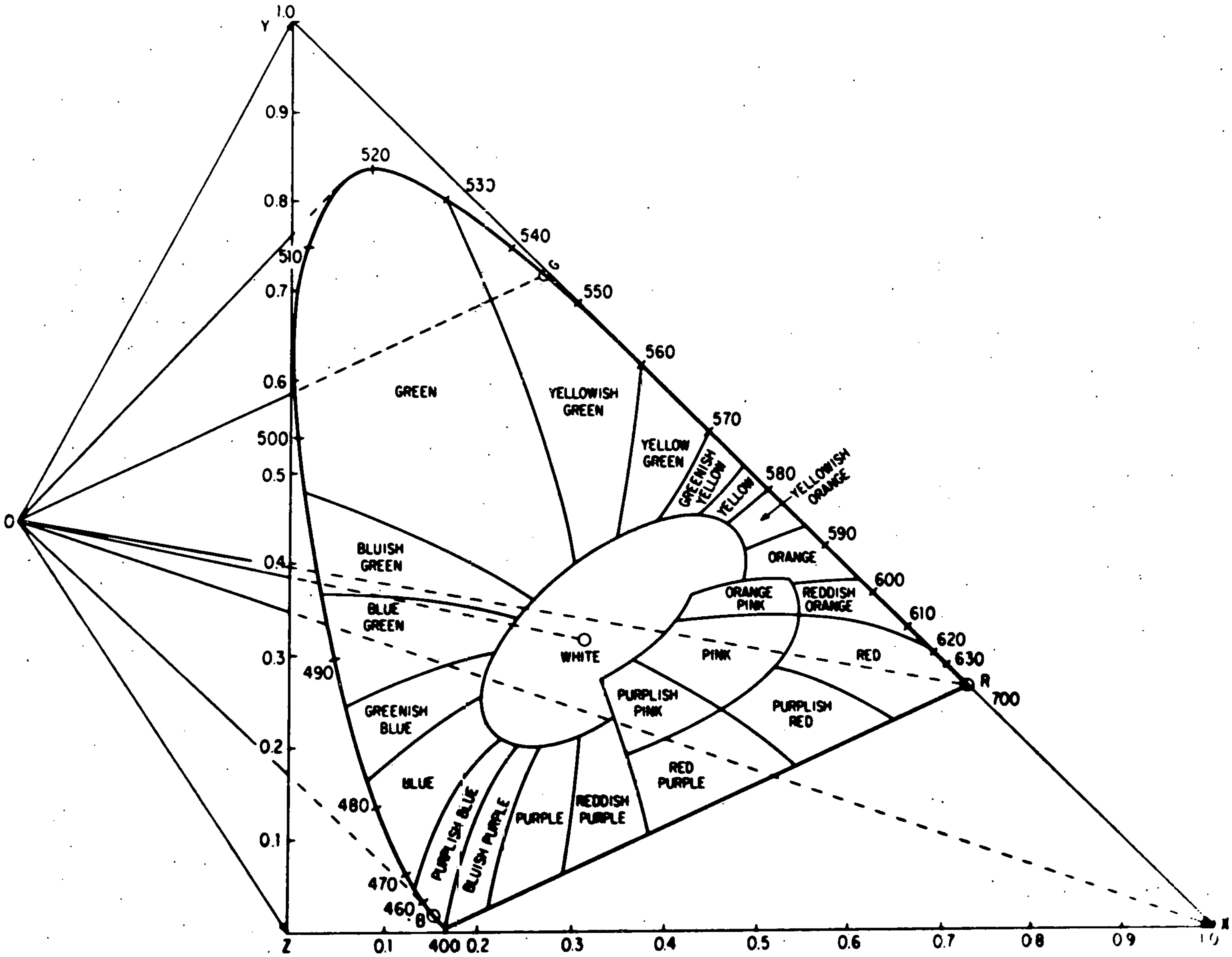


Figure 2.8. Standard Chrcmaticity Diagram

2.5 Two-Color Perception

Dr. Edwin H. Land's two-color experiments show some striking characteristics of the color perception mechanism.[1-4] Land produced color-separation positives by taking two photographs, one through a filter transmitting the longwave third of the visible spectrum (585 - 700 mμ with Kodak Wratten No. 24), and the other through a filter transmitting the middle third (490 - 600 mμ with Kodak Wratten No. 58). These two positives are respectively called the long and short wave records. The long-wave record is usually projected with red light and the short-wave record with incandescent lamplight. Other projecting lights have also been used. With the two images properly registered on the screen, Land observed the following results.

If the projection wavelengths are sufficiently different, a variety of colors appear. The colors that do not appear for the various combinations are shown in Figure 2.9 drawn from Land's empirical data. There is an achromatic region near the diagonal and it corresponds to projection wavelengths of insufficient separation. The color reversal effect, achieved when the shorter projection wavelength is used with long-wave record and vice versa, is shown below the diagonal. In this instance complimentary colors appear. Land also found that when red and white light were used to project the long- and short-wave records, the projected picture could be photographed with color film yielding a quite realistic colored picture. The relative intensities of the two projecting beams was varied between wide limits and did not produce any serious distrubance of the colors perceived. The chromatic effects were more prominent with random type scenes.

In explaining his results, Land is of the view that "the color, at least in images derived from primaries, depends neither on the wavelengths of these primaries nor on the relative energy of these primaries at a given

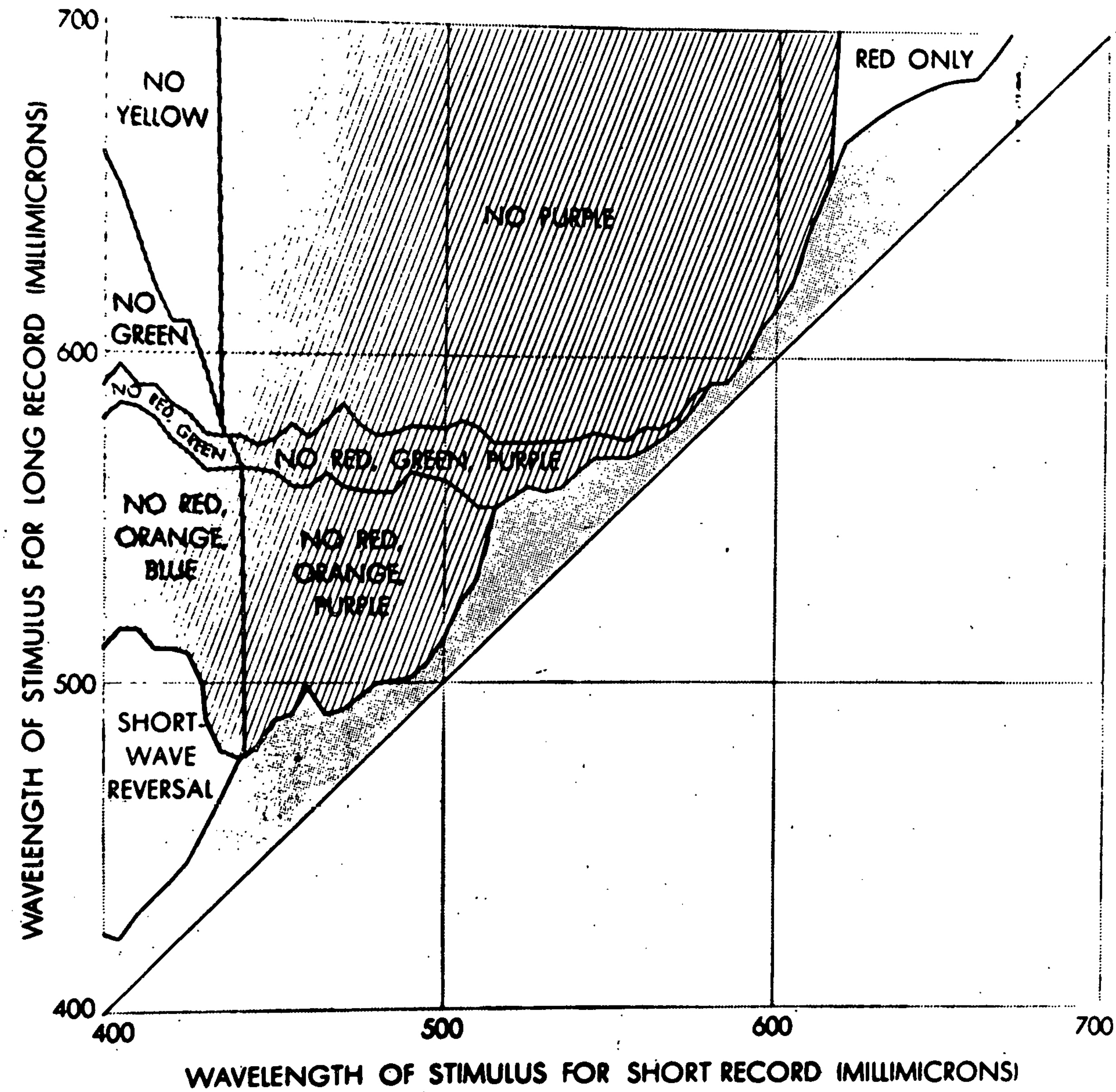


Figure 2.9. Land Color Versus Long and Short Wave Sources

point in the image." Instead, "color at a point in an image depends on the ratio of ratios; namely, as numerator, the amount of long-wave stimulus at a point as compared with the amount that might be there; and, as denominator, the amount of a shorter wave stimulus at that point as compared with the amount that might be there."

This view is refuted by Judd, Woolfson and several others[22-24] who are of the opinion that all of Land's results could be explained within the framework of the classical color theory. Empirical formulas for the prediction in terms of hue, lightness and saturation of the color perceived of any object viewed in any kind of light have been developed by Judd.[25] The illuminant color is discounted by defining, on the Maxwell triangle, a point that corresponds to the perception of gray in the object mode. This achromatic point is close to the chromaticity point of the illuminant color. By Helson's principle,[26] this point is also a function of the luminance of the object relative to the average luminance of the scene. Judd combined these two principles in the Helson-Judd formulation and successfully applied this to predict colors in Land's two-primary projection.

Judd also refers to some possible effect due to simultaneous and successive contrast and memory color. But he summerizes, "The hypothesis that middle-wave and long-wave information provides all the information necessary to determine the object-color perception is obviously doomed to failure. ----- Two-primary color processes must fail to yield faithful color rendition to an extent essentially greater than the all too large departures from reality afflicting current three-primary color processes."

Woolfson applied the Young-Helmboltz theory of color vision to Land's two-primary projection and came up with similar results. Recently, Pearson, et al.[27-29] have applied the Helson-Judd formulation to quantitatively predict Land's results in two-primary projection and television situations. The success of the Helson-Judd formulation in predicting the Land color points to the fact that the so-called phenomenon of color-constancy is responsible to a great extent for the appearance of Land color.

2.6 Retinex Theory

Land later proposed his retinex theory to explain his results. He accepted the hypothesis that the retina contains receptors having peak sensitivities in the regions of approximately 600, 550 and 470 mμ and that the response curves for these receptors widely overlapped each other. But Land proposes "that all of the receptors with maximum sensitivity to the long waves in the spectrum, for example, operate as a unit to form a complete record of long wavelength stimuli from objects being observed." He calls this suggested retinal-cerebral system a 'retinex'. Thus, there are three retinexes. The retina-cortical system draws three independent conclusions in three retinexes about the lightness of the object. The result of the comparison of these three conclusions gives the sense of color. Land explains the red-white projection experiments in terms of the retinex theory in the following stanzas.

"In red and white projection, the long-wave retinex system will form a lightness scale from the optical image of the black and white slide projected in red light. This perceived lightness scale will be invariant to changes in the brightness of the projector, to variations in the uniformity of illumination of that projector, and to reducing the time of projection to a microsecond. The other color separation slide, the one usually photographed through a green filter, is projected with white light. All three retinexes, the long, the middle and the short-wave, will form lightness scales of this optical image. We can assume that these retinex images in terms of lightness will be like each other and that the objects within them will have the same rank order. The lightness scale on the long-wave retinex will be determined by the composite of the long and the middle wave optical image. The lightness scale on the short-wave retinex is identical to the one on the middle wave retinex in this experiment. The middle-wave record is the one that is on both the middle and short retinexes, so that the small difference in behaviour of the middle retinex and the short retinex manifests itself by the appearance in binary projection of both red objects on the one hand and blue or green objects on the other, depending on subtle differences in the absorption curve of these latter objects. Both the short and middle retinexes, because of their similarity in behaviour, contribute together and without conflict to the sensations of grays, browns, oranges and so on, when they are simultaneously correlated with the lightness scale of the long retinexes."

There is yet no physiological basis against the existence of the retinex. Land's retinex theory postulates an information processing viewpoint presuming certain physiology for the color vision mechanism as opposed to the usual psychological or psychophysical explanations of the color perception process. More experiments have been recently reported[30,31] to corroborate Land's retinex theory. But we are still far from the point when the visual system can be examined from an information-processing point of view so as to relate its function to the structure of the retina-cortical system. In the next few sections we examine some of the psychological effects working in favor of Land effect and look for the morphological basis for all these phenomena.

2.7 Visual Adaptation

Visual adaptation is the ability of the visual system to respond over wide ranges of luminance and chrominance. This is accomplished by adapting the chemical processes at the receptor level. Visual adaptation also refers to 'cerebral adaptation' which automatically biases the cerebral mechanism to perceive familiar objects much the same way under different conditions of luminance and chrominance. One such example: A white paper looks the same under daylight as under tungsten light though the color temperature and luminance levels are widely different. This is also sometimes termed color constancy. Another illustration of the influence of expectation on perception is the problem of memory color which is discussed in the next section.

2.8 Memory Organization and the Problem of Memory Color

Numerous researchers have proposed a large number of different models of the memory in the human brain and its functional relation with the perceptual processes like vision and speech. For example, auditory recognition is modeled in terms of short-term memory, long-term memory and different associative mechanisms. There is a labyrinth of association fibers that connect various sensory receptor regions with various other regions in the brain. What is perceived is the result of the sensory input and the different associative activities that it excites.

What we remember about an object influences the way it appears. People tend to remember the dominant attributes of familiar objects and color is such an attribute. Such remembered color attributes are called memory colors. Sometimes, the memory color of an object is different from the actual color and the visual system would prefer to have a perception of the memory color. This effect is known in color television where peoples' memory color of the human face is more tanned than it really is and they prefer to see such a tanned color rather than the real color.

2.9 Visual Induction

'Induction' also called 'contrast' refers to the fact that the response at one place influences the response at another place in the retina. A white dot in a black surrounding looks whiter than it really is. The problem of induction over small areas has been investigated to a great extent. Here, we are more concerned with the large-area induction effects which are thought to play a major role in producing Land color. It should be mentioned that all of Land's experiments are large-field experiments. The juxtaposition of various widely differing stimulus areas enhances the chromatic and luminance difference. This involves interaction between the various inducing elements in the experimental field.

2.10 Brain and Visual System Organization in Relation to Color Vision

An illuminating discussion on the neuronal organization of the color vision mechanism is given by Ekaterina Skol'nik-Yarros.[32] Some of the salient points pertaining to color vision are given here.

The morphology of the color vision mechanism at the receptor level has been investigated in great detail and with some success, but there are extremely contradictory views on the morphological basis of color vision at the cortical and sub-cortical level. A diagram of the components of the visual system is given in Figure 2.10. It shows the different centripetal and centrifugal interconnection paths between the cortical and the sub-cortical structures. It also gives one a reasonable qualitative feel about the neuronal structure of the cortical areas 17, 18, and 19. The optic

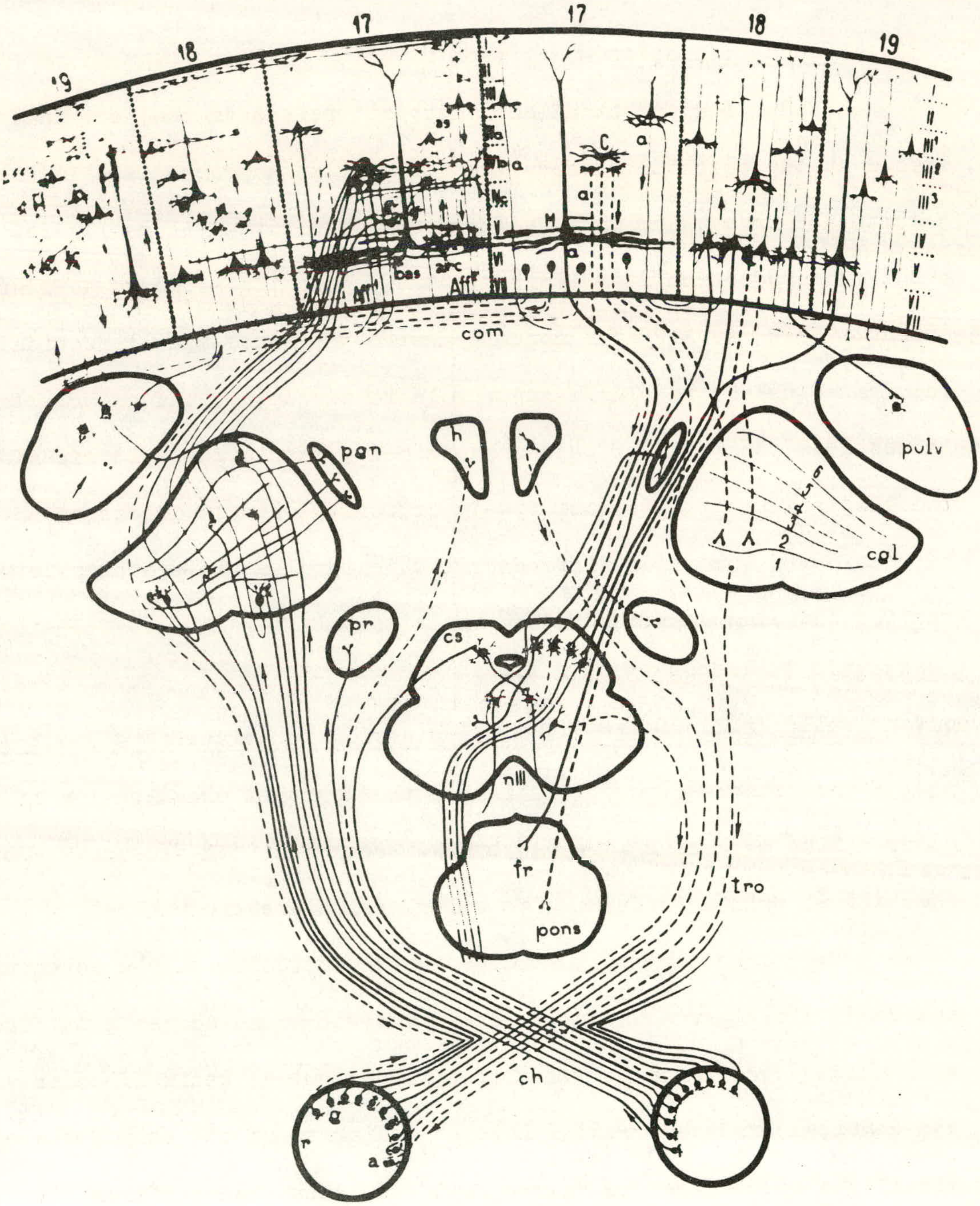


Figure 2.10. Diagram of Components of the Visual System in Primates[32]

nerve is a projection bundle of centripetal and centrifugal fibres from the cortex and the sub-cortical structures. The afferent fibres from the lateral geniculate bodies give off terminal branches in Area 17, layer IV, sublayers b and c. The areas surrounding Area 17 have a high concentration of pyramidal cells that have the capability of forming thousands of connections with surrounding and distant neurons. This is said to be the morphological basis for association of visual images with others.

It is now generally accepted that three types of cones transmit the color stimuli. How further processing takes place is a controversial question. Le Gros Clark hypothesized that the six layers of the lateral geniculate bodies link to the three cone systems. Some have ascribed color vision capability to the subcortical structures and still others mainly to the cortex. To ascertain the morphology responsible for color vision Shkol'nik-Yarros compared the neuronal structure of man and primates having color vision with those which do not have color vision. She noticed an important cytoarchitectonic difference in the lateral geniculate body. This is the presence of midget neurons which are numerous in the upper layers of the lateral geniculate body in primates with well-developed color vision. These midget cells resemble the small round neurons having few dendrites found in large numbers in sublayer IVc of Area 17 of monkeys and man. Polyak had observed in primate retina the existence of bipolar cells termed 'midget cells' connecting individually with each cone. This midget bipolar cell is connected with a midget ganglion cell. Polyak described this cone-midget-bipolar-midget ganglion cell system as the cone system. From these observations Skol'nik-Yarros concludes that,

> "The proven presence of midget (in the sense of the extent of their axo-dendritic connections, not of their size) cells in the central part of the visual system and the fact that color

vision may be lost in patients with brain lesions leads to the conclusion that a special cone-midget system exists in the visual analyzer of the primates. The macular part of this system is most extensive, and it is evidently concerned not only with the perception of color stimuli, but also with visual acuity, with the fineness and precision of visual discrimination i.e., with the properties characteristic of macular vision. The peripheral part of this system (the rare midget cells in layers 1-2 of the lateral geniculate body corresponding to the midget bipolar and ganglion cells at the periphery of the retina) is much less extensive."

This morphological specialization of the retina-cortical system supports Dr. Land's retinex theory which assumes independent sets of retinexes.

2.11 A Synthetized Theory of Color Vision

In previous sections we discussed various theories of color vision. The trichromatic theory emphasizes the physical aspects of color vision at the receptor level. The Hering theory is based on psychological opponent responses. There are numerous other variations of these theories that model the color vision mechanism at the receptor level. Land's retinex theory is an attempt to examine the retina-cortical system as a whole instead of ignoring the cortical processes. Considerable advances in neurology and cybernetics are called for before we can have a viable theory that accounts for the morphological and information-processing basis of the color vision mechanism.

The investigations of DeValois, et al.[33-35] have at least shown evidence that color vision in man is represented by two simultaneously working systems, the trichromatic system and the Hering system. DeValois observed in the lateral geniculate body that layers 1 and 2 do not respond to color stimuli but the neurons of layers 3, 4, 5, and 6 do respond differentically to spectral stimuli. Single neurons in layers 3 and 4 gave either on or off responses. For example, an on response is evoked with blue light and an off response with yellow light i.e., it responded to complimentary colors. Neurons of layers 5 and 6 evoked both on and off responses to the stimuli of the same color. But different neurons responded to different light stimuli. Thus layers 3 and 4 are a mechanism working in accordance with Herings' opponent-response theory. Layers 5 and 6 are a mechanism working in agreement with trichromatic theory.

It could be now argued that color vision at the receptor level is a three-component mechanism but that the visual information is coded into different forms in subsequent processing steps prior to transmission of this information to the cortex. In conclusion to this section on human color vision, we again note that we are far from understanding fully the intricacy of the color vision process. Any such understanding coming from the works of Neurologists and Information Scientists will not only shed light on brain mechanisms but also stimulate research on Artificial Intelligence Machines that are capable of human perceptual processes.

3. COLOR PERCEPTION IN MACHINES

The computer-controlled world of the future needs machines that will carry on intellectual pursuits besides doing their unintelligent and repititive chores. We will require machines that can perceive, recognize and act upon their world. Vision being such an important perceptual process, machines will be called upon to 'see' the world. Though these 'seeing machines' or the visual computers need not be homomorphic, we might draw upon the experience of a comparative study of the human perception system to understand machine perception. So an attempt is made here to examine the visual systems in the light of machine vision, specifically color vision.

3.1 Visual Information Processing Systems

A visual information processing system is shown in Figure 3.1. It has a set of receptors that receive the visual stimuli, a processor that filters out the data relevant to the system and a decision unit that interpretes the current information on the basis of associated past experience.

Since the early years of Artificial Intelligence, statistical procedures have been employed for vision systems, especially for pattern recognition purposes such as optical character recognition, etc. In Statistical Pattern Recognition Theory, a visual information processing system is described in terms of cascaded stages of picture preprocessors, classifiers and interpreters. The input stimuli is preprocessed to extract the information relevant to the particular pattern recognizing activity. Features are extracted from this information and the feature values are

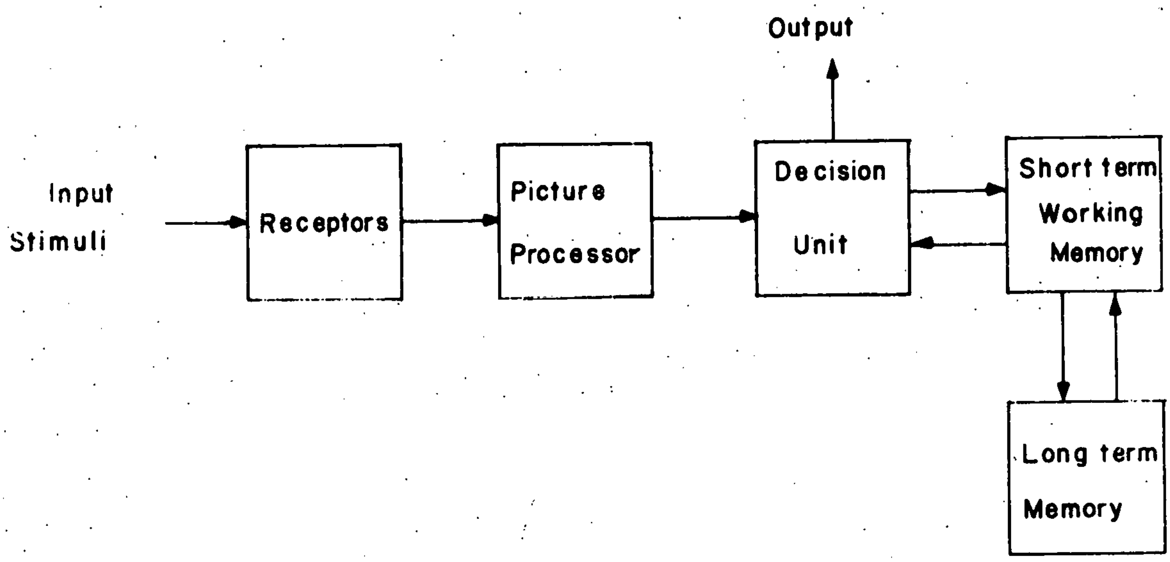


Figure 3.1. Visual Information Processing System

used to classify the picture into various categories. A subsequent stage interpretes the result of the classification process. Pattern classification by statistical decision theory becomes unwieldly when the feature-space becomes large. In a more efficient and realistic pattern recognition system, there should be feedback between the preprocessing and classification stages and the interpretation stages. Such feedback control is incorporated into the human visual system where higher cortical centres adjust the filtering and the processing steps, depending on the mode of activity and the results of the interpretation phase. A feedback controlled artificial pattern recognition system is shown in Figure 3.2. The specific nature of feedback between the various stages is less settled at this time but it should be recognized that the mathematical formalism of statistical classification theory, though adequate for optical character recognition, is unwise in the analysis of real scenes. In scene analysis the problems of semantic and syntactic ambiguity arising from imperfect edgedata, shadows, occlusion of objects, and the slow variation of texture, brightness complicates the problem of machine vision. In such cases the interpretation is guided by a priori knowldge of the world. The world-model is the visual memory that stores this knowledge of the world from past learning experience and updates it as it reacts with the environment.

3.2 Color as an Attribute in Vision Systems

There are various attributes such as color, shape, size, and texture that characterize a pattern. A pattern recognition process consists of searching for these attributes and then comparing them with the model of the attributes that has been built by past experience. Color is a

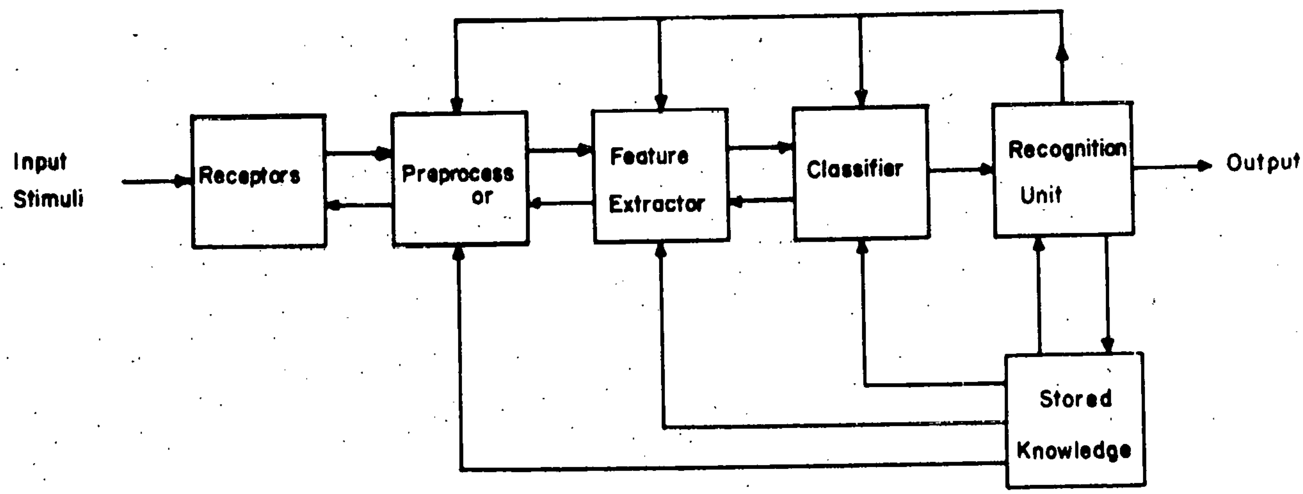


Figure 3.2. Pattern Recognition System

very important attribute of any object. The power of any color information, however crude it may be for pattern recognition purposes, is exemplified by recent vision systems.[36,37] Use of color information greatly simplifies pre-processing, segmentation, and semantic procedures on the pictorial data.[38] In the past, acquisition of color information for pattern recognition systems has not been incorporated because of the lack of proper hardware and a desire to reduce the amount of data. The fact that we almost get all the necessary information from a black and white television picture does not prove the insignificance of the color information. Here we rely on the highly complex human data processing system and the associated world-model, the internalization of the external world.

It should be emphasized at this point that color is a psychophysical attribute that has direct correspondence to the human world. One could always design a visual machine that would spectrally analyze the input picture in 2, 3, 4 or any number of dimensions. But, if there is no direct transformation to the human color world it would be difficult to supply any human experience so as to build the world-model. Different members of the animal world have different morphology for their vision systems and their perception of the world is different from ours. So also, could visual computers be designed with special hardware and the corresponding perceptive rules. To communicate with humans, they must transpose their perception to the human perceptive system. This may not be an easy task. So it is reasonable for us to design machine color perception systems modeled after the human color perception system.

3.3 The Retinal Computer

Gregory said, "Seeing machines should have visual illusions." Humans have visual illusions that are characteristic of the organization of the visual system. To have human-like illusions the visual computers have to be functionally homomorphic. Another advantage of having functionally homomorphic organization is the ease of communication between humans and machines and convenience in relating of their experiences to each other. Such a computer, called the Retinal Computer, having hardware-software functional parallels with the human visual system, is shown in Figure 3.3. The analogous functional elements of the human visual system are also indicated in dashed lines.[39] Corresponding to the red, green and blue cone system in the eye there are three television cameras equipped respectively with red, green and blue filters. Binocular cameras are used for depth perception. The contrast networks correspond to the interconnection network in the retina. The range finding system corresponds to the lateral geniculate bodies. Some information about the visual mechanism is also transmitted to the superior colliculus that determines and controls the direction of gaze. The information from the lateral geniculate bodies are sent to the occipital cortex Area 17 and some to Area 18 and 19. We do not know the exact preprocessing steps in these cortices. But we identify these activities in visual machines as segmentation, region growing interpretation, etc. The world-model computer represents the knowledge of the world internalized in the machine. The central computer co-ordiantes the activities of all the subsystems and the feedback control mechanism is included in this central computer.

Properties like chromatic adaptation and color constancy which are characteristic of the human visual system could be mimicked by the visual machine by proper adjusting of the camera filters. In this connection one could mention some of the hardware sensing elements for the receptors. Photocells and phototransistor arrays have been used in the past in addition to television cameras. Another possibility is the use of ferroelectric

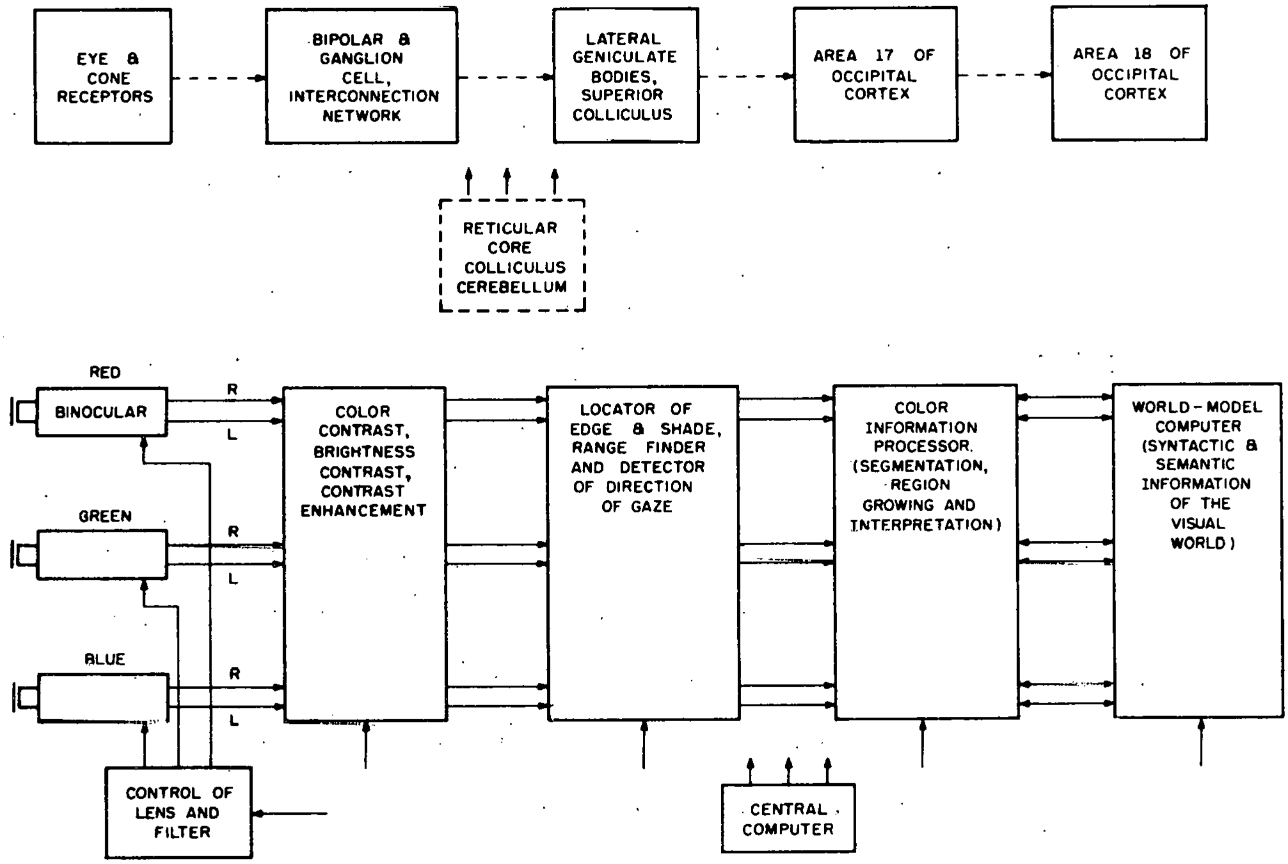


Figure 3.3. Retinal Computer: Machine and Human Models

ceramics or ferroelectric-ferroelastic elements. These elements could be arranged in a grid pattern and the filtering properties of each region could be independently controlled in a feedback control environment. Such a receptor scheme would be the hardware equivalent of the adaptive physio-chemical elements in the retina.

3.4 Machine Representation of Color Information

As described in the last section, the XYZ-system is generally used for the representation and measurement of color. It has the added advantage over the RGB system in that the tristimulus value Y carries all the luminance information. The XYZ system is similar to representing color in terms of intensity, hue and satruation. The difference is that the former employs a rectangular co-ordinate system whereas the latter employs a polar co-ordinate system. Broadcast Color Television employs a color representation based on the XYZ system.

The sensor hardware extracts the separate red, green and blue information from the scene. The chromatic coefficients at a point (k,l) in a two-dimensional pattern can be calculated from the red, green and blue components (R_{kl}, G_{kl}, B_{kl}) of light. If, $T_{kl} = R_{kl} + G_{kl} + B_{kl}$

then
$$r_{kl} = \frac{R_{kl}}{T_{kl}}, \quad g_{kl} = \frac{G_{kl}}{T_{kl}}, \quad \text{and } b_{kl} = \frac{B_{kl}}{T_{kl}} .$$

The xyz chromaticity co-ordiantes could be calculated from the rgb set of coefficients by the following transformations:

$$x = \frac{0.49000r + 0.31000g + 0.20000b}{0.66697r + 1.13240g + 1.20063b},$$

$$y = \frac{0.17697r + 0.81240g + 0.01063b}{0.66697r + 1.13240g + 1.20063b},$$

$$z = \frac{0.00000r + 0.01000g + 0.99000b}{0.66697r + 1.13240g + 1.20063b}.$$

Instead of calculating the x, y, z chromaticity co-ordinates of each point it would be more realistic (from the consideration of the amount of calculation involved at each point) to represent the points by r, g, b co-ordinates. All the pre-processing like edge-following, segmentation, and the development of the color map should be carried out with this internal representation. Once the color map has been developed with the list structure corresponding to the boundary lines and a (r, g, b) triad denoting the color of the region, we could transform the (r, g, b) triad to a color name. This would be done by calculating x and y chromaticity co-ordinates and then plotting it on the chromaticity diagram. The color name could be identified from there. The regions would be identified by a color name or by the wavelength sensation they excite and the purity. Any high-level syntatic interpretation based on world-modeling could use this color naming for interpretation of the visual scene.

Alternately, the chrominance information could be represented by a single number by properly quantizing the area in the color triangle. For effective use of the information, one would quantize such that there are more points in the regions where our sensitivity is high such as the green-red region in contrast to the blue region.[41,42]

3.5 Processing of Color Information

The picture is first segmented into component subsets and then the subsets are classified with the help of Statistical Classification Theory and World modeling. The picture can be segmented to different regions on the basis of the color at each point. Two points corresponding to color co-ordinates (r, g, b) and (r', g', b') or (x, y, z) and (x', y', z') would be equivalent if the distance D between the two vectors is within a certain limiting value. The distance D is calculated by choosing one of the following criteria:

1. $\sqrt{(r-r')^2 + (g-g')^2 + (b-b')^2}$
2. $\{|(r-r')|+|(g-g')|+|(b-b')|\}$
3. $\max \{|(r-r')|, |(g-g')|, |(b-b')|\}$
4. $\sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2}$
5. $\{|(x-x')|+|(y-y')|+|(z-z')|\}$
6. $\max \{|(x-x')|, |(y-y')|, |(z-z')|\}$

The metric D could be chosen to have different criteria and different values for analyzing different regions.

In another method the (r, g, b) or (x, y, z) sets of co-ordinates would be plotted respectively on the RGB or XYZ diagram. By joining this point with the white point W and finding the intersection of this line with the boundary of the chromaticity diagram, we determine the radiation wavelength equivalent to the color sensation. This corresponds to hue. The distance between the color point and the white point is the saturation. The color mapping could be carried out using either the hue alone or hue and saturation together. The distance metric should be nonlinearly controlled to match the sensitivity in different regions of the chromaticity diagram. Some perception phenomena like color constancy (as in the Land effect) could be taken care of by suitably shifting the white point W with the help of the Helson-Judd formulation.

The methods used for segmentation of the picture mainly fall into two categories; microtechniques that operates on local neighborhoods and macrotechniques that operate globally.[43] Contour following is one of the microtechniques that is used to derive the cartoon of the picture after which all the bounded regions are labelled. When a color boundary point is determined, the boundary is followed through. Contour following is very susceptible to noise and some smoothing is necessary prior to the contour following operation.

For developing the color map one may also use a region-growing macrotechnique that starts from a seed point and then propagates in all directions. Such a technique is less susceptible to noise. Once the scene is segmented into different color regions we can consider grouping some of the regions based on contiguity, color and context.

3.6 World-Modeling and Interpretation

The color regions developed in the processing would be analyzed to form color super regions. Such grouping of color regions must be guided by other considerations like contiguity, texture, shape, size and the semantic structure of the picture. Any such regrouping and subsequent interpretation phases are supported by an internalized world-model. The machine representation of the world is a difficult philosophical question and once the representation question for a problem is solved the answers may follow directly. In Pattern Recognition Systems, the external world is internalized by storing different pictures and their cues and then comparing and contrasting this with the input stimuli. In scene analysis such a scheme is very inadequate. What is needed is the representation of the world in terms of a set of relations. The relational structure is then stored in the computer. Such picture languages, describing the visual patterns, have recently been described in the literature.[44,45] Interpretation is a complex process of associating the generated description of the input stimuli with the world-model. It is very difficult at this moment to build up a world-model that would be general enough to cope with all kinds of objects and scenes. Such a model would require a vast amount of memory and logic and would be extremely hard to control. Visual computers have been developed that limit their world to, say, the world of three-dimensional polyhedra[46] or landscapes. In this way, they can be more efficient in their limited domain. This is not a limitation of visual computers per se, but rather has direct analogy with humans who specialize their functions for better efficiency also.

4. EXPERIMENTS IN COLOR VISION

4.1 Land Projection Experiments

Some of the experiments performed by Dr. Land were repeated by taking the picture of a scene through a red filter (Wratten No. 24) and a green filter (Wratten No. 58). The picture taken through the red filter was projected on the screen with the same red filter filtering the light from the projector. The picture taken through the green filter was projected with white light. Neutral density filters were used to control the relative intensity of the light from the two projectors. The projectors were kept side by side and the projected picture was registered on the screen. It was difficult to register the picture over the whole field as the lenses in the projectors were not properly matched and had non-uniform magnification over the field. Despite this slight misregistration one could observe a colored picture with blues, greens and reds in it. The experiments were performed with the following different kinds of scenes.

1. Scenes of mostly red objects: Such scenes could be produced quite well with two-primary red-white projections. If the red and white fields are not properly registered, the misregistered area of the white field looks blue-green as is expected from color constancy.
2. Scenes of mostly green objects: It is difficult to produce saturated green. The green obtained is mostly blue-green.
3. Scenes of mostly blue objects: It is again difficult to produce saturated blues. The blues are dark and sometimes little blue-green.

4. Checker board pattern: The two-primary red-white projection experiments were repeated with the checkerboard pattern shown in Figure 4.1. One would anticipate a pattern with a varying amount of red saturation corresponding to mixture of different amounts of red and white light. But, we also observed other colors.

5. Scenes of all different colored objects: Reds, greens and blues were observed in such projections. The blues were dark blues. It was observed that the degree of the Land color effect was most pronounced when the scene had a juxtaposed set of various differently colored objects.

Some of these experiments were repeated by putting a Mondrian density pattern in front of the projector to spatially vary the intensity of the projected light. No appreciable change was observed in the colors perceived.

The projected superimposed picture of the scene with all different colored objects was photographed using ordinary Kodachrome II slide film. The developed slide, when projected with white light, showed the same Land effect. These films were exposed only to red light but still we see greens and blues upon projection. When a region of the film representing a green object was examined through a microscope over a small area, it looked grayish not greenish. This confirms that the Land effect is a large field effect.

4.2 Sequential Projection Experiments

To examine the feasibility of a sequential color system based upon the Land experiments a preliminary test was made on a set-up where the red

R	G	B	Y
B	Y	R	G
R	G	B	Y
B	Y	R	G

Figure 4.1. Checkerboard Pattern

and green scenes were sequentially projected on the screen. As shown in Figure 4.2, a synchronous motor (1800 rpm, 1/100 H.P.) was mounted on the front plate of a box on which the projectors were placed. The synchronous motor drove a filter wheel made of epoxy-glass, half of it painted black and the other half left transparent. The filter wheel was large enough to cover both the projectors. When driven by the motor it sequentially allowed the projected light from the two projectors to be registered on the screen. A red filter was kept in front of the projector that had the longwave record slide in it. Thus, red and white fields were successively projected on the screen.

The Land color effect was still present with this sequential presentation. As anticipated, our eye integrated the red and white fields and one still observed the Land color effect. There was some flicker present as the color frame frequency was only 30 frames per second corresponding to the speed of 30 revolutions per second for the filter wheel.

4.3 McCulloch Effect Experiments

McCulloch[47] projected a grating of vertical black stripes on an orange ground for a few seconds alternating it with an identical grating of horizontal stripes on a blue ground. He reported that an observer watching this for a few minutes would see weak negative colors when watching black horizontal and vertical stripes. The vertical stripes had a blue-green negative color and the horizontal stripes an orange negative color. Stromeyer[48] has recently shown a McCulloch effect analog of two-color projections. He employed black-and-red striped horizontal gratings and black-and-green striped vertical gratings for adaptation. A neutral test matrix of alternating vertical and horizontal gratings of various

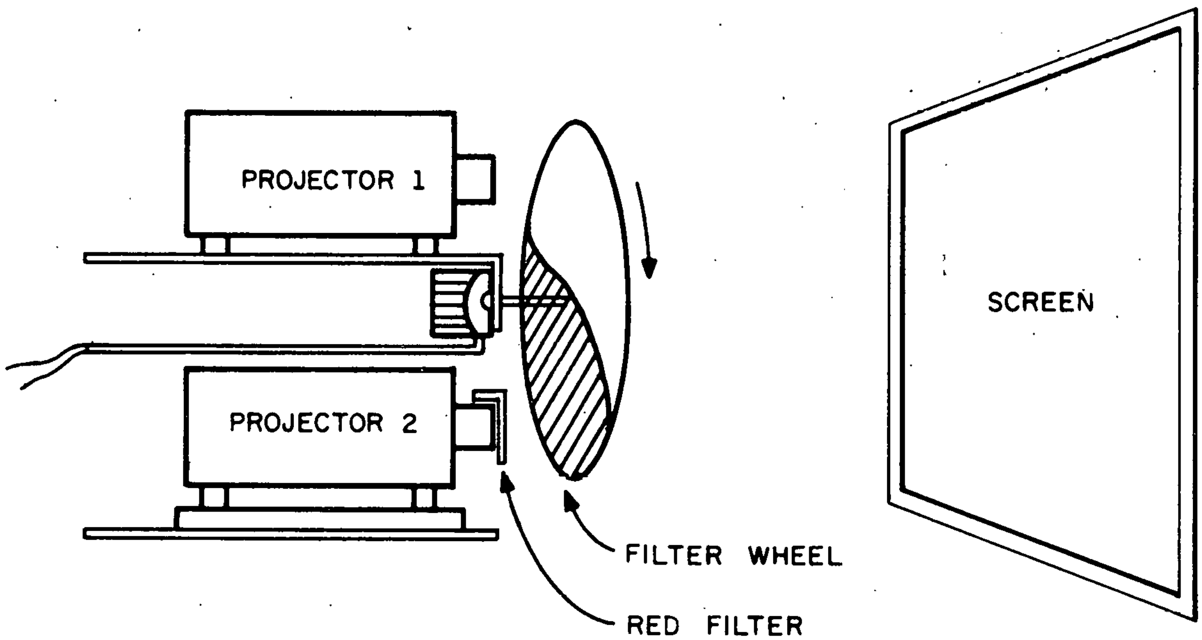


Figure 4.2. Sequential Projection Experiment

lightness and contrast was viewed thereafter and colors of various hues and lightnesses were observed.

We repeated the McCulloch effect experiments and employed the red and green after-effect to observe the test pattern described by Stromeyer. We observed different weak colors on this pattern.

However, our main interest has been the following: Having observed these two experiments could we say anything about the Land effect. McCulloch explained the color after-effect in terms of 'color adaptation of orientation-specific edge-detectors.' 'They indicate that edge-dectector mechanisms in the visual system are subject to color adaptation, responding with decreased sensitivity to these wavelengths with which they have recently been most strongly stimulated.' We also noted from the work of Festinger, et al.[49] that patterns of temporal intensity-changes with a constant background could produce flicker colors. This is attributed to 'artificially creating, somewhere in the visual system, a temporal pattern of neural firing, a sequence of intensity changes of the retina that produce the proper modulation of firing rates.'

We conclude that some of these color adaptation phenomena are also contributing somewhat to the Land effect. Assuming a temporal modulation theory of color coding, some of the colors can be created by movements that essentially impose a temporal pattern on the same receptors.

5. PENTECOST SYSTEM

5.1 System Goals

The Penetron Electronic Color System (PENTECOST) is a two-primary color television system intended to examine the scope and the limitations of using the Land two-primary scheme for high resolution color information displays. The goals are to determine the degree of the Land effect using both static and dynamic displays. In addition, the Penetron tube as a color display tube is evaluated and the use of an electronically controlled solid state filter for color display systems is considered.

5.2 System Organization

The PENTECOST system is a two-color closed circuit television system based on Dr. Land's two-color red and white projection experiments. The selection of the cathode ray tube, a special Penetron tube, is described in Appendix A. This Penetron tube has layers of red emitting and white emitting phosphors. The red and green version of a scene are sequentially presented on the CRT by synchronously switching the beam voltage to alternately excite the layers of red and white emitting phosphors. A black-and-white monitor was modified to drive the Penetron CRT. The use of the Penetron tube calls for special high voltage switching circuits and gain correction circuits.

The camera is a black and white vidicon camera that was modified to accept a Plumbicon tube. A two-color red and green filter wheel rotates in front of the camera. An electronically controlled solid state filter could also be used in place of the filter-wheel. The Pentecost system with the Penetron and the solid state filter is shown in Figure 5.1. Section 6 describes the Pentecost Receiver system.

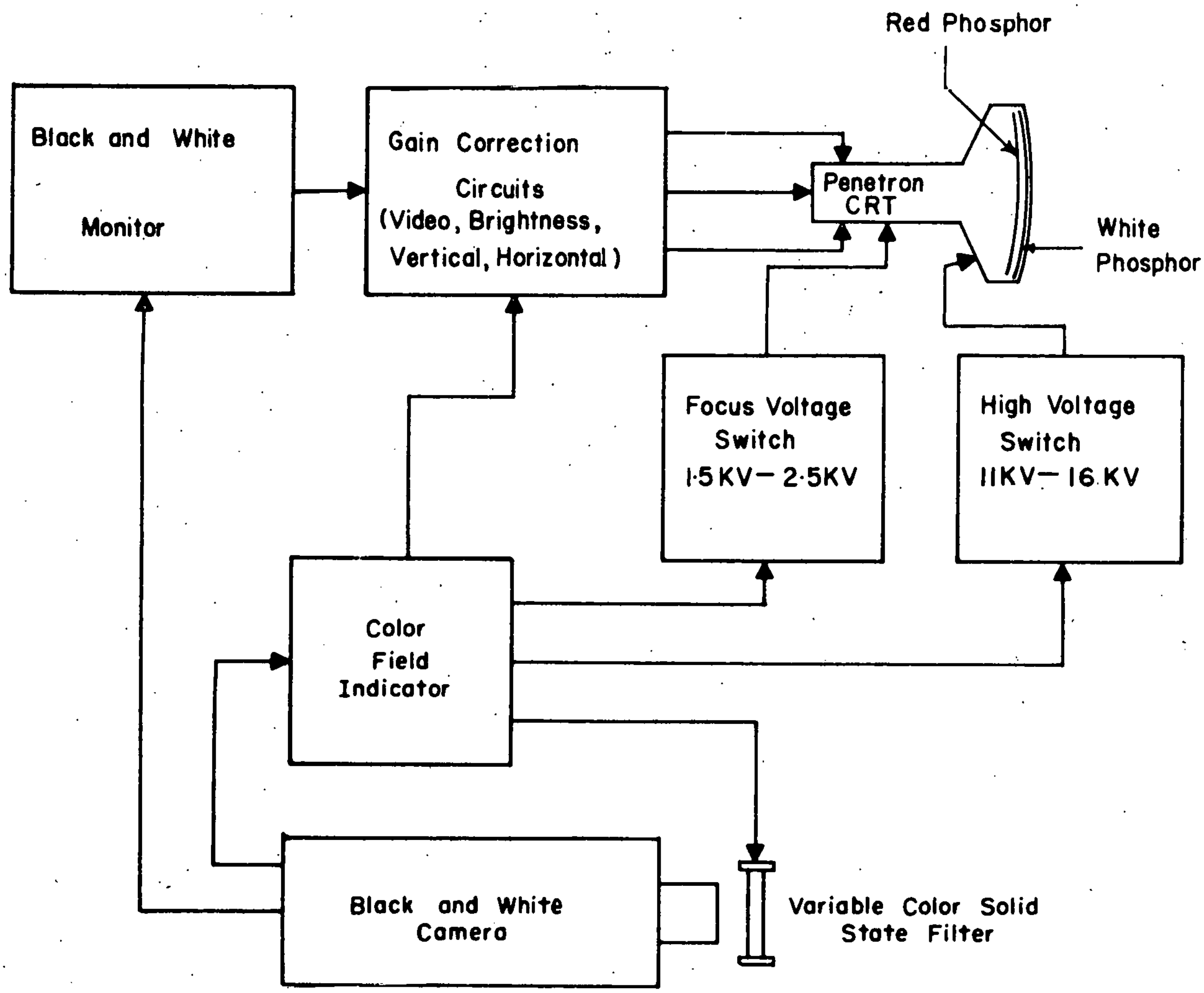


Figure 5.1. Pentecost System

A pattern generating system for displaying a random checker board pattern was designed and built and is described in Section 7. The camera system is described in Section 8 and the solid state filter is evaluated in Section 9. Experimental observations on the PENTECOST system are noted in Section 10.

6. PENTECOST RECEIVER

A black-and-white video monitor (Conrac CQF 17/N, 525 lines, 60 fields) was modified for the Pentecost receiver system. The CQF 17 is a high resolution monitor having a video frequency response of 30 MHZ ± 1 dB. A block diagram of the receiver system is shown in Figure 6.1. The modified portions of the monitor are shown by dashed lines. The modifications incorporated are:

1. Penetron Cathode ray tube
2. High voltage switch
3. Focus voltage switch
4. Horizontal Deflection Control
5. Vertical size control
6. Video analog switch
7. Brightness control and blanking circuits
8. Sync. separator circuits
9. Receiver timing circuits

These are described in the following sections.

6.1 Penetron Cathode Ray Tube

The heart of the receiver system is the Penetron tube which has a voltage sensitive multi-phosphor screen.[49-53] The screen consists of two different layers of colored light emitting phosphors usually separated by an insulating barrier. The color of the luminance is a function of the screen voltage since the low energy electrons cannot penetrate through the insulating barrier, whereas the high energy electrons can excite the second phosphor. The transition of color with voltage is gradual and various combinations are possible.

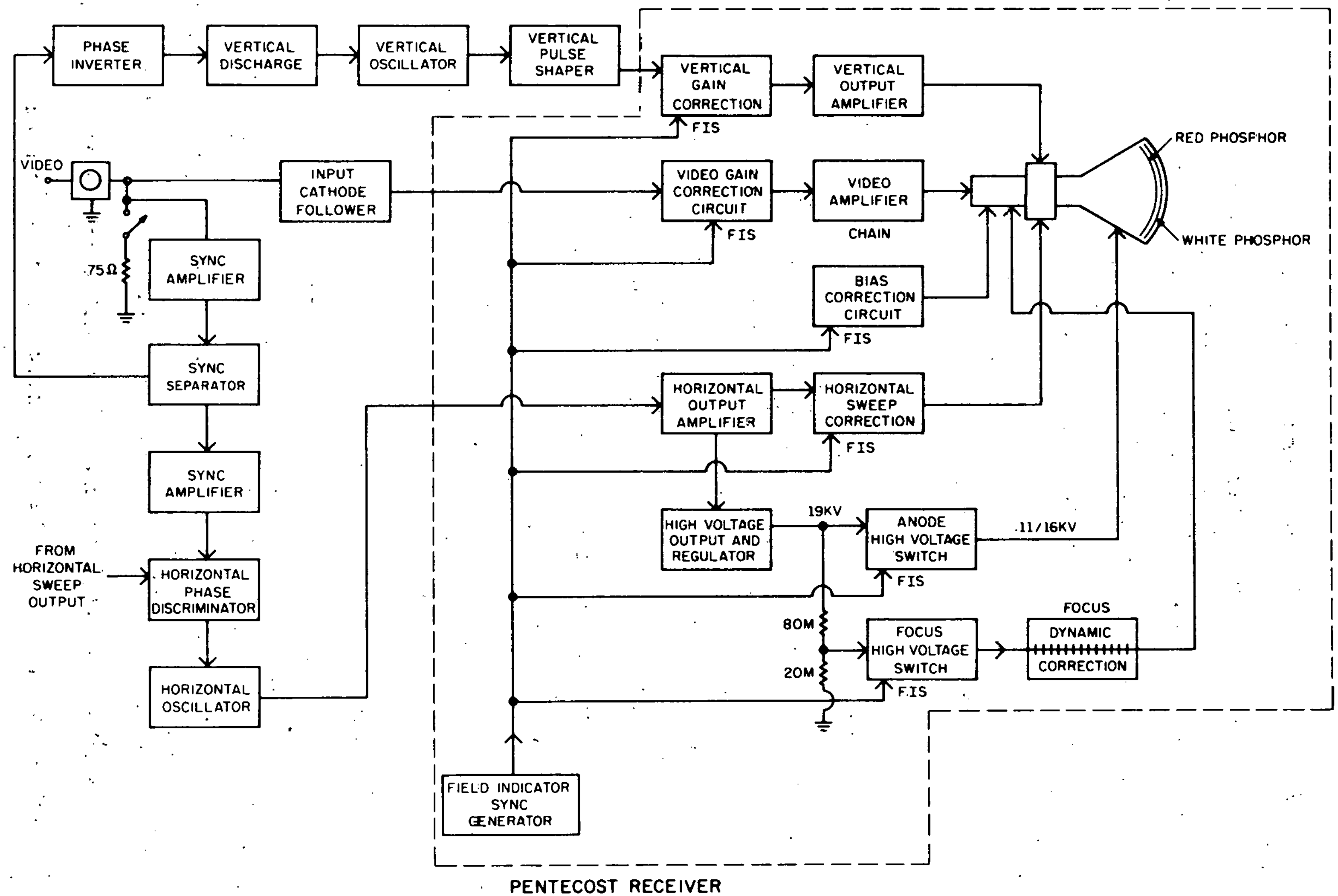


Figure 6.1. Pentecost Receiver

The characteristics of the penetration type tube are achieved by using linear and nonlinear phosphors. The linear phosphor emits light proportional to the accelerating potential whereas the nonlinear phosphor starts emitting rapidly after a threshold accelerating voltage. One can make the tube by first depositing a conventional screen of phosphor for the high voltage color. Over this a thin penetrable dielectric layer followed by a layer of phosphor for the low voltage color is deposited. This results in good saturation of the colors and uniformity over the whole screen. Alternately, in the multi-layered or onion-skin particle method, the penetron phosphor is produced separately with each particle having its own dielectric barrier. This is mixed with the linear phosphor and then deposited on the screen. This gives good color separation and uniformity between different tubes.

The Penetron tube has some of the following limitations. It is difficult to have a fully saturated high voltage color since the low voltage color is also excited. The brightness levels also differ because of the differing electron energies. The difference in the brightness levels and the separation between the two colors are inter-related phenomena. Another drawback of the Penetron is that accelerating voltage, focus voltage, vertical, horizontal, brightness and video signals have to be switched whenever the color has to be changed. This imposes additional circuitry. The Zenith two-gun Penetron obviates the switching problem by having one gun each to excite the phosphor layers. But it introduces the necessity of keystone correction, raster registration circuits and yoke crosstalk compensation. Current-sensitive single gun color tubes simplify the switching problem but the difficulty with these tubes is their limited color separation and the problem of simultaneous variation of brightness with color.

The Penetron tube used was a RCA developmental type (similar to the C24092) having a dual color phosphor screen, a 17" rectangular dimension, 70° magnetic deflection and a single high-voltage electrostatic-focus electron gun. This kinescope repreduces pictures in either red, at a dominant wavelength of 6070° A, or in a white that is approximately equivalent to C.I.E. illuminant C. It is supplied with a filter glass face plate (transmission factor 66%). The luminance is 21 foot lamberts for the red display at an anode voltage of 11KV and focus voltage of 1450-1850V and 42 foot lamberts for the white display at an anode voltage of 16KV and focus voltage of 2100-2700V.

6.2 High Voltage Switch

A high voltage switch capable of switching the penetron screen voltage between 11KV and 16KV during the vertical blanking period (1.4 ms) was built.[54] This is shown in Figure 6.2. The color frame indicator signal is applied to the input of the MOSFET differential amplifier through the 2N3644 transistor amplifier. The output from the differential amplifier is applied to the base of the 40327 transistor that switches the collector output between low and high states. When the collector output is high the lower 7235 tube is off and the plate voltage is 8KV. The series zener diodes drop 8KV (200V x 40) across them so that the output voltage is 16KV. When the collector output of the 40327 is low, the lower 7235 tube is on and the output high voltage is discharged to 11KV through this tube. When the collector voltage is high, the lower 7235 is off but the upper 7235 tube V_1 charges the load to 16KV. This charging tube is driven by an emitter follower transistor amplifier. The supply for this transistor is obtained by a voltage tripler that rectifies the 6.3V AC filament voltage from the 20KV isolation filament transformer. The high voltage output is attenuated by a high-voltage, high-resistance voltage divider and then

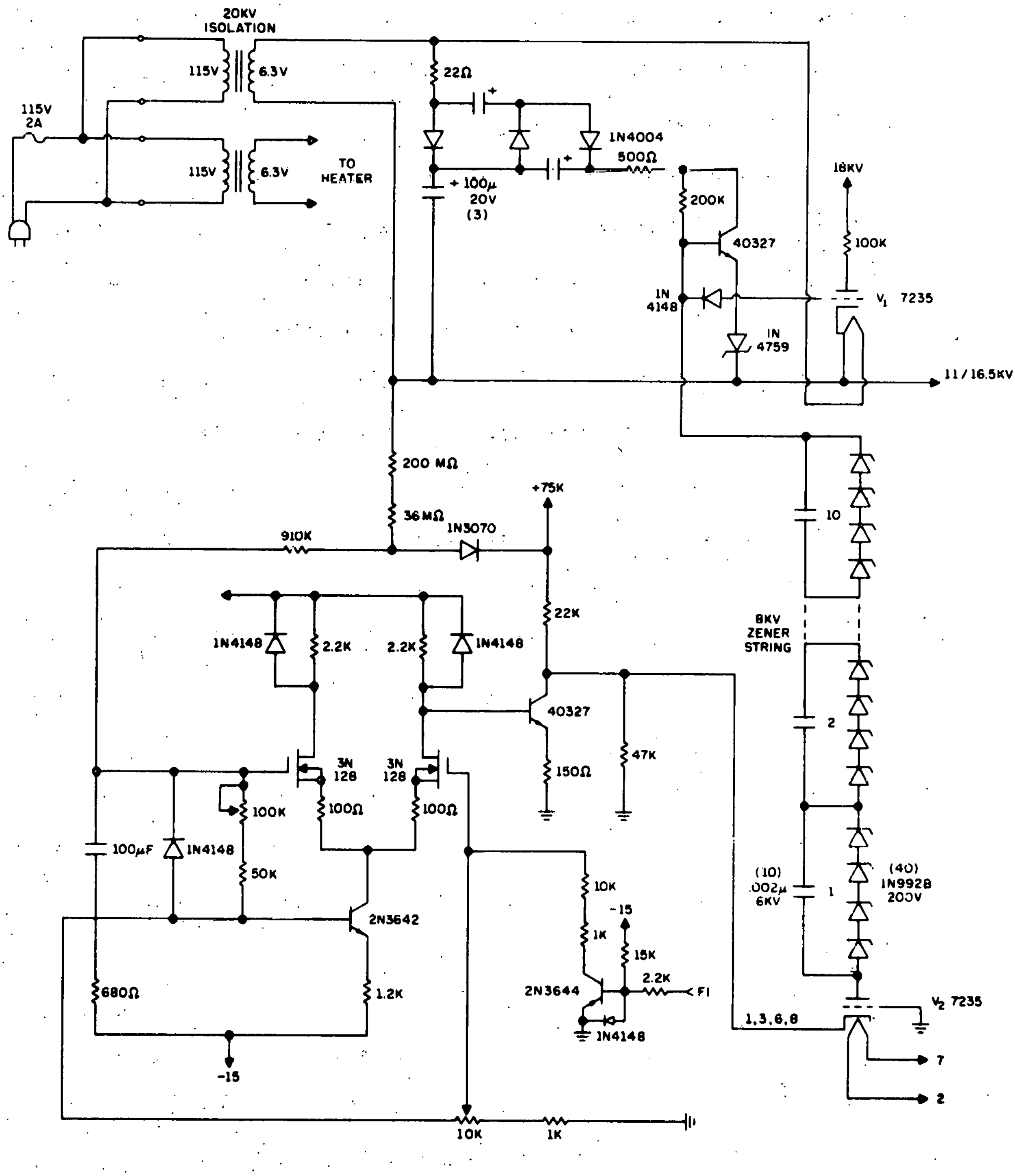


Figure 6.2. Screen Voltage Switch

applied to the negative input of the differential amplifier. The MOSFET differential amplifier was built using matched transistors and resistors. 2N3642 transistor is a constant current source for the differential amplifier. The output level of the differential amplifier is controlled by varying the 10K potentiometers.

Originally, the high-voltage output from the monitor was used as the constant high-voltage supply for the screen voltage switch. It was contemplated to employ a set of width control coils in parallel and series that could be switched in and out of the circuit such that the yoke current could be switched but the load to the flyback would remain constant. That would keep the high voltage constant. Subsequently, this approach was discarded because of its complexity in favor of an independent high voltage supply. Thus, a separate high voltage power supply (10KV-20KV) was obtained from CPS Inc. This allows the horizontal size to be independently controlled without interacting with the monitor high voltage output.

6.3 Focus Voltage Switch

With the change in the beam voltage from 11KV to 16KV, the electron beam would be defocussed unless the focus voltage is also switched along with the beam voltage. The focus voltage required is directly proportional to the beam voltage. In the present case the focus voltage switch was designed to switch between about 1600V to 2400V. The focus voltage switch (Figure 6.3) is similar to the screen voltage switch but is less sophisticated. The MOSFET differential amplifier output drives the base of 40327 transistor which in turn controls the plate voltage output of 7235 tube. The 10K potentiometers control the high and low voltage levels.

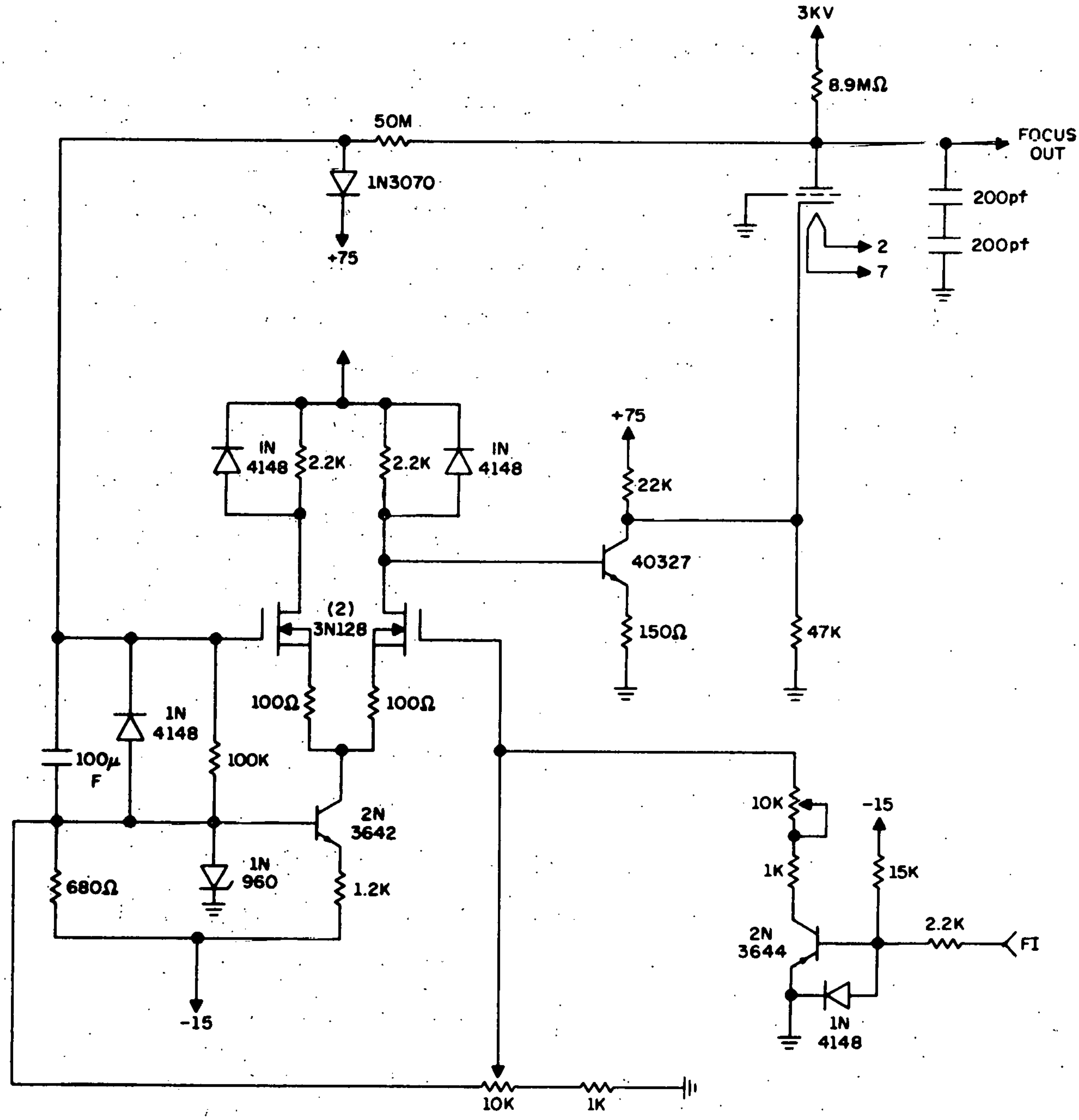


Figure 6.3. Focus Voltage Switch

6.4 Horizontal Deflection Control

The deflection sensitivity is inversely proportional to $V^{1/2}$ for magnetic deflection where V is the beam voltage. To take care of this change in the sensitivity with the change of the beam voltage, the horizontal deflecting signal must be controlled to maintain the same raster size over the two fields. This is achieved by a switching attenuation circuit that controls the amplitude of the horizontal signal input to the horizontal output amplifier. This horizontal size control circuit is shown in Figure 6.4. The circuit switches the amplitude of the large horizontal signal to either of two levels. These levels can be adjusted by R_1. The 2N5416 transistor is connected as an emitter follower and isolates the analog input. The opto-coupled-isolators (OCI) are connected as multiplexed analog gates and by turning on either of the two opto-isolator branches, the output point is connected to the corresponding amplitude level. Outputs from the TTL circuits control the switching and they are completely isolated from the large horizontal signal.

The opto-isolators Monsanto MCT-2, have typical ratings of BV_{CEO} = 65V, BV_{CBO} = 165V and BV_{ECO} = 14V. When OCI-1 and OCI-2 are on and OCI-3 is off there is a reverse voltage across OCI-3 which should not exceed the BV_{ECO} rating. To take care of the smaller BV_{ECO} rating, a 1N3070 diode is connected in series with OCI-3 so that most of the reverse drop is across the diode. When OCI-3 is on, OCI-1 and OCI-2 are off and the voltage across either OCI-1 or OCI-2 should not exceed the BV_{ECO} rating. Two opto-isolators were put in series to increase the overall voltage rating. The offset voltage is equal to V_{CE}(saturated) and is only 0.1V. The off resistance is hundreds of Mego-ohms corresponding to a leakage current, I_{CEO}, of a few nanoamps.

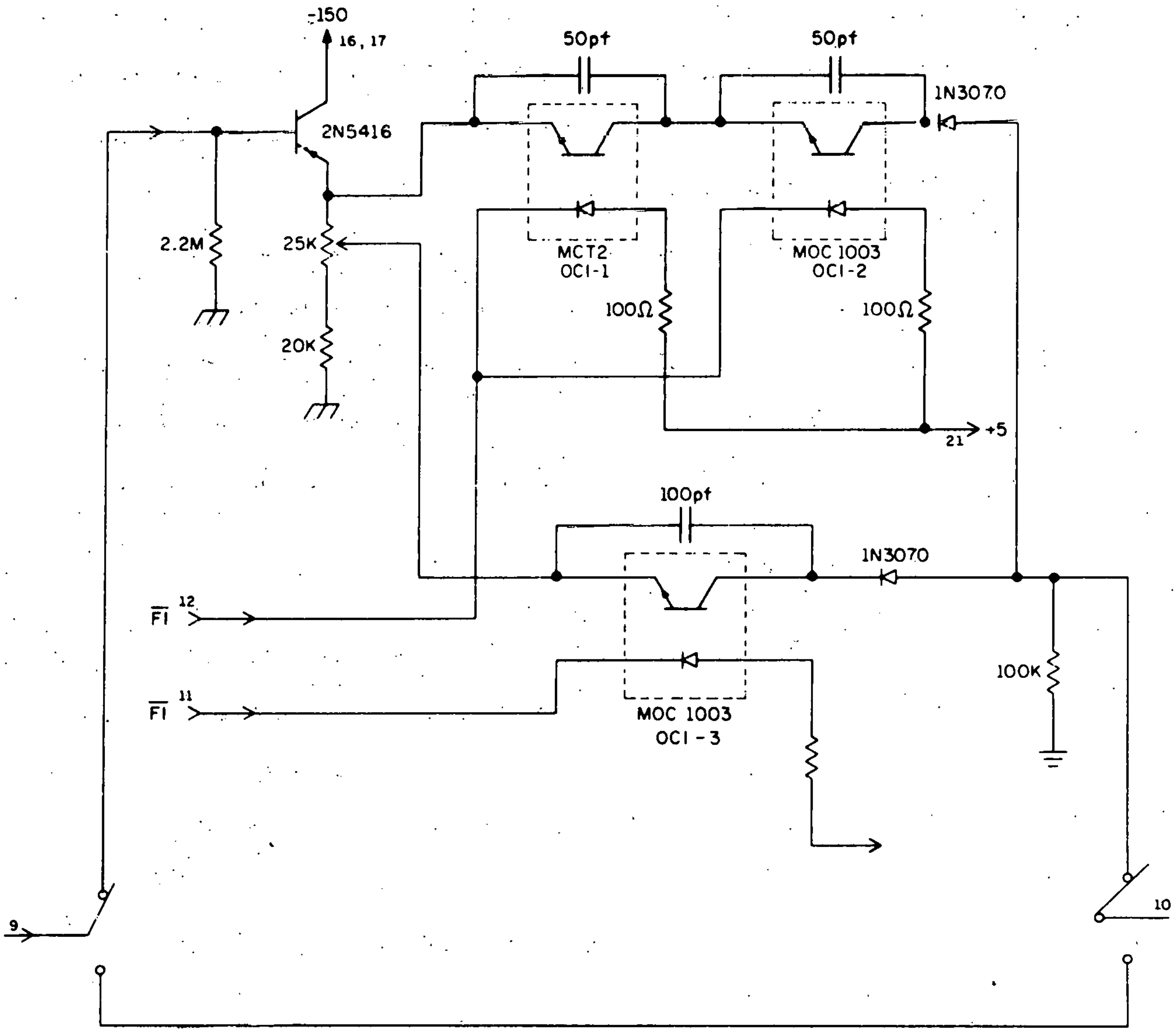


Figure 6.4. Horizontal Size Control

The speed at which the output level can be changed is dependent on the photo-transistor time constants (t_{on} = 5 μs, t_{off} = 25 μs in the saturated mode) and the output resistor R_2. The time in which the output changes from the high amplitude level to the low level is slower compared to the other transistion and corresponds to the time that OCI-1 and OCI-2 take to discharge through R_2. This time is about 400 μs and is quite adequate for our applications.

It should be noted that an alternative to the use of the opto-isolators is to use bipolar analog switches which is difficult for such large signals. Similarly, MOSFET and JFET analog switches cannot handle such large amplitude signals. Photo-coupled resistors typically have response times of few milliseconds and cannot meet the speed requirements.

6.5 Vertical Size Control

To compensate for the change in the vertical deflection sensitivity, the vertical deflecting signal must be controlled to maintain the raster size constant over the two alternating fields. This is achieved by varying the input signal to the vertical output amplifier with the help of the switching attenuation circuit shown in Figure 6.5. It employs two diamond type analog gates[55] to switch the amplitude of the output vertical signal between two amplitude levels.

The direct coupled emitter followers isolate the previous vertical tube circuits and bring down the output impedance of the analog source. This enables the analog source to drive the high resistance load through the gate and minimizes the error introduced by the analog switch. Four matched 1N3070 silicon diodes form the diode bridge. Two transistor constant current sources T_1 and T_2 in their common base connection supply the current for the bridge. The resistor network biases the zener diode so

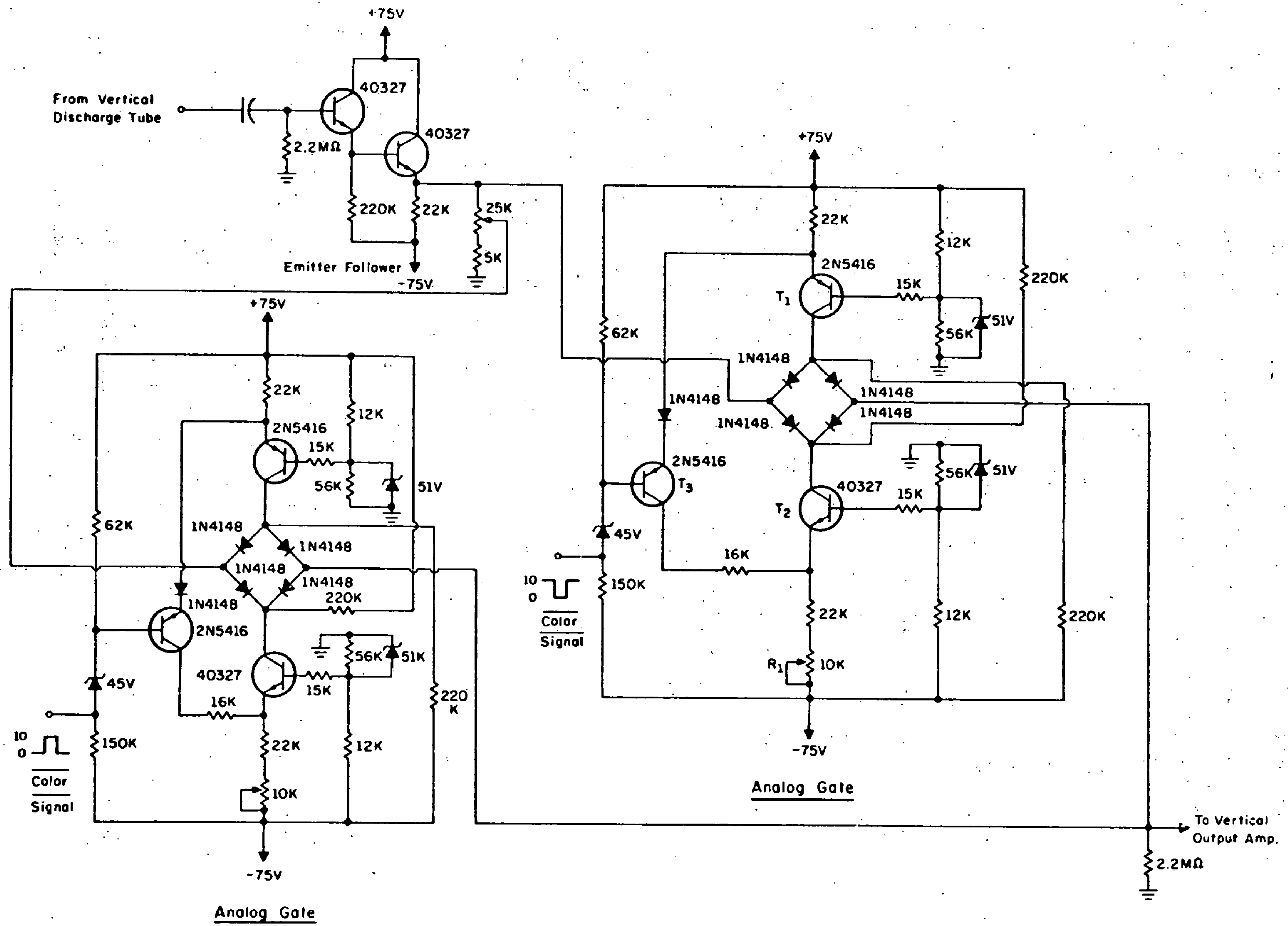


Figure 6.5. Vertical Size Control Circuit

that transistor T_3 can be conveniently controlled by the gate voltage. The 220K resistors are used to back-bias the diode bridge when T_1 and T_2 are off. The 10K potentiometers are used to match the current sources. This analog gate can handle analog signals of magnitude $\pm$50V, is fast and has negligible offset voltage.

6.6 Video Analog Switch

To compensate for the change in the electron beam voltage, the video signal also must be switched. The video analog switch circuit is shown in Figure 6.6. A voltage follower using a fast operational amplifier (μA715C) isolates the previous video stage and has low output impedance to drive the analog gates. The analog gate employs a 2N5638 n-channel junction FET and a bipolar circuit using the diode drive technique.[56] The analog gates have little offset voltage and the driving source uses a non-saturated transistor so that this switch is capable of being operated at very high speed. It can handle analog voltages of about $\pm$10V which is quite adequate for this application. When the color signal is high, the 2N3644 is off and the collector voltage is -15V. The 1N4148 diode is forward biased and the JFET gate is kept reverse biased for negative analog signals of amplitude corresponding to -15V minus the pinch-off voltage. The gate leakage current flows through the driving diode and clamps the gate to -15V. The capacitor is put across the diode to speed up the turn on time so that the gate-to-source capacitance C_{gs} is discharged quickly.

When the color signal is low, the 2N3644 is turned on and the voltage at the collector is +15V. The gate junction is forward biased with only the leakage current of the reverse-biased 1N4148 diode flowing through it. The gate to source voltage is zero. It is noted that the source to

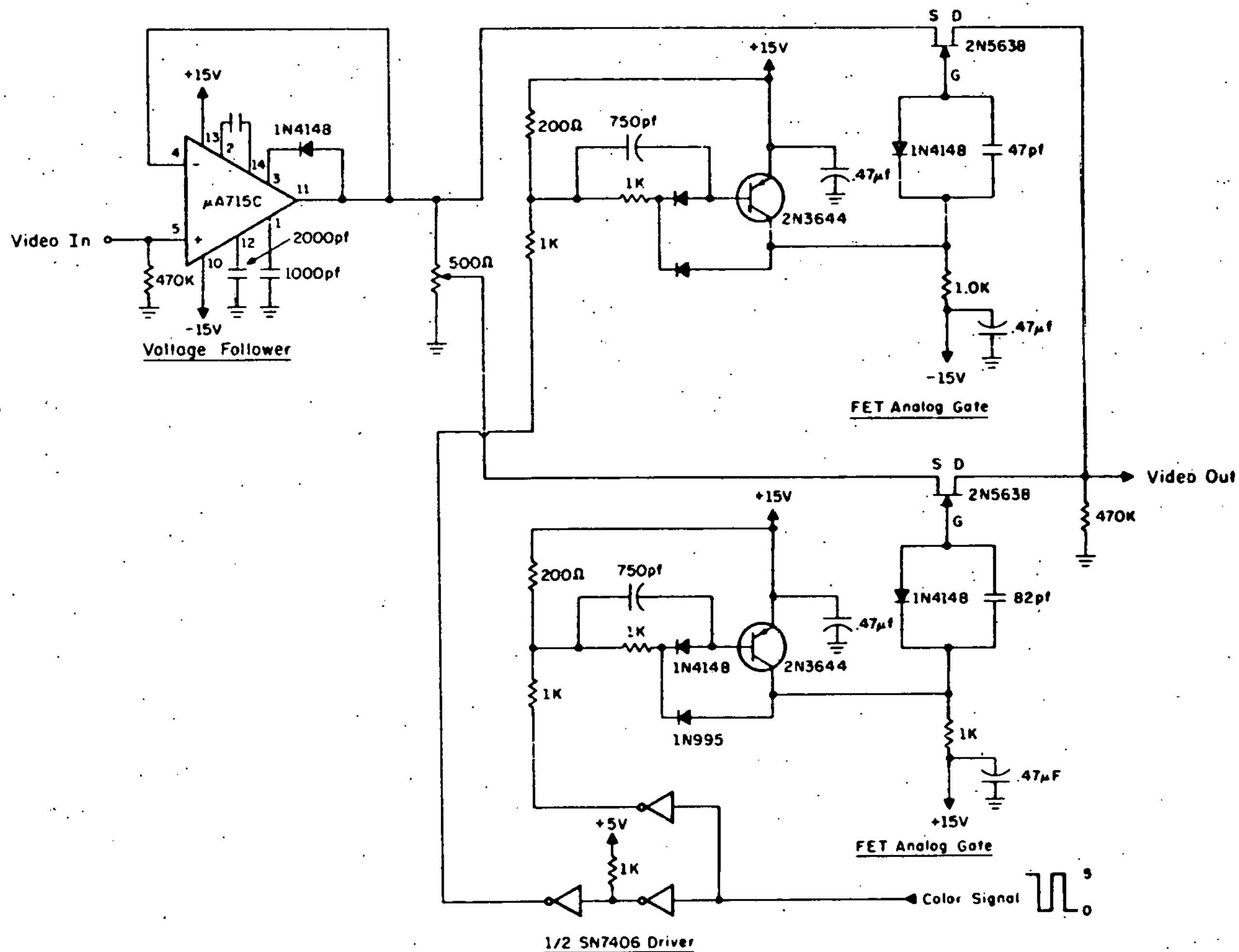


Figure 6.6. Video Analog Switch

drain resistance r_{DS} is minimum for $V_{GS} = 0$ and that a constant impedance is presented to the analog source irrespective of the amplitude of the analog signal.

The two JFET analog gates alternately connect the output point to the corresponding video signal level. This is then fed to the succeeding video amplifier stages in the Conrac monitor.

6.7 Brightness Control and Blanking Circuits

The red phosphor emits 21 foot-lamberts of light whereas the white phosphor emits 42 foot lamberts. To compensate for this mismatch in the luminance level and to have control over the relative intensity of the two fields, the brightness level is changed every field. This is achieved by the brightness control and blanking circuits shown in Figure 6.7. The opto-isolators controlled by the color frame indicator signals generate sixty-cycle square wave voltage whose lower and upper levels can be adjusted with potentiometers R_1 and R_2. The use of the opto-isolators affords an easy way of controlling the voltage levels from 0 to 75 volts and they are fast enough for the present application. The sixty-cycle square wave voltage is applied through an emitter follower to the collector load resistor of the final stage transistor, T_2. The horizontal and vertical blanking signal derived from the receiver circuits is level shifted through the zener diodes and drives the base of transistor T_2. When driven by the blanking signal the collector of T_2 is clamped to -75V and at all other times T_2 is off and the collector voltage is the voltage selected by the opto-isolator circuit. The collector output is now capacitively added to the brightness dc level selected by the brightness control potentiometer in the Conrac monitor circuit. This brightness dc level can

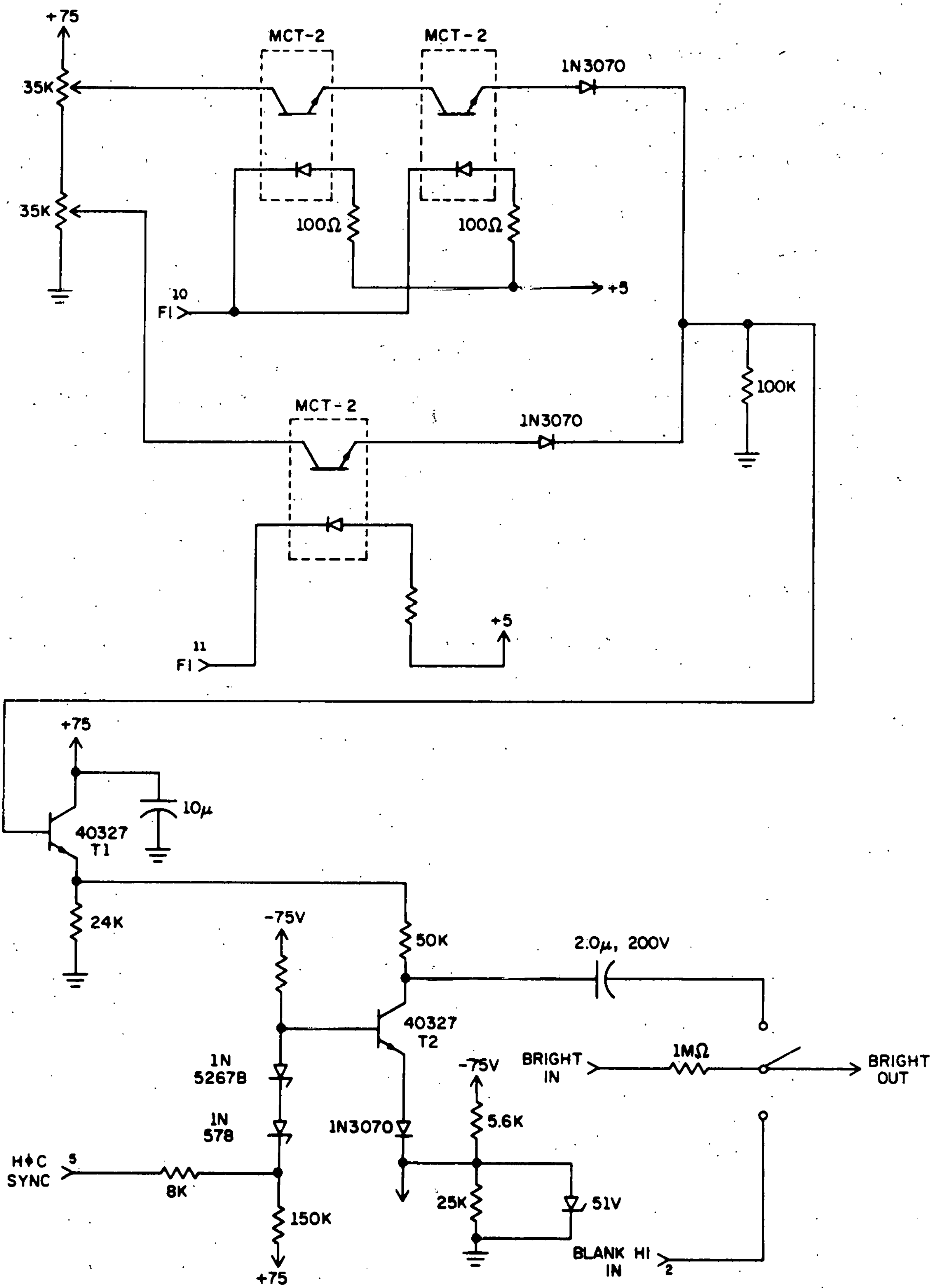


Figure 6.7. Brightness Control

be varied from 0V to 120V. Thus we have the freedom to control the brightness in many ways. A SPDT switch is provided which capacitively couples either the brightness and blanking signal generated in the present circuit or the high blanking signal obtained from the Conrac monitor, as desired.

6.8 Vertical Sync Separator and Multivibrator

The vertical sync separator and multivibrator circuit was built to separate the vertical sync from the video signal and then derive synchronous field signals. The circuit is shown in Figure 6.8. T_1 and T_2 amplify the composite video to drive the sync clipper T_3. T_1 and T_2 are biased such that they almost eliminate the video. The clipped sync is applied to phase splitter T_4. The emitter output is sent through a vertical integrator and then to an emitter follower that drives the multivibrator.

6.9 Receiver Control Circuits

All the receiver switching circuits (Figure 6.9) are controlled by the color frame indicator signal. The field indicator signal from tho Pentecost Camera system is brought by cables and drives the inverter gates and the monostable multivibrators through the 7437 gates. The 7406 open-collector drivers produce 15 volt signal swings whereas the 7404 drivers produce TTL swings of 5 volts. The 74123 monostables produce short field indicator signals whose width can be varied.

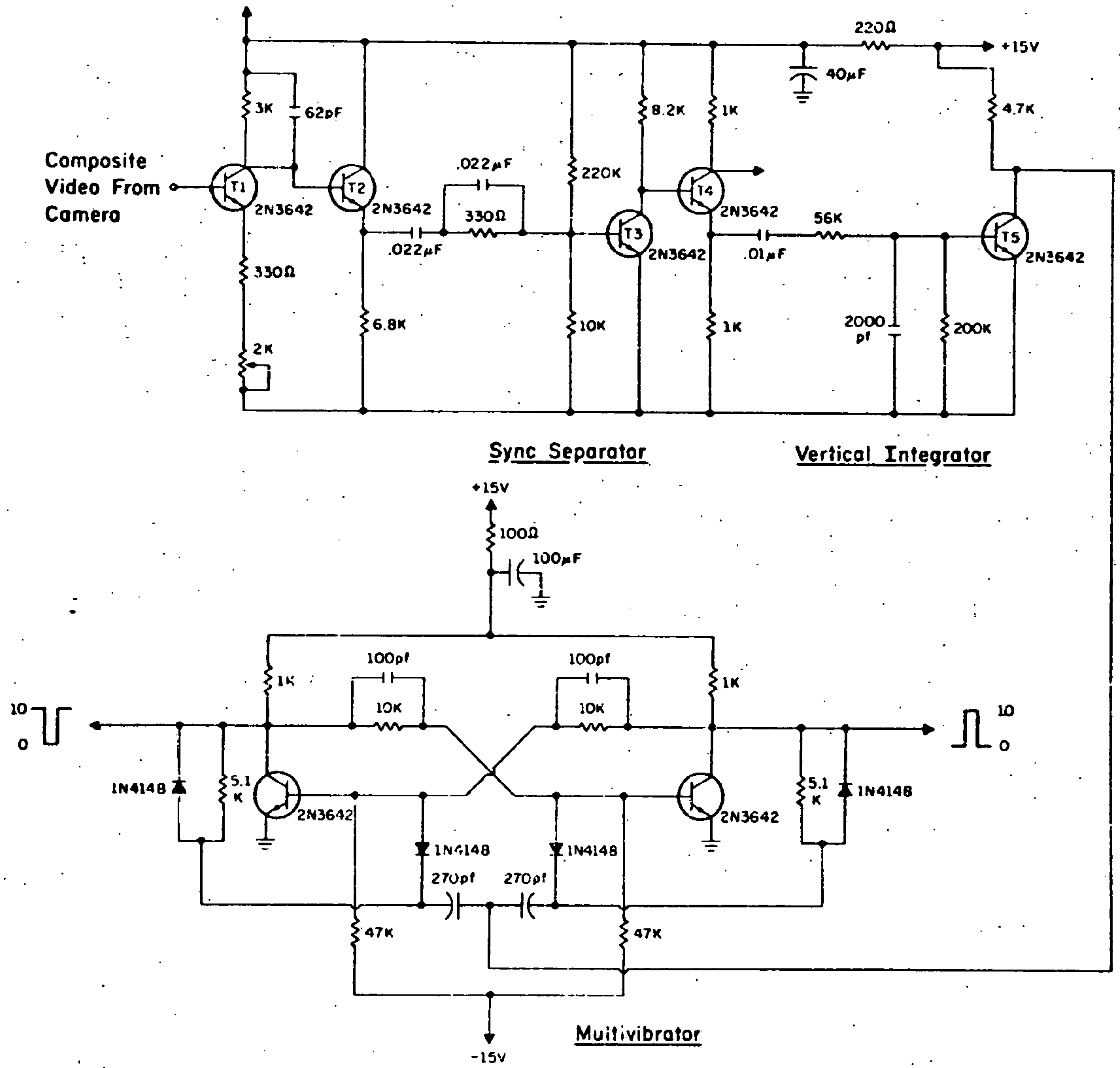


Figure 6.8. Vertical Sync. Separator

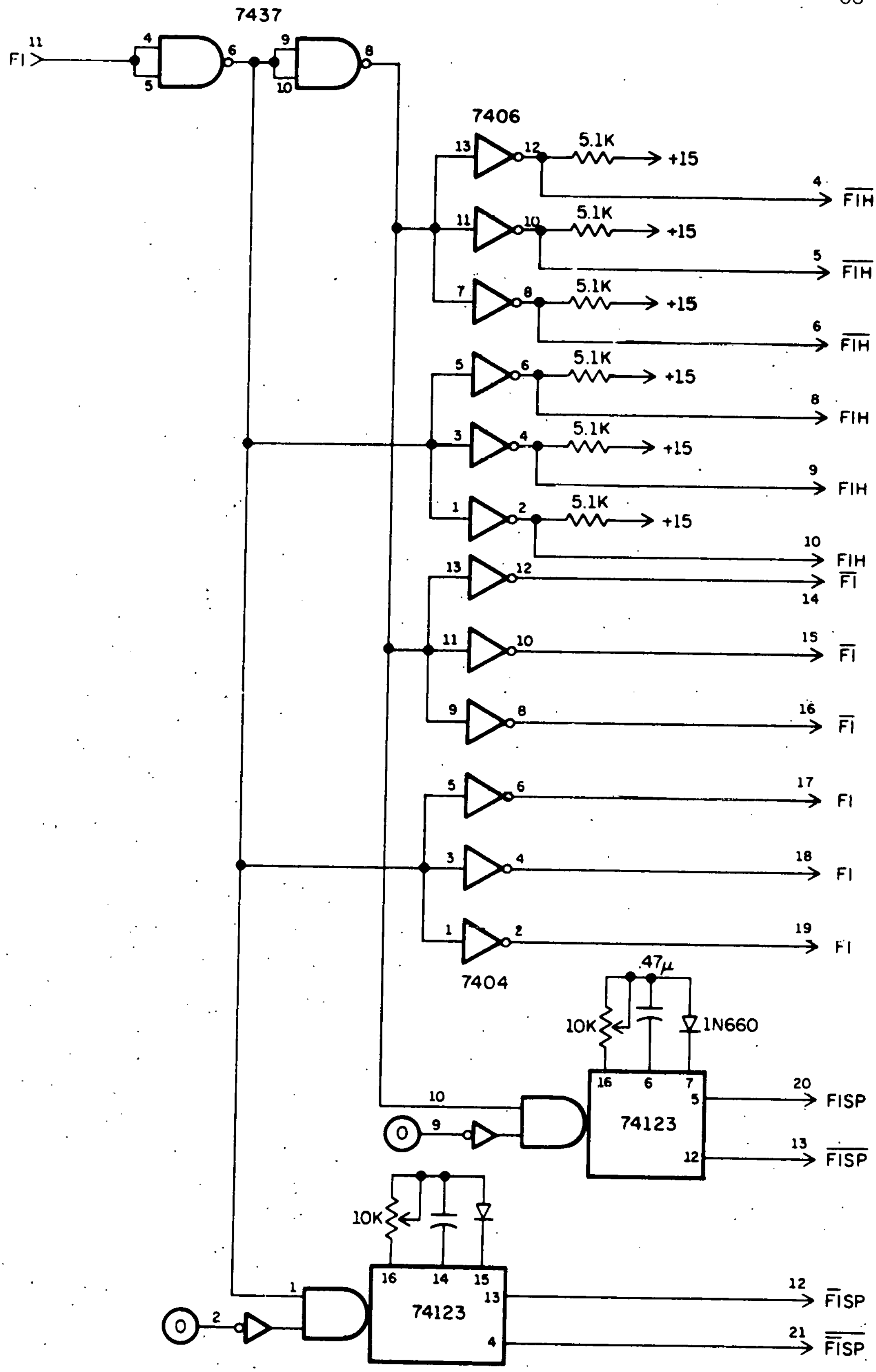


Figure 6.9. Receiver Control Circuits

7. PATTERN DISPLAY SYSTEM

The color perceived in a two-color television system is influenced by factors like the average illumination of the scene and the relative luminance of the projected fields. The other most important factor that influences the color perception is the stochastic structure of the image. It has been qualitatively observed that very many colors are observed when the picture has a jumbled set of different colored objects. Land also observed that the color perceived in an image is not changed when a Mondrian (random) pattern is placed in front of the projector. To test these observations, we designed a random pattern display system that produces a random 16 x 16 checkerboard pattern that can be displayed on the screen either by itself or superimposed with the image.

7.1 Organization of the Pattern Display System

The pattern display system is shown in Figure 7.1. The white field memory and the red field memory store the checkerboard patterns (16 x 16 raster with 4 bits of gray levels) for the respective fields. The pseudo-random binary sequence generator produces the random sequences which are written into the memory units. The checkerboard pattern is read synchronously in the standard television format, converted to an analog signal by the digital-to-analog converter and then mixed with the video if intended. It is then displayed on the monitor. The different pattern display circuits are described in the following sections.

7.2 Pseudo-random Binary Sequence Generator

The pseudo-random binary sequence generator produces a cyclic sequence of binary bits. The usual way of producing such a sequence is to

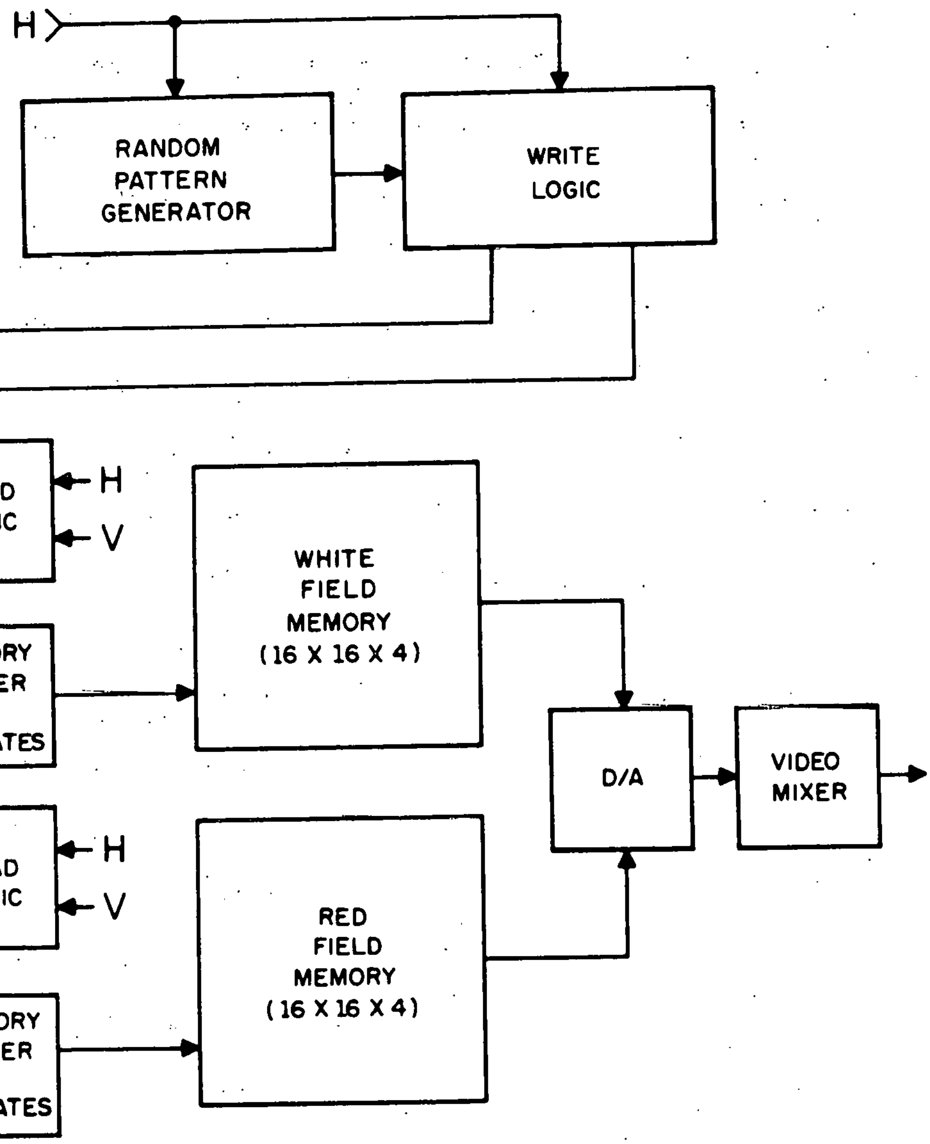
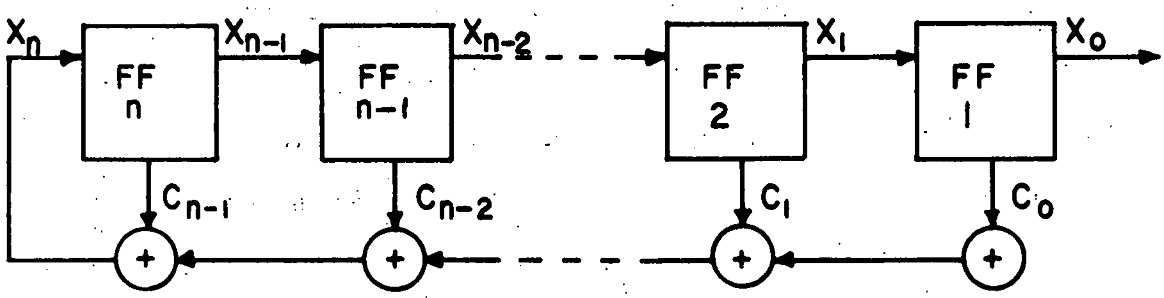


Figure 7.1. Pattern Display System

use shift register chains with linear (modulo-2) feedback logic. For an n-stage shift register, the feedback logic calculates a new term for the last shift register based on the previous n terms. The n-stage shift register shown in Figure 7.2, has 2^n possible states. But if it is driven to an all-zero state it remains in that state and hence this state must be excluded. So a linear n-stage shift register can have a maximum length sequence of $2^n - 1$. The necessary and sufficient condition that the linear n-stage shift register produces the maximum length sequence is that the feedback polynomial be irreducible and primitive. These irreducible polynomials corresponding to the maximum length sequence have been discussed in the literature.[57-59] Table 1 lists the linear feedback logic required for the maximum length sequences, from n = 1 to n = 16.

Using the feedback logic shown in the table, we have built a maximum length pseudo-random generator that is shown in Figure 7.3. The pseudo-random generator is constructed with shift registers consisting of SN7474 D-type positive edge-triggered flipflops and linear (modulo -2) feedback logic consisting of SN7486 Exclusive-OR gates. It has provision for programming n at 2, 4, 6, 8, 10, 12, 14 or 16 by the help of the 3 line-to-8 line decoder. Digital gates were inserted at the feedback points to control the data flow. When the decoder output is low, data from the feedback logic is gated through, but the data from the previous registers is blocked and vice versa. The AMP dual-in-line switches provide an easy way of programming the initial conditions. The switches for the F-Fs which must be preset to 1 are closed allowing them to be set to one initially. Programming the length of the maximum sequence allows us to control the degree of randomness or the auto-correlation of the pattern.



$$X_n = C_{n-1} X_{n-1} + C_{n-2} X_{n-2} + \cdots + C_1 X_1 + C_0 X_0$$

$C_i = 0$ or 1

Figure 7.2. Shift Register with Linear Logic

n	LOGIC (period 2^n-1)	n	LOGIC (period 2^n-1)
1	$X_n = X_{n-1}$	9	$X_n = X_{n-5} \oplus X_{n-9}$
2	$X_n = X_{n-1} \oplus X_{n-2}$	10	$X_n = X_{n-7} \oplus X_{n-10}$
3	$X_n = X_{n-2} \oplus X_{n-3}$	11	$X_n = X_{n-9} \oplus X_{n-11}$
4	$X_n = X_{n-3} \oplus X_{n-4}$	12	$X_n = X_{n-2} \oplus X_{n-10} \oplus X_{n-11} \oplus X_{n-12}$
5	$X_n = X_{n-4} \oplus X_{n-5}$	13	$X_n = X_{n-1} \oplus X_{n-11} \oplus X_{n-12} \oplus X_{n-13}$
6	$X_n = X_{n-5} \oplus X_{n-6}$	14	$X_n = X_{n-2} \oplus X_{n-12} \oplus X_{n-13} \oplus X_{n-14}$
7	$X_n = X_{n-6} \oplus X_{n-7}$	15	$X_n = X_{n-14} \oplus X_{n-15}$
8	$X_n = X_{n-2} \oplus X_{n-3} \oplus X_{n-4} \oplus X_{n-8}$	16	$X_n = X_{n-11} \oplus X_{n-13} \oplus X_{n-14} \oplus X_{n-16}$

Table 1. Linear Feedback Logic

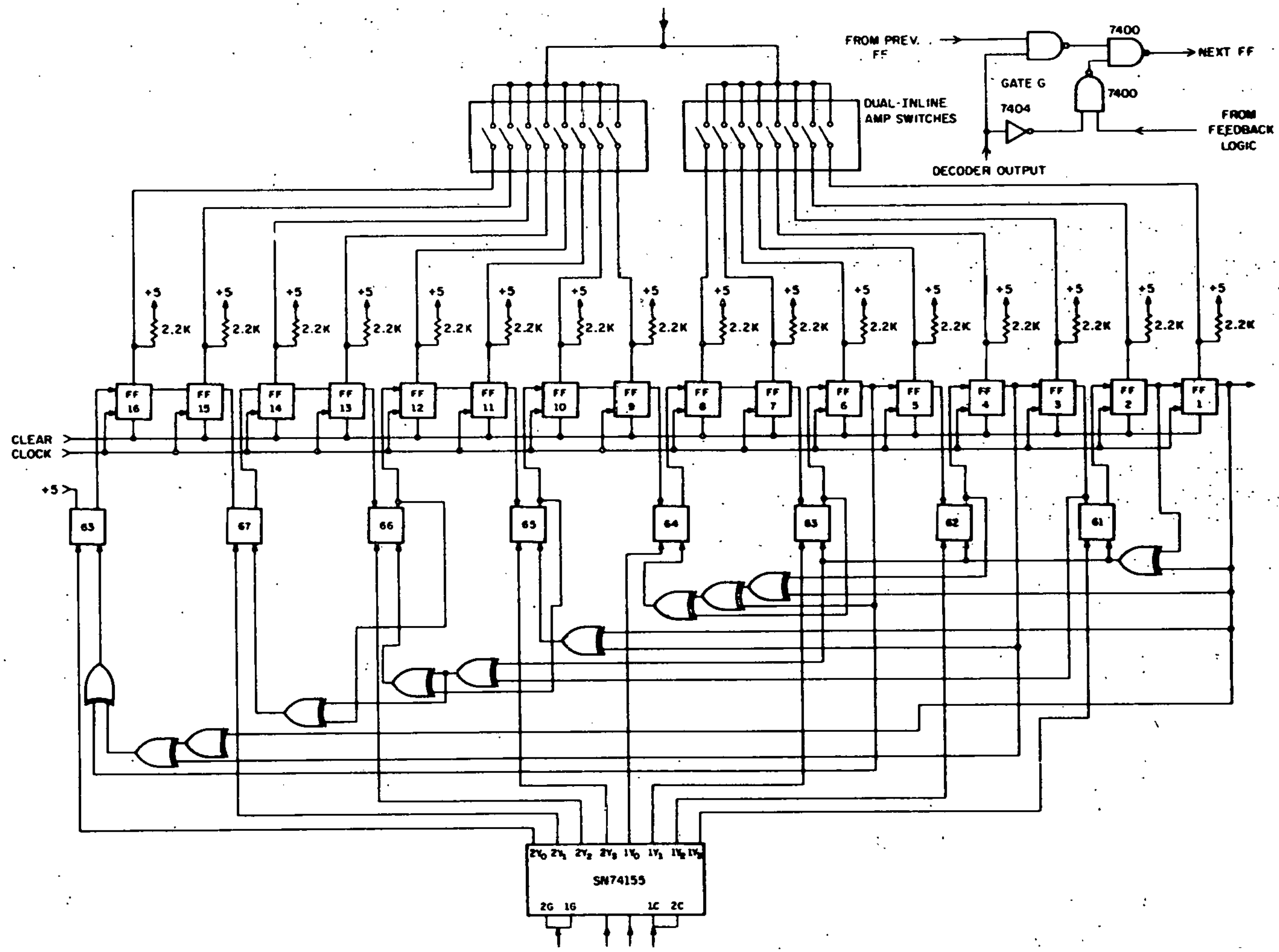


Figure 7.3. Pseudo-random Binary Noise Generator with Programmable

Maximum Length and Initial Conditions

7.3 Pattern Memory and Driving Logic

The chosen random patterns for the white and red fields are written into the respective memories. The memory is organized as 16 x 16 x 4 bits or 256 words of 4 bits each. The Y-address selects one of the sixteen SN7489 memory chips and the X-address selects one of the 16 words of 4 bits each in the selected chip. The semiconductor memory circuit is shown in Figure 7.4. The addressing logic for each memory is shown in Figure 7.5. One of these two memories is selected every field by enabling the respective SN74154 decoder chip.

7.4 Read-Write Logic

The random pattern obtained from the pseudo-random generator is written into the semiconductor memory in the raster format. This is done by the write addressing logic and the write memory buffer shown in Figure 7.6. The SN7474 D-type flipflops store the four successive outputs of the random sequence generator. The clock applied to the X-Y counter is H / 4, so that after every four horizontal pulses the counter is advanced by one ensuring that 4 new bits are now stored in the D-storage registers. There is one set of storage registers and counters for the white field memory and another set for the red field memory. The read-logic shown in Figure 7.7 allows the pattern stored in the memory to be displayed synchronously in the television raster format. The Vertical Counter C1 starts counting at the onset of the vertical sync pulse. After it counts a programmed number of pulses H (say, maximum 16), the carry out pulse clears M2 which starts the counting for C2 and C3. C2 is connected as a divide by 15 counter. C3 is a 4 bit binary counter. In each field the display memory is read after a maximum delay of 16H lines from the start of vertical sync. After every 15H lines the next row in the memory is read.

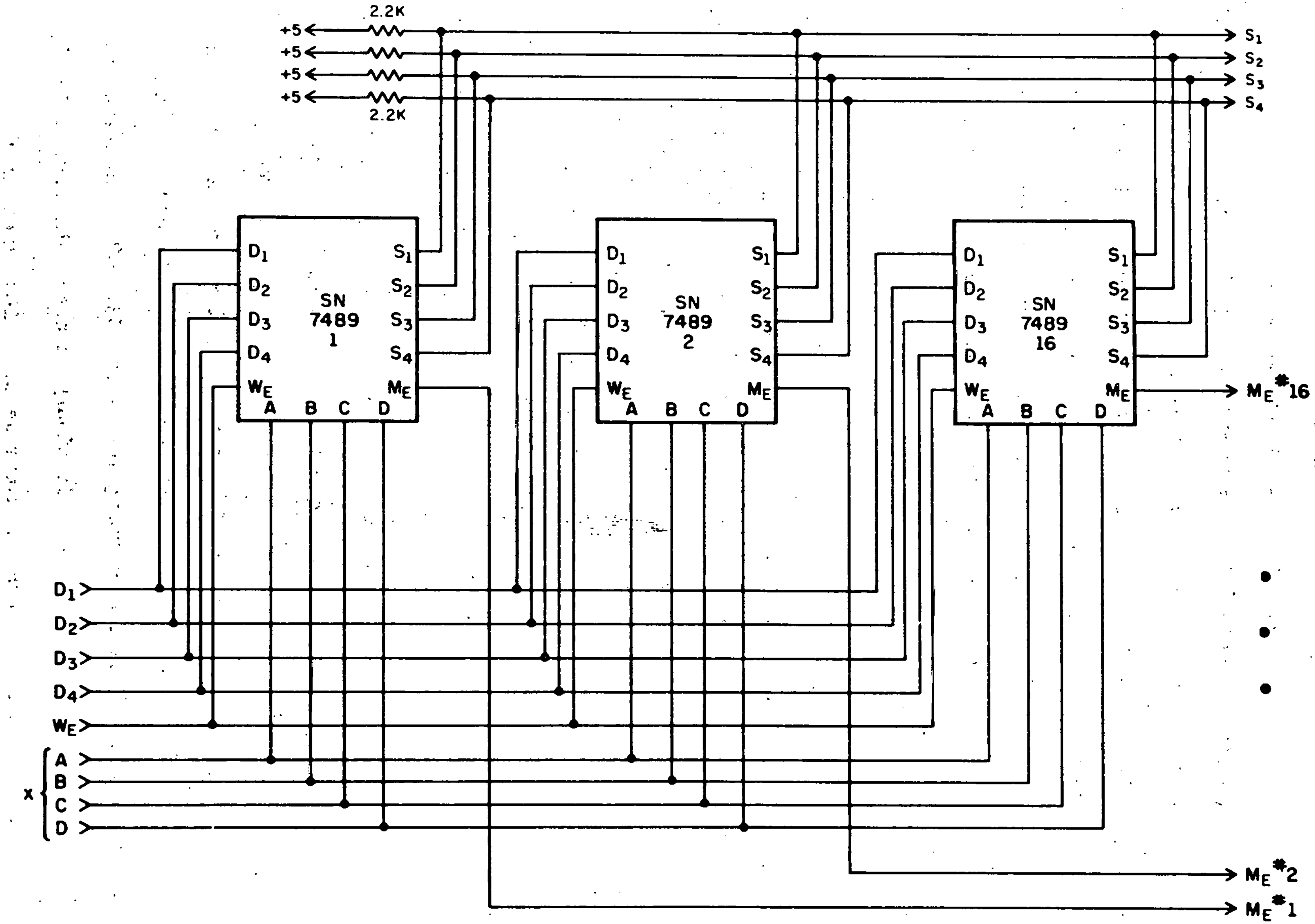


Figure 7.4. Semiconductor Memory

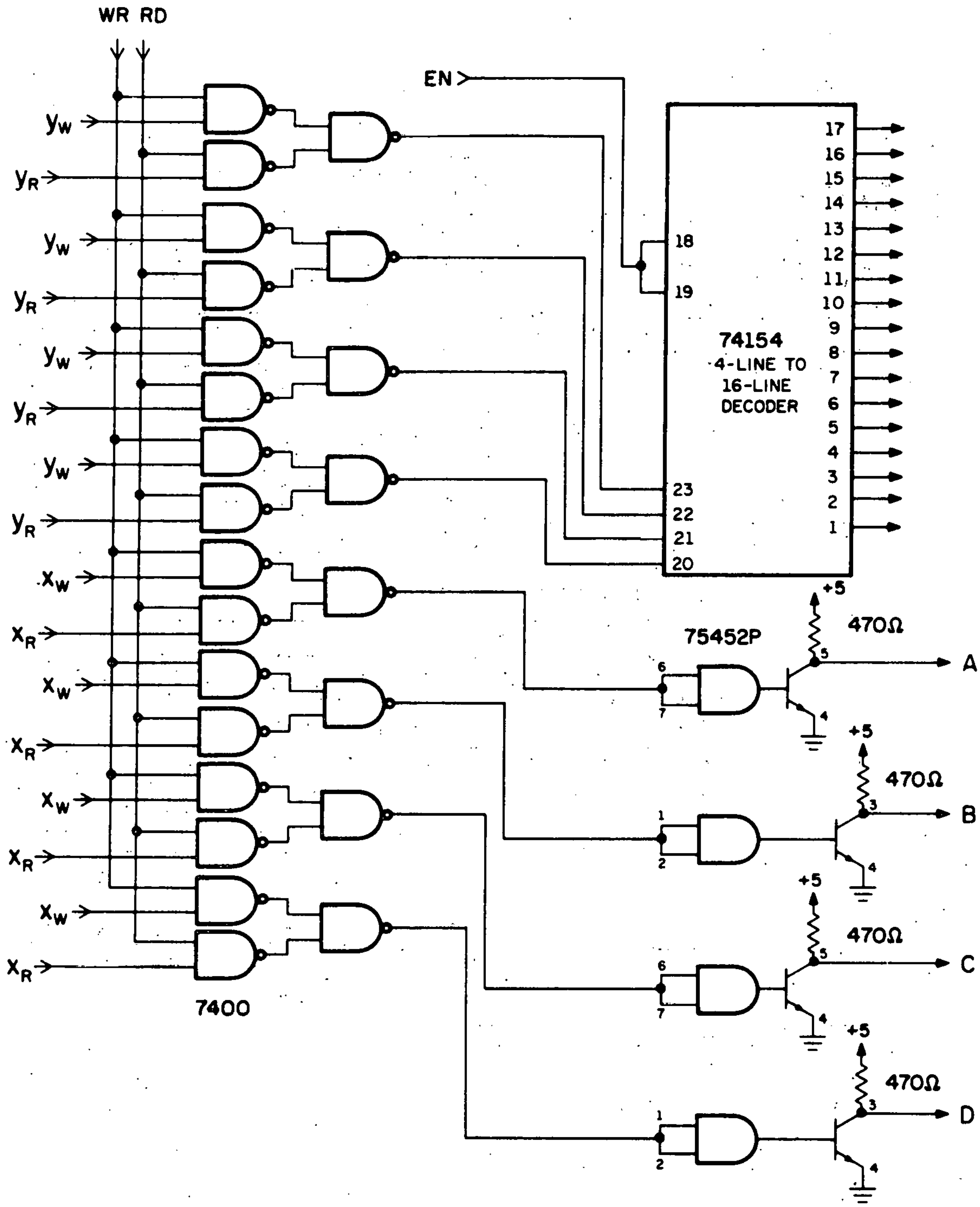


Figure 7.5. Addressing Logic

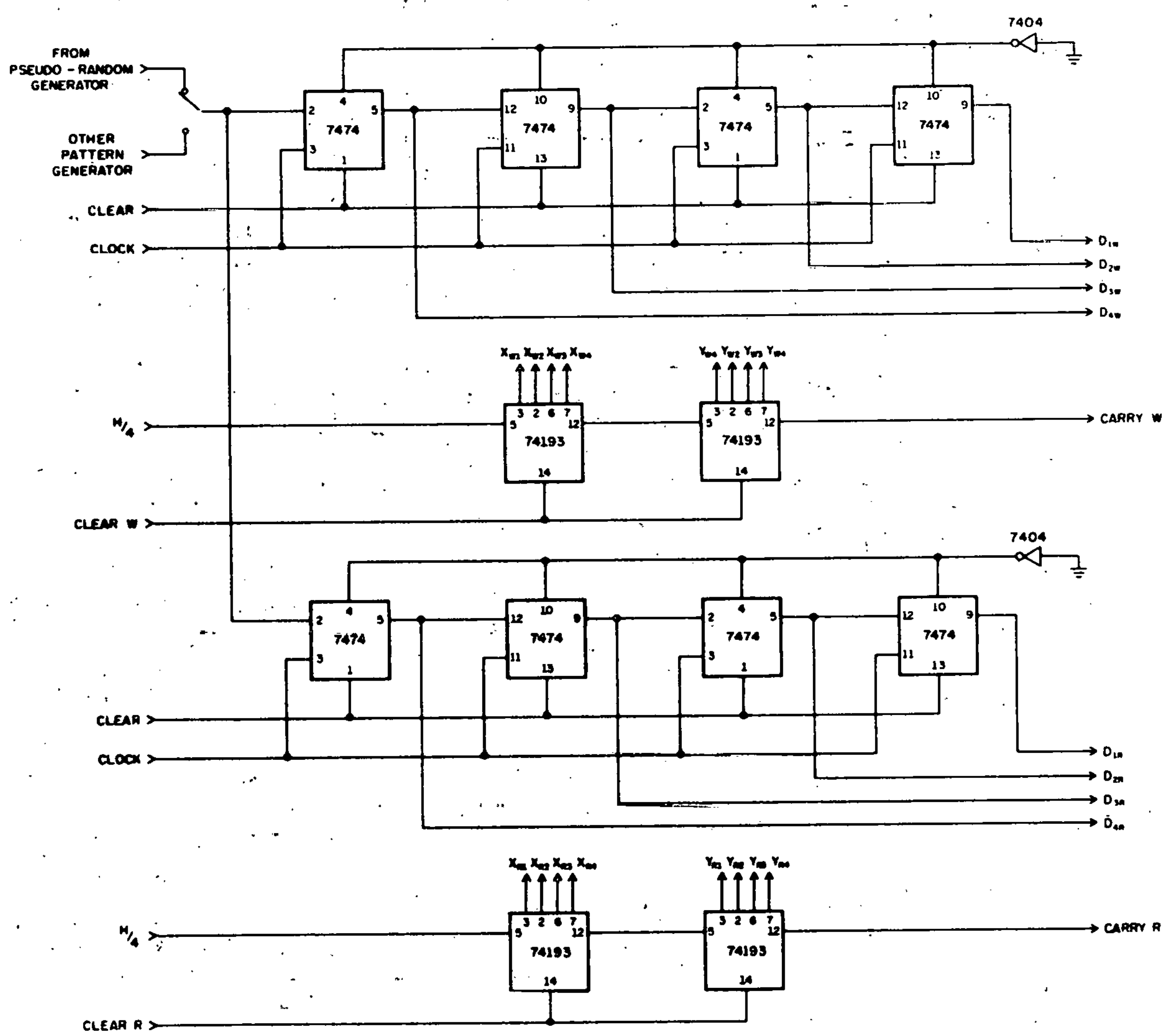


Figure 7.6. Write Logic and Buffer

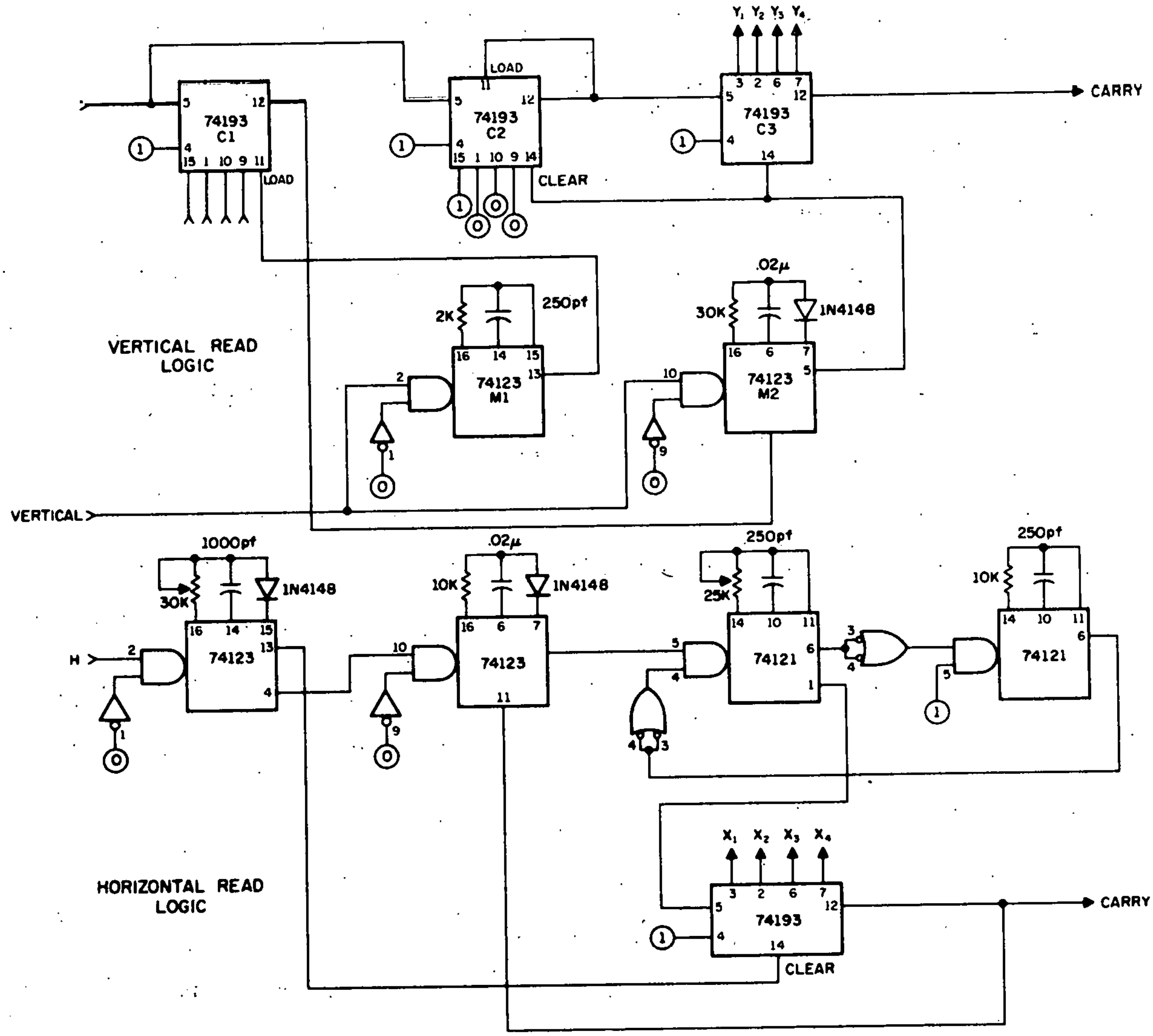


Figure 7.7. Read Logic

The horizontal counter starts counting after a controllable delay by M3. After this delay, M4 is triggered which in turn triggers the cross-coupled monostables M5 and M6. The pulse frequency can be adjusted by varying the resistance R. When the counter has finished counting 16 pulses the carry-out pulse clears M4 which in turn inhibits the oscillation of the cross-coupled multivibrators.

7.5 Pattern Timing Logic

Different timing signals are derived in the Pattern timing logic shown in Figure 7.8. The Read-Write DPDT switch selects whether data is read out of the memory or written into it. In the write mode, M1 produces a clear pulse to clear the white field memory write counter. M2 produces a pulse equal to the duration for which the white field memory is to be written into. The clear R pulse clears the red field memory write counter until that time. W_{EW} enables the write for the white field memory. The chip enable decoder SN74154 is also enabled during this period. M3 produces a pulse whose width is equal to the interval for which the red field memory is written into.

7.6 D/A Converter and Video Mixer

The four bit digital information read from the semiconductor memory is converted to an analog signal by the digital-to-analog converter. The DAC consists of eight high-speed JFET analog gates described earlier in Section 6.6 and a weighted resistance network connected at the input of a μA715C high speed operational amplifier. The video mixer is another operational amplifier that mixes the image and the checkerboard pattern or outputs any one of them. The D/A converter and the video mixer are shown in Figure 7.9.

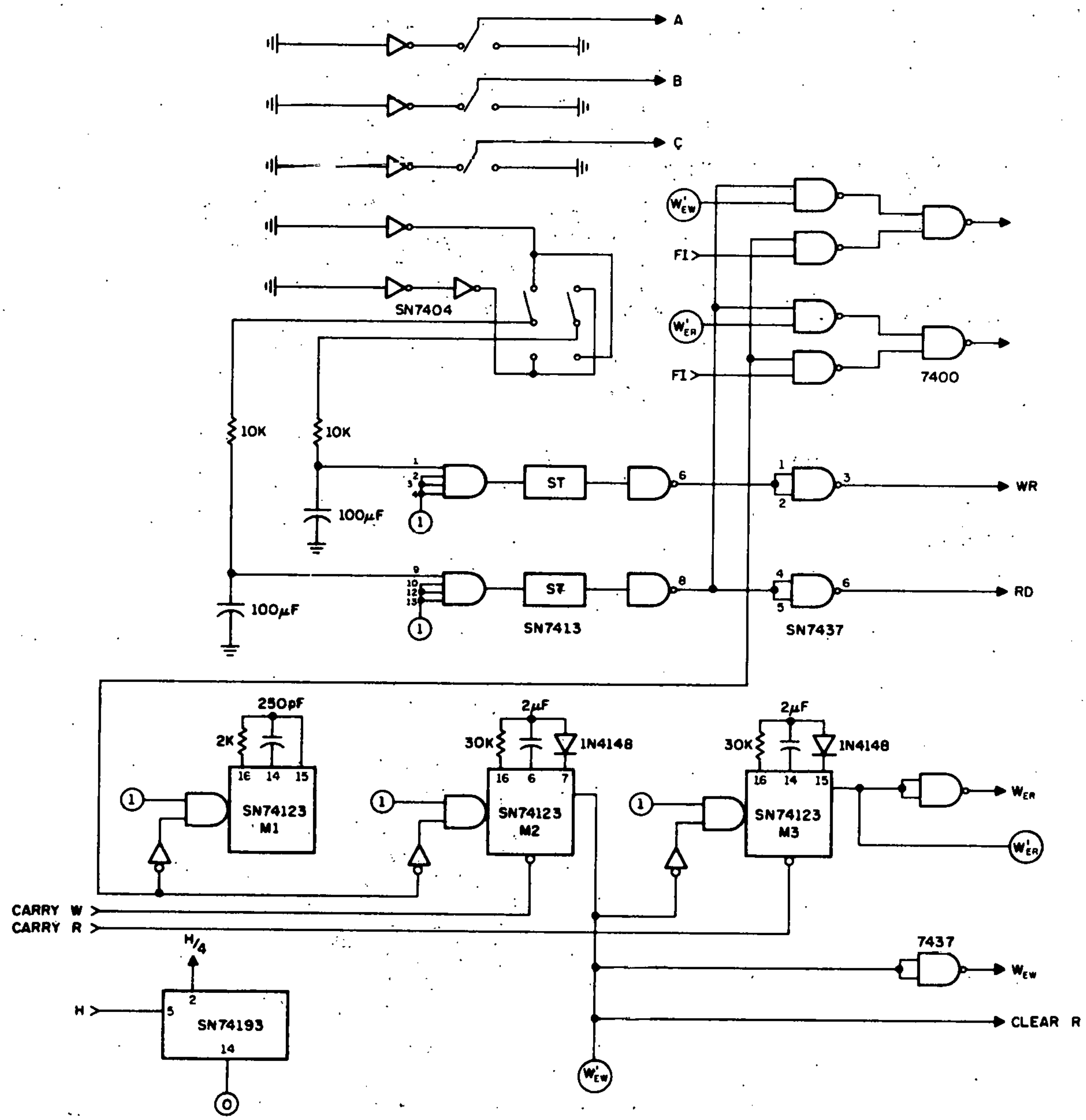


Figure 7.8: Pattern Timing Logic

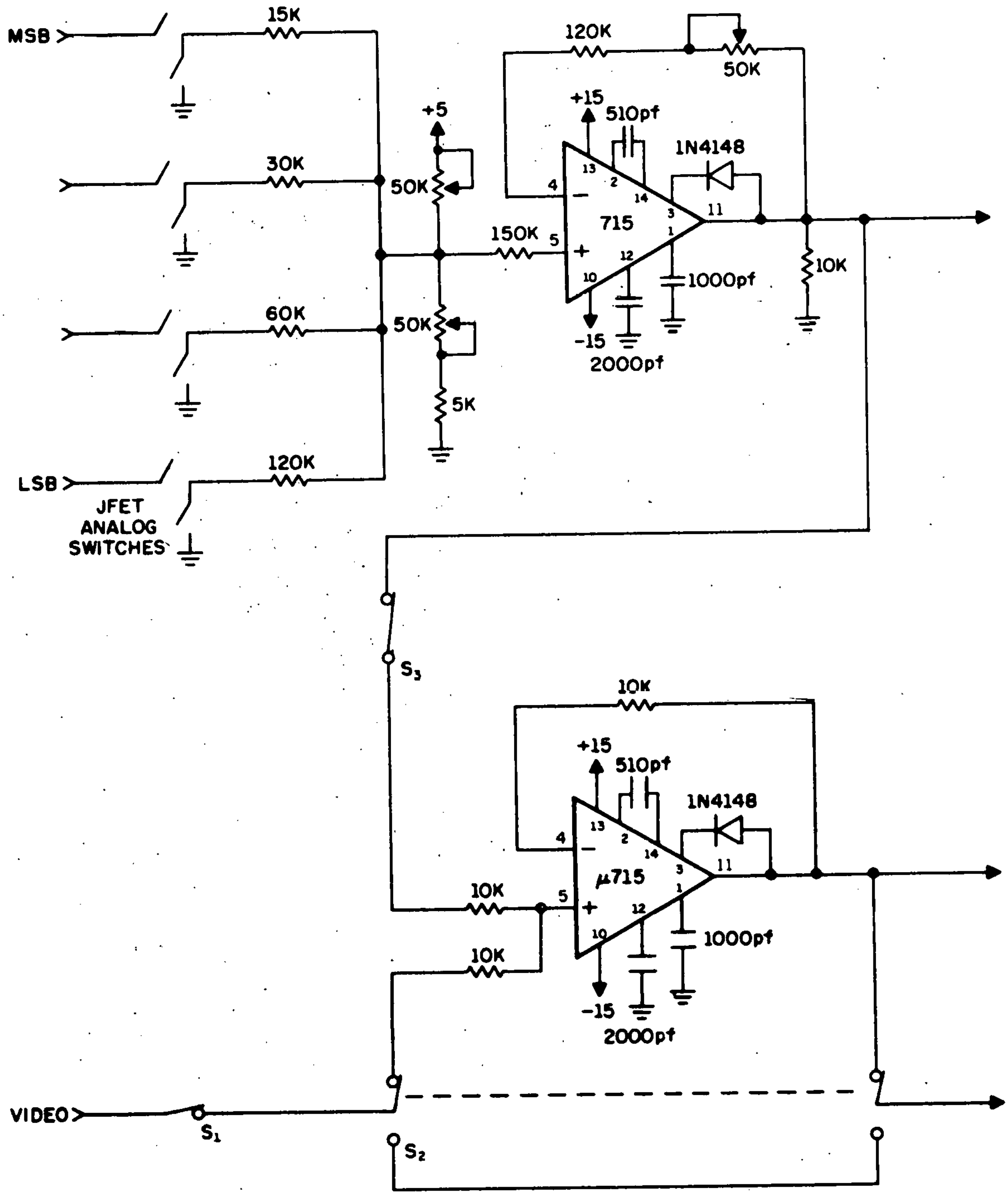


Figure 7.9. D/A Converter and Video Mixer

8. PENTECOST CAMERA SYSTEM

The Pentecost camera system generates a field-sequential color signal using a single imaging tube and a color filter wheel driven by a synchronous motor. A schematic of the camera system is shown in Figure 8.1. The light from the object passes through the filter wheel and is focused by the lens system onto the face of the pick-up tube. The LED-photo-transistor pair produces a signal indicating the position of the color wheel. This signal is amplified by the photo-detector amplifier and then used to synchronize the camera and derive the color field indicator signals. The various components and subsystems of the camera are described in the following sections.

8.1 Camera Tube

In a field-sequential color system like ours, it is essential that we have a pick-up tube having fast response so that there is no carryover of the signal from one field to the other. This and other considerations that led to the selection of a Plumbicon camera tube and a black-and-white camera system are described in Appendix B.

The Plumbicon is a vidicon type television pick-up tube that has a photoconductive layer of lead-monoxide (PbO) instead of antimony trisulphide. This results in high sensitivity, negligible dark current, fast response and independence from temperature variation.[60] This photosensitive layer acts as a p-i-n structure with the red PbO layer behaving as an intrinsic layer.[61,62] The vapor deposited PbO layer has crystallites of dimension about 1μ x 1μ x 0.1μ. The small size of the crystals gives rise to numerous surface states[63] and these surface states compensate the

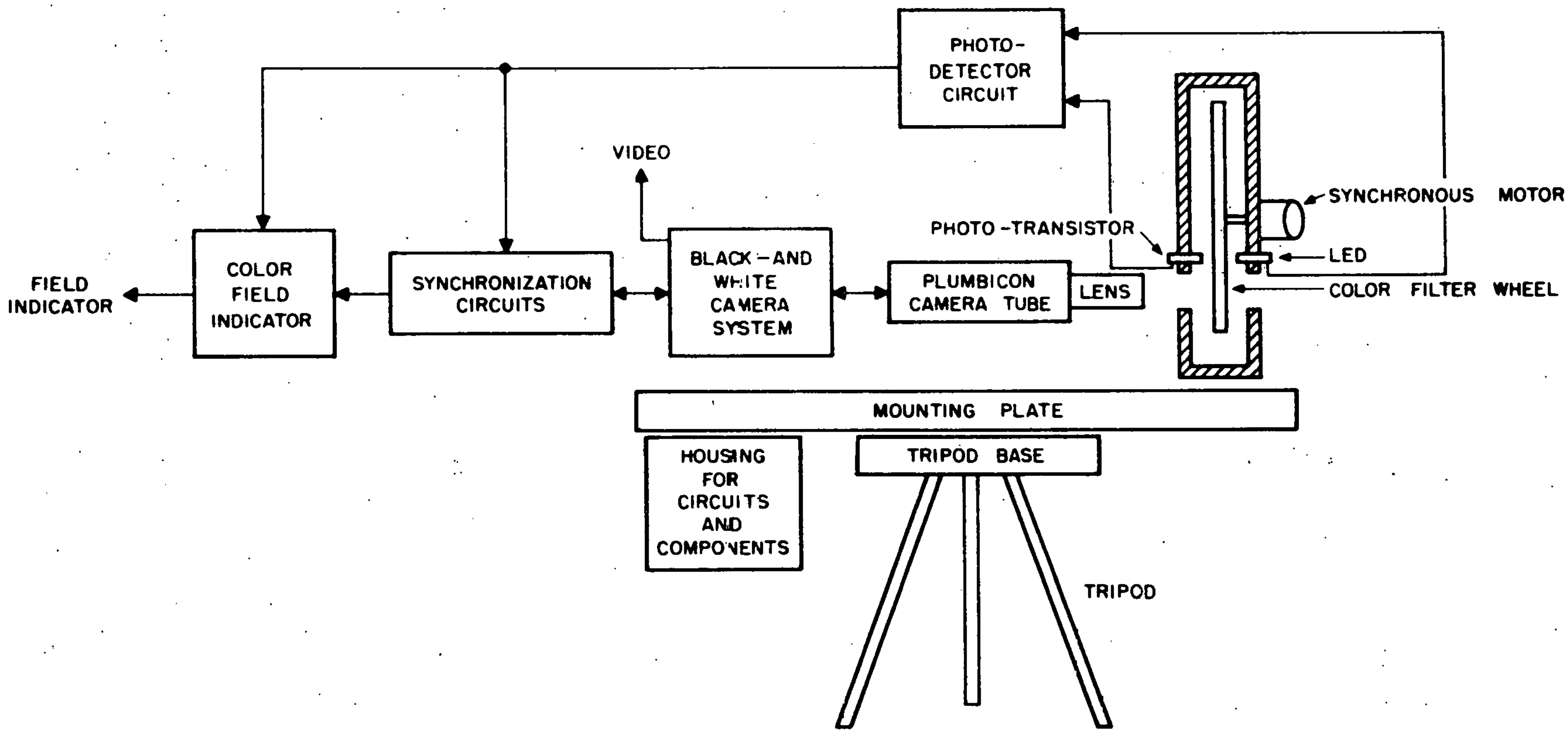


Figure 8.1. Pentecost Camera System with Filter Wheel

bulk impurity giving rise to essentially intrinsic behaviour. The PbO layer is deposited on a transparent electrode layer of SnO_2 which acts as the n-region of the p-i-n structure. A thin p layer is formed on the other side of PbO layer. The SnO_2 electrode is usually biased to around 40V with respect to the cathode. The p-i-n layer is thus reverse biased and very little dark current flows.

It should be mentioned that in the red region the response of the Plumbicon decreases very rapidly. To enhance the absorption in the red region the intrinsic thickness is increased to 10-20μ. In red-extended tubes this absorption is enhanced by creating a lead oxy-sulphide layer having smaller bandgap.

The camera tube selected is a red Plumbicon (Amperex 16 x QRIG). It employs a separate mesh construction in a 1" diameter envelope. Some of the salient features of the tube[64] are:

Signal Electrode Voltage: 45 volts

Dark current: 3 nA max

Sensitivity at Color Temperature of Illumination = 2850°K:
60 μA/lumen

Gamma Transfer characteristic: 0.95 ± 0.05

Limiting Resolution: 600 TV lines

Highlight signal current: 0.1 μA

Lag: (measured with 100% signal current of 0.1 μA and with a light source with color temperature 2850°K. Red filter inserted).

Residual signal after dark pulse of 50m sec: max 5%

Residual signal after dark pulse of 200m sec: max 2%

Spectral Response:

Region of max response: 4700-5200°A

Regions of 50% response: 5800 $\pm$ 100°A

Cut-off: 6200 Å

8.2 Filter Wheel

The color filter wheel has two sections of red and green Wratten filters sandwiched between two Plexiglass plates. It is driven by a 1/100 H.P. capacitor-start hysteresis synchronous motor operating at 1800 rpm. The color wheel rotates at 30 rps to yield two fields per revolution at the color frequency of 30 fps. As shown in Figure 8.1 the filter wheel is enclosed in a housing on which the synchronous motor is mounted. The whole assembly is mounted on the base plate of the tripod just in front of the camera lens assembly. The filter wheel is large enough to cover the entire camera lens area and sequentially passes the red and green fields. The LED-Photo-transistor pair is mounted on this filter assembly to detect the position of the filter wheel.

8.3 Photo-detector Circuit

Refer to Figure 8.2. Light from the red-emitting LED passes through the rotating filter wheel to the photo-transistor. The photo-transistor is connected as an emitter follower. Since the speed requirements are not stringent, the emitter load is kept high to have larger output signal. The output voltage is amplified and then applied to an output stage through an emitter follower to decrease the loading on the previous stage. The output drives the schmitt trigger to give clean pulses at 30 Hz.

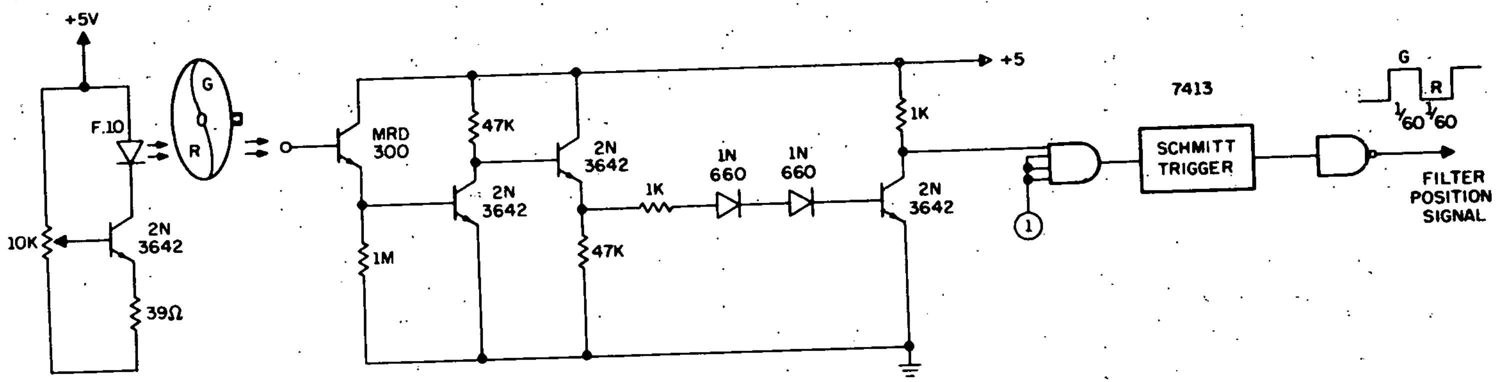


Figure 8.2. Photo-detector Amplifier

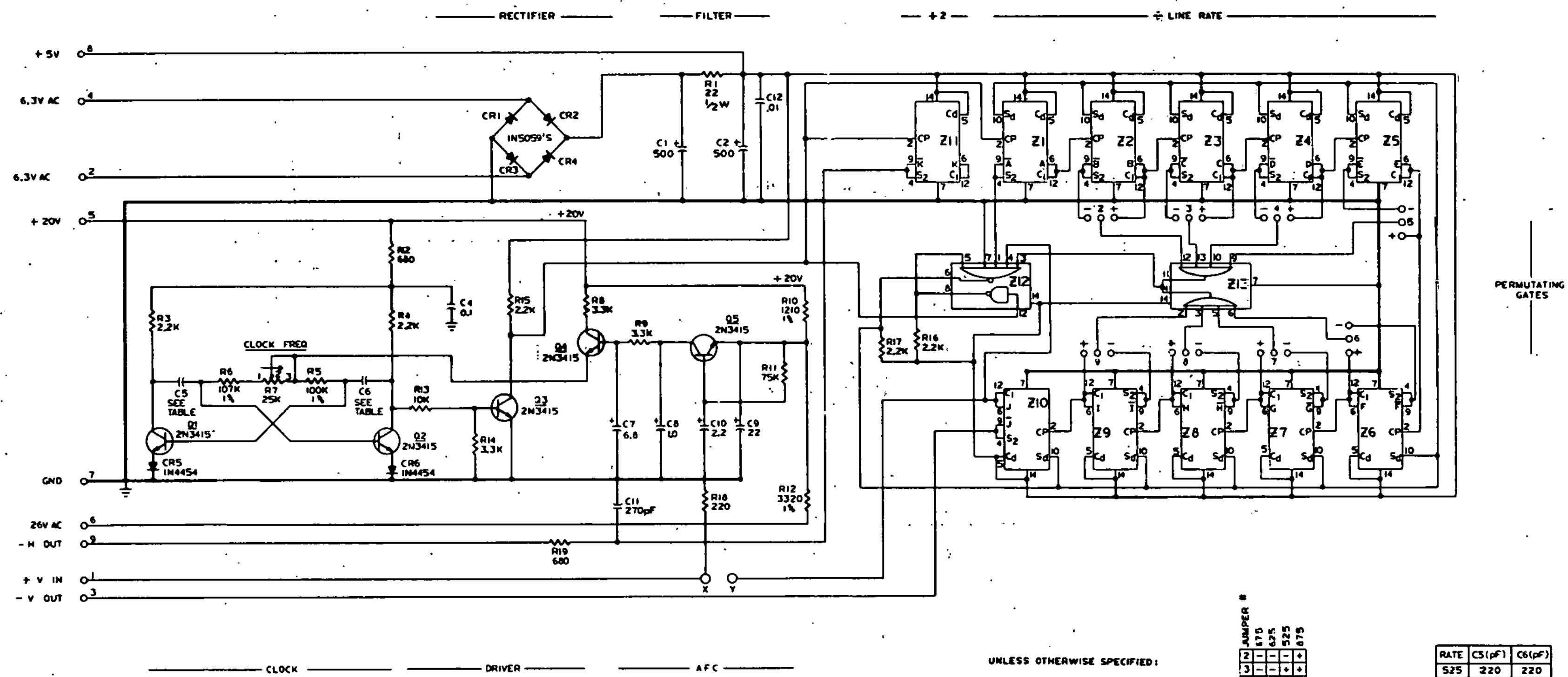
8.4 Camera Synchronization Circuit

Rather than synchronize the hysteresis synchronous motor with the camera sync signal it was decided to use the field signal from the photodetector circuit to synchronize the camera system with the motor. This is accomplished by modifying the 2:1 interlace synchronization circuit shown in Figure 8.3. This has a free-running multivibrator having a frequency of 31.5 kHz. Dividing this frequency by two gives the horizontal frequency. It is also divided by a chain of ten divide-by-two counters with proper gating to get a division of 525, thus giving at the output a sixty hertz vertical signal. This 60 Hz signal is compared with 26V A.C. derived from the mains and depending upon their phase difference we get an output at the phase comparator which is then integrated and applied through an emitter follower to the base return resistor of the free-running multivibrator, which in turn changes the frequency of the multivibrator. Thus the vertical and the horizontal signals are locked to the power frequency.

To synchronize the filter wheel with the camera we replace the 26V A.C. signal with one derived from the photodetector circuit. To accomplish this we derive sixty-cycle pulses denoting the start of the red and the green fields that are derived from the photo-detector signal. This signal is then applied to the integrator which produces a 60 Hz sawtooth signal that are used in place of the 26V A.C. input. This part of the synchronization circuit is shown in Figure 8.4. R_2 and R_3 allow us to vary the amplitude and the dc-level, respectively, of this sawtooth output.

8.5 Color Field Indicator

The color field indicator circuit is shown in Figure 8.5. At the output of this circuit we get a thirty hertz TTL signal with the high level



ALL COMPONENTS PREFIX 'S'

UNLESS OTHERWISE SPECIFIED:

ALL RESISTOR VALUES ARE IN OHMS TOL ± 5% AND 1/4 WATT.

ALL CAPACITOR VALUES ARE IN MICROFARADS, pF = PICOFARADS.

JUMPER #	675	625	525	875
2	−	−	−	+
3	−	−	+	+
4	−	−	+	+
5	−	+	−	−
6	+	+	−	+
7	−	+	−	+
8	+	−	−	−
9	−	−	−	+

RATE	C5(pF)	C6(pF)
525	220	220
625	220	220
675		
875	120	150

Figure 8.3. Sync. Generator Board

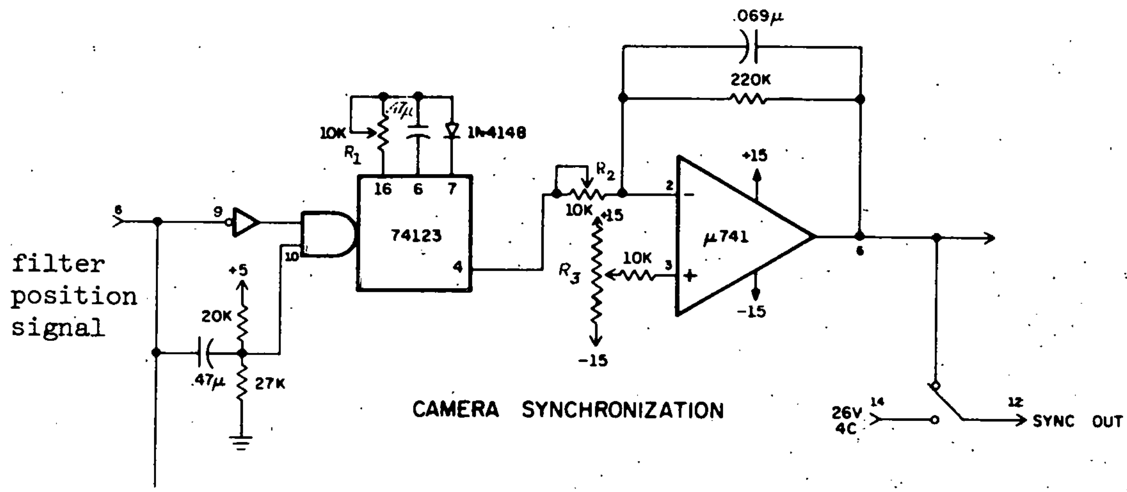


Figure 8.4. Camera Synchronization Circuit

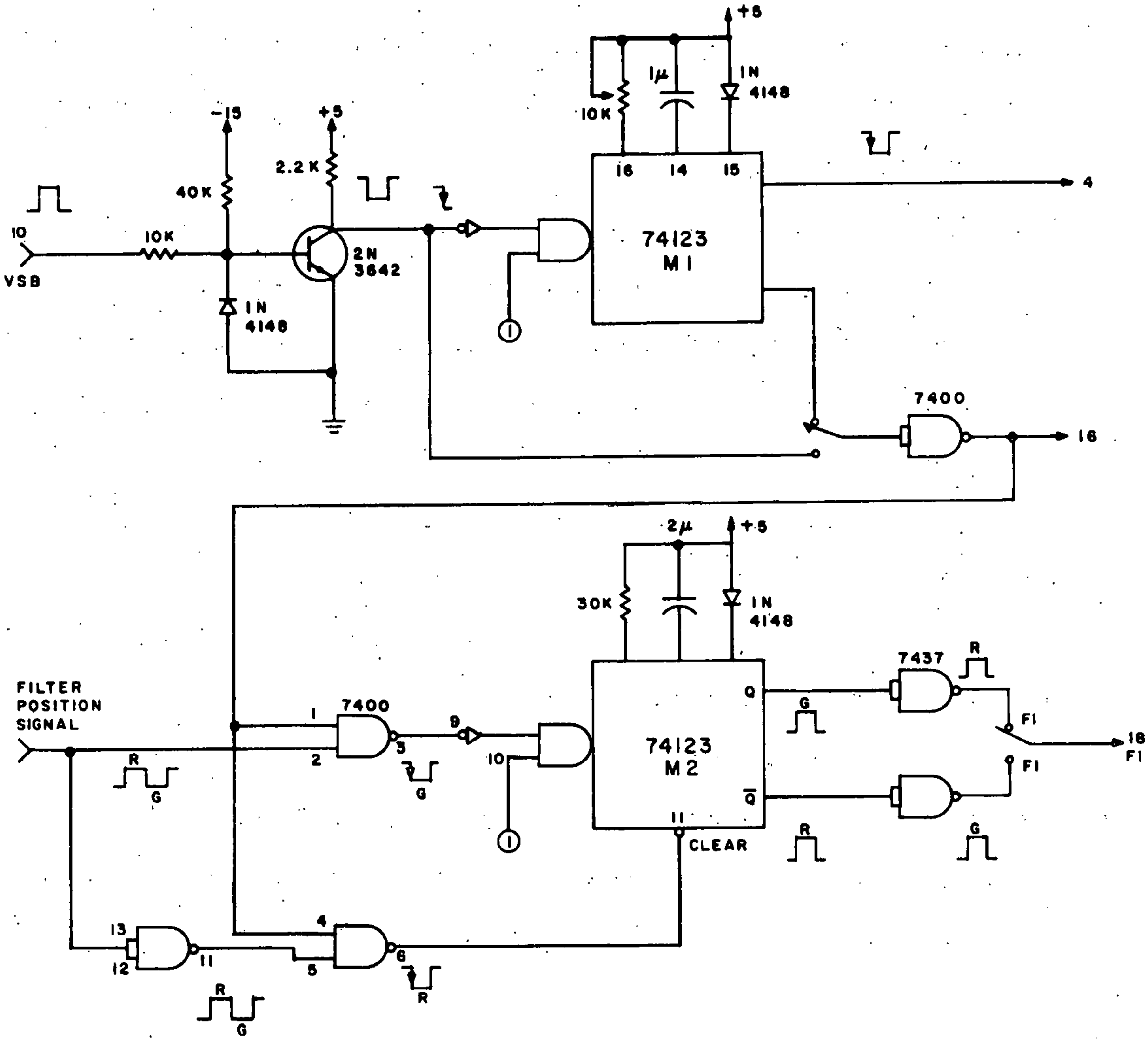


Figure 8.5. Color Field Indicator

denoting the green field and the low level denoting the red field. These field signals start at the beginning of vertical blanking so that all the switching that is controlled by this signal in the receiver system has the blanking time to complete their transitions. The vertical system blanking obtained from the camera system is level-shifted and then applied to the monostable M1 which produces a blanking pulse whose width can be controlled. The vertical blanking signal selected by the SPDT switch is inverted and then applied to the SN7400 gates. The other input to these NAND gates is the filter position signal obtained from the photo-detector circuit. At the output of the upper NAND gate we have a pulse whose negative transition refers to the start of the green field. At the output of the lower NAND gate we have a pulse whose negative transition refers to the start of the red field. These two pulses are respectively applied to the negative going gated input and the clear input. At the Q output of M2 we get a pulse whose high level refers to the green field. The SPDT switch allows us to select the normal color field signal or a complimentary field signal which controls the receiver system such that the camera red field is projected on the white phosphor and the camera green field is projected on the red phosphor. This corresponds to the television analog of color reversal effect in Land two-color projections.

9. ELECTRONICALLY CONTROLLED COLOR FILTERS

There have been several attempts in recent years at making a color television camera using a single pick-up tube. One such camera, developed by RCA, uses a patterned dichroic filter of red, green and blue strips area-sharing at the front end.[65] Another color camera using a single pick-up tube is the Apollo-11 color camera which uses a color filter-wheel. The advances in Ferroelectrics and other solid state materials has spurred interest in having a solid state filter that can be controlled electronically and used in place of the color wheel.

9.1 Solid State Color Filters

Presently, there are three possible types of such solid state filters. They are:

1) Voltage tunable interference filter
2) Ferroelectric Ceramic filter
3) Ferroelectric ferroelastic filter

Voltage-tunable Interference Filter:

These are voltage-tunable interference filters such as the Optichron.[66] These types of filters are made from some piezoelectric crystal such as Barium Titanate that show changes in the length of the sample upon application of an electric field of the order of 10^3 volts/cm. The operation of the filter can be explained in terms of the tetrogonal distortion of the crystallites. An unpolarized sample has its crystallites polarized in more or less arbitrary directions. When a field is applied, some of the crystallites become oriented in directions nearer that of the field. If such a sample is used as the element of an interference filter, then the thickness of the sample can be changed with the application of the field and consequently the transmission characteristics change with thickness. The Optichron passes a different color upon application of a voltage. Cascading two such Optichrons along with application of a suitable voltage to each of them allows us to selectively pass the red, green or blue portion of the spectrum.

9.2 Ferroelectric-Ceramic Filter

Another promising possibility is to construct a filter of thin polished plates of hot-pressed rhombohedral lead-zirconate lead-titanate (PLZT) ferroelectric ceramics.[67-69] Coarse-grained ceramics that have grain diameters greater than about two microns have light scattering properties that can be varied by switching the orientation of the ferroelectric polarization. Fine grained ceramics having grain diameters less than about two microns have an effective birefringence that can be varied either by applying a biasing field and/or by partially switching the ferroelectric polarization.

When a dc electric field of sufficient strength is applied to a ferroelectric ceramic, domains favorably oriented with respect to the field grow. When the field is removed, the ceramic retains part or all of this polarization. Under these circumstances it is said to be electrically poled. The direction of poling is the ceramic polar axis. By poling these fine-grained ceramics, the ceramic polar axis and the optic axis are made coincident and they become optically uniaxial crystals having refractive indices n_e and n_o. n_e is the refractive index for light with its electric vector parallel to the optic axis, and n_o, the refractive index for light with its electric vector perpendicular to the optic axis. Birefringence, Δn, is defined as $n_e - n_o$. Retardation R, the path difference between the two components for any incident polarized light is

$$R = (\overline{n_e - n_o})t = t\overline{\Delta n}$$

for plate thickness t. $\overline{\Delta n}$ is the macroscopic birefringence which is measured to be about 0.64 Δn. Since Δn can be varied by orienting the domains with an electric field, the retardation is under electrical control. (The effective binefringence $\overline{\Delta n}$ also depends on the incident light wavelength).

A device made of electrically controlled fine-grained ceramics may be configurated as shown in Figure 9.1 where y is the poling axis and Ψ is the polarization angle of incident light. If $\emptyset$ is the angle at which the analyzer is oriented, then the transmittance for $\emptyset = 90°$ is

$$T = \text{Sin}^2 \frac{R\pi}{\lambda}$$

$$\text{for } \emptyset = 0°,\ T = \text{Cos}^2 \frac{R\pi}{\lambda}$$

The retardation is varied by adjusting the remanent polarization or bias field. If

$R = N\lambda$,	$T = 0$ for $\emptyset = 90°$	
	$T = 1$ for $\emptyset = 0°$	$N = 0,1,2...$
$R = (N-1/2)\lambda$,	$T = 1$ for $\emptyset = 90°$	
	$T = 0$ for $\emptyset = 0°$	

If white light is incident, those wavelengths for which $R = (N-1/2)\lambda$ will be preferentially transmitted when $\emptyset = 90°$ and those wavelengths for which $R = N\lambda$ will be preferentially transmitted when $\emptyset = 0°$.

As the ceramic polarization is changed either by incremental switching or applying a bias field, the resulting change in retardation will change the preferentially transmitted color. For example, if the ceramic plate transmits red at P_R, it may be switched incrementally to transmit orange, yellow, green or white as shown in Figure 9.2.

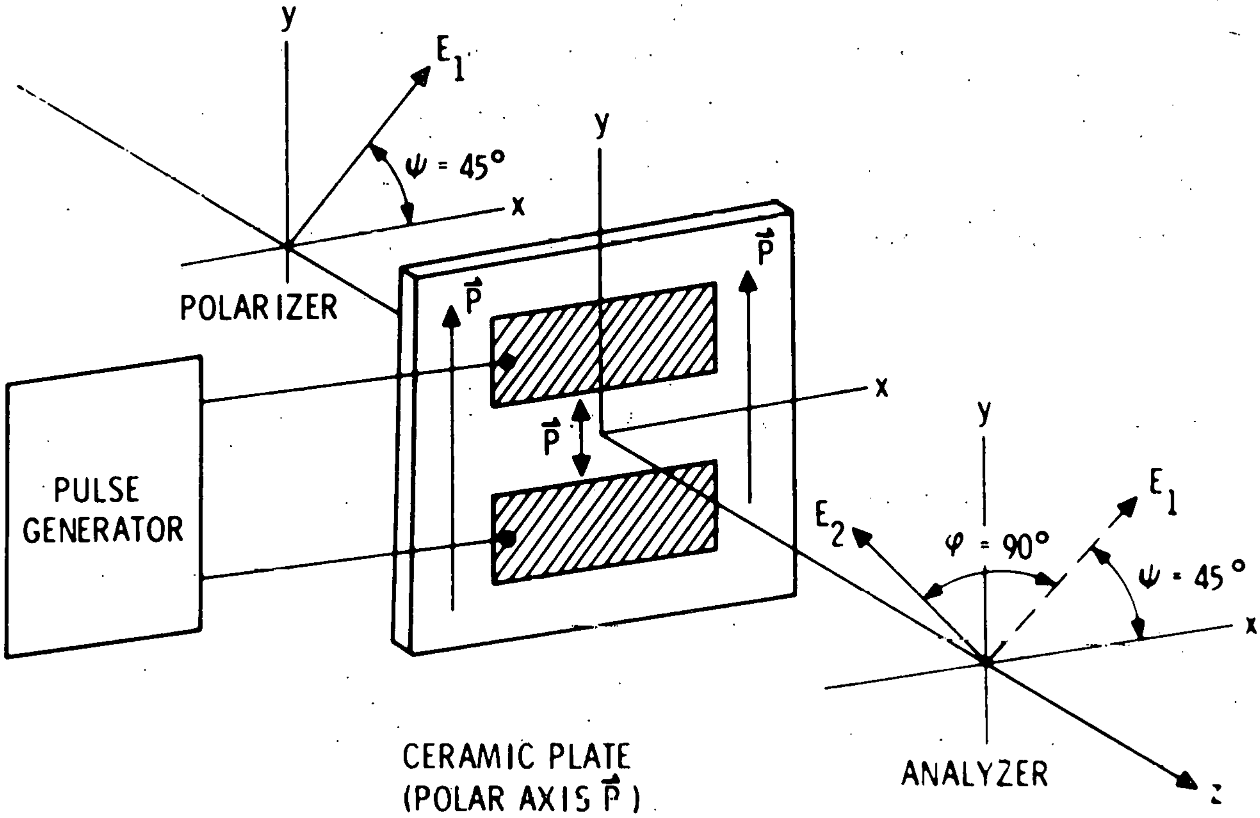


Figure 9.1. Ferroelectric Ceramic Filter

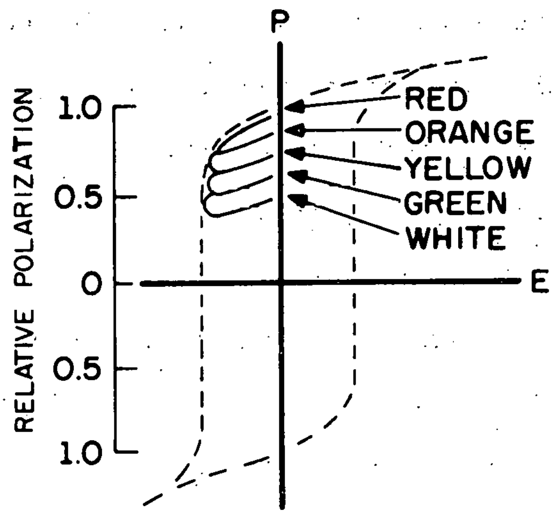


Figure 9.2. Hysteresis Loop of Ferroelectric Ceramic

Some of the limitations of fine-grained ceramics are:

1. Fine-grained ceramics also scatter transmitted light. This is undesirable in that it tends to obscure birefringence. It is thought that the dominant scattering mechanism in fine-grained ceramics is the scattering from inclusions, impurities, voids, and structural discontinuities at grain boundaries.
2. The transmission ratio is only in the range of 0 to 45% in the visible range.
3. Domain switching processes can take place in the ceramic in times of the order of microseconds. But questions still remain of whether large enough amounts of polarization can be switched fast enough with reasonable voltages and without causing the sample to fracture.

An attempt was made to obtain a sample of a ferroelectric ceramic filter from Bell Telephone Laboratories or Sandia Laboratories, but we were unsuccessful in getting any such sample for our experimentation.

9.3 Theory of the Ferroelectric-Ferroelastic Color Filter

According to Aizu,[70] "A crystal which is simultaneously ferroelectric as well as ferroelastic and in which all polar properties of every even rank tensor can be changed by the application of an electric field or a mechanical stress is said to be ferroelectric-ferroelastic."

Godolinium molybdate ($Gd_2(M_oO_4)_3$) has been observed to have the ferroelectric-ferroelastic effect[71-74] and belongs to the same species as KH_2PO_4. Above T_c, $Gd_2(M_oO_4)_3$ is optically uniaxial with a tetragonal space group, and below T_c it is optically biaxial. It has the following optical properties.

$$n_c = 1.8409 + 1.917 \times 10^6 \quad \lambda^{-2}$$

$$n_a \approx n_b = 1.7950 + 1.6500 \times 10^6 \quad \lambda^{-2} \quad \text{with } \lambda \text{ in } \mathring{A}$$

Since $n_c > n_a \approx n_b$, $Gd_2(M_oO_4)_3$ is optically positive as contrasted with KH_2PO_4 which is optically negative. The value of birefringence $\Delta n_{ab} = n_b - n_a$ was obtained to be -4.08×10^{-4} at room temperature.

The birefringence, Δn_s, in the biaxial phase, occurs opposite in sign to electric field E_b and mechanical stress X_s. When the electric field or the mechanical stress is reversed, Δn_s diminishes in value. This is shown in Figure 9.3. The existance of bistable states is utilized to make the color modulators in the following way. One birefringent crystal such as Rochelle salt having retardation R_o is cascaded with two MOG plates having retardation R_{G1} and R_{G2}. The total retardation R is then

$$R = R_o \pm R_{G1} \pm R_{G2}.$$

By properly selecting the plate voltages we could make,

$$R_1 = R_o + R_{G1} + R_{G2} = 1313\text{m}\mu \ (= \tfrac{5}{2} \times 525\text{m}\mu)$$

$$R_2 = R_o + R_{G1} - R_{G2} = 1138\text{m}\mu \ (= \tfrac{5}{2} \times 455\text{m}\mu)$$

$$R_3 = R_o - R_{G1} - R_{G2} = 975\text{m}\mu \ (= \tfrac{3}{2} \times 650\text{m}\mu).$$

If the angle Ø at which the analyzer is oriented with respect to the polarizer is 90°, then the emerging light is

$$I = I_o \operatorname{Sin}^2 \frac{R\pi}{\lambda_o}.$$

So, green (525mμ), blue (455mμ) and red (650mμ) corresponding to the retardations R_1, R_2 and R_3 may be transmitted. Since $R = t\Delta n$, knowing the required R and Δn we can calculate the plate thicknesses. Solving

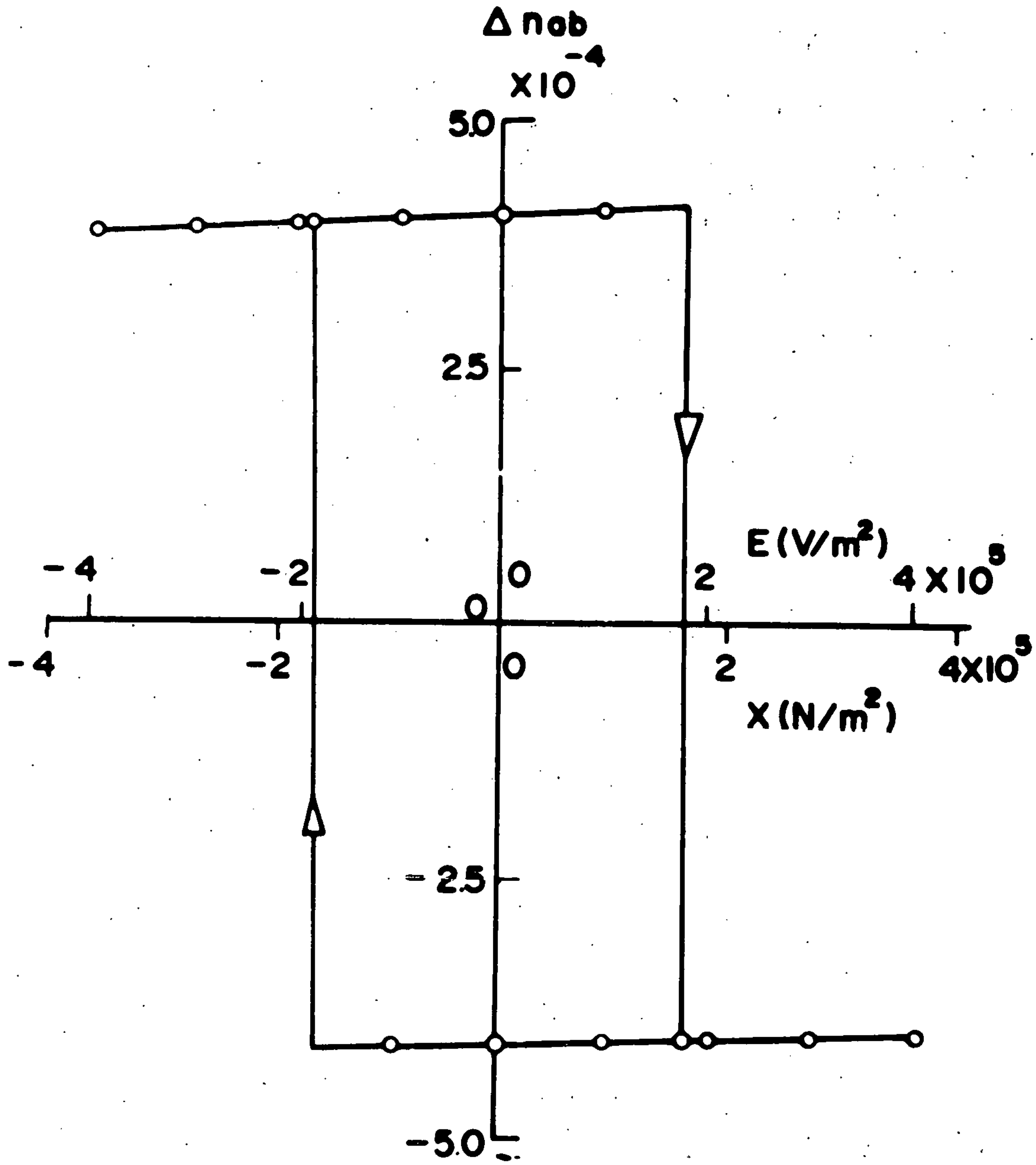


Figure 9.3. Hysteresis Loop for $Gd_2(m_0O_4)_3$

the above equations we find, R_o = 1144mμ, R_{G1} = 195mμ and R_{G2} = 210mμ. Plate thicknesses corresponding to these retardation values are 133μ, 195μ and 210μ. The next section describes such a filter obtained from Hitachi Ltd. of Japan.

9.4 Hitachi Gadolinium Molybdate Color Modulator

The Central Research Laboratory, Hitachi Ltd. of Japan generously donated to us two samples of the Gadolinium Molybdate solid state filter for experimentation and possible application in our system. The cross-section of filter sample No. 1[75] is shown in Figure 9.4. As noted in the previous section, the modulator consists of a polarizer, two $Gd_2(MO_4)_3$ plates whose birefringence is controlled, a retarder plate and an analyzer.

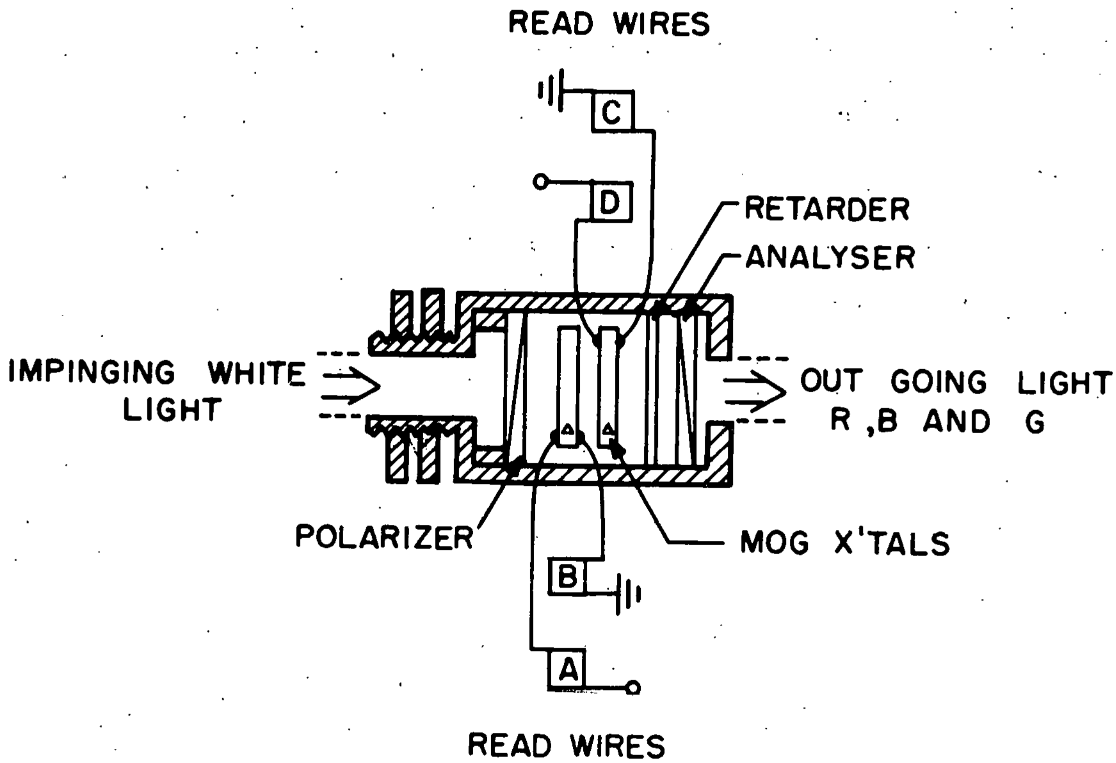


Figure 9.4. Cross-section of MOG Color Modulator

10. SYSTEM PERFORMANCE AND RESULTS

In this section we evaluate the PENTECOST system performance and note some of the experimental results. The specimen color modulators are also evaluated.

10.1 PENTECOST Receiver

The PENTECOST Receiver is shown in Figure 10.1. The high voltage section of the screen voltage switch and the focus voltage switch are housed below the Penetron tube. The CPS high voltage supply is mounted on the rear near the high voltage switch enclosure. It has provision for varying the output voltage from 10KV to 20KV. A voltage of about 17KV is used as the supply voltage for the screen voltage switch. The pattern generator circuits are mounted on a Printed Circuit Board rack just above the Conrac black-and-white monitor. The gain correction circuits and the high voltage switch driver circuits are mounted on another PCB rack below the Conrac monitor. The lower two racks house various low voltage supplies for +5V, +15V, -15V, +75V and -150V. The bottom rack is the focus voltage supply which has provision for varying the output voltage from 0V to 3100V. A voltage of 3KV is used as the supply voltage for the focus voltage switch.

The screen voltage switching circuit was very carefully adjusted and then packaged to achieve freedom from high voltage breakdown and corona effects. There was difficulty in achieving the high voltage switching within the vertical blanking period. Difficulties were also encountered in adjusting the vertical and the horizontal registration circuits. One needs to adjust the magnitude of the deflecting signal to control the

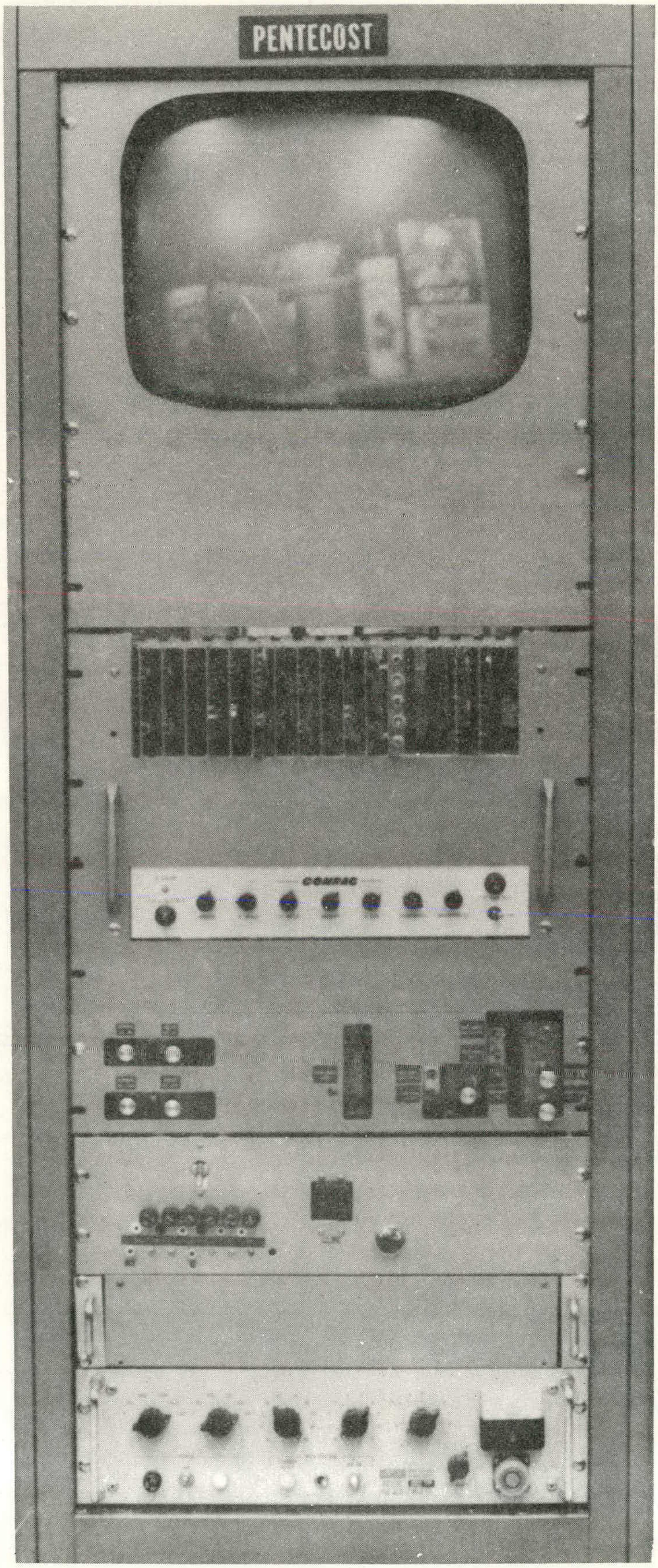


Figure 10.1. Pentecost Receiver

size. But this in turn changes the dc biasing point. A compensating dc voltage was applied every alternate field for proper centering of the red and white displays. Video amplitude switching was necessary for compensating the contrast variation for the two anode voltages, so that flicker is minimum. In addition, the Plumbicon tube has rather poor sensitivity in the red region, and hence the video amplitude needs to be compensated. The waveforms of various receiver signals are shown in Figure 10.2.

PENTECOST Receiver Controls

SCREEN HV UP: Controls the upper limit of the screen voltage corresponding to the excitation of the white phosphor. The screen voltage should be adjusted around 16KV for a white display.

SCREEN HV LOW: Controls the lower limit of the screen voltage corresponding to the excitation of the red phosphor. The screen voltage should be adjusted around 11KV for a red display.

VIDEO GAIN: The screw driver adjustment sets the relative contrast of the red and white fields. By changing the position of the Video Field Indicator switch just below the video gain control, the relative contrast of either the red or the white field can be controlled. In normal circumstances, the red video signal must be increased to compensate for the smaller signal from the Plumbicon camera and also for the decrease in contrast due to the lower screen voltage. The Video switch above the video gain control either routes the video through the video gain correction circuit or bypasses it completely.

FOCUS HV UP: Controls the upper limit of the focus voltage corresponding to the excitation of the white phosphor with screen voltage of 16KV. The upper focus voltage should be adjusted around 2200V.

FOCUS HV LOW: Controls the lower limit of the focus voltage corresponding

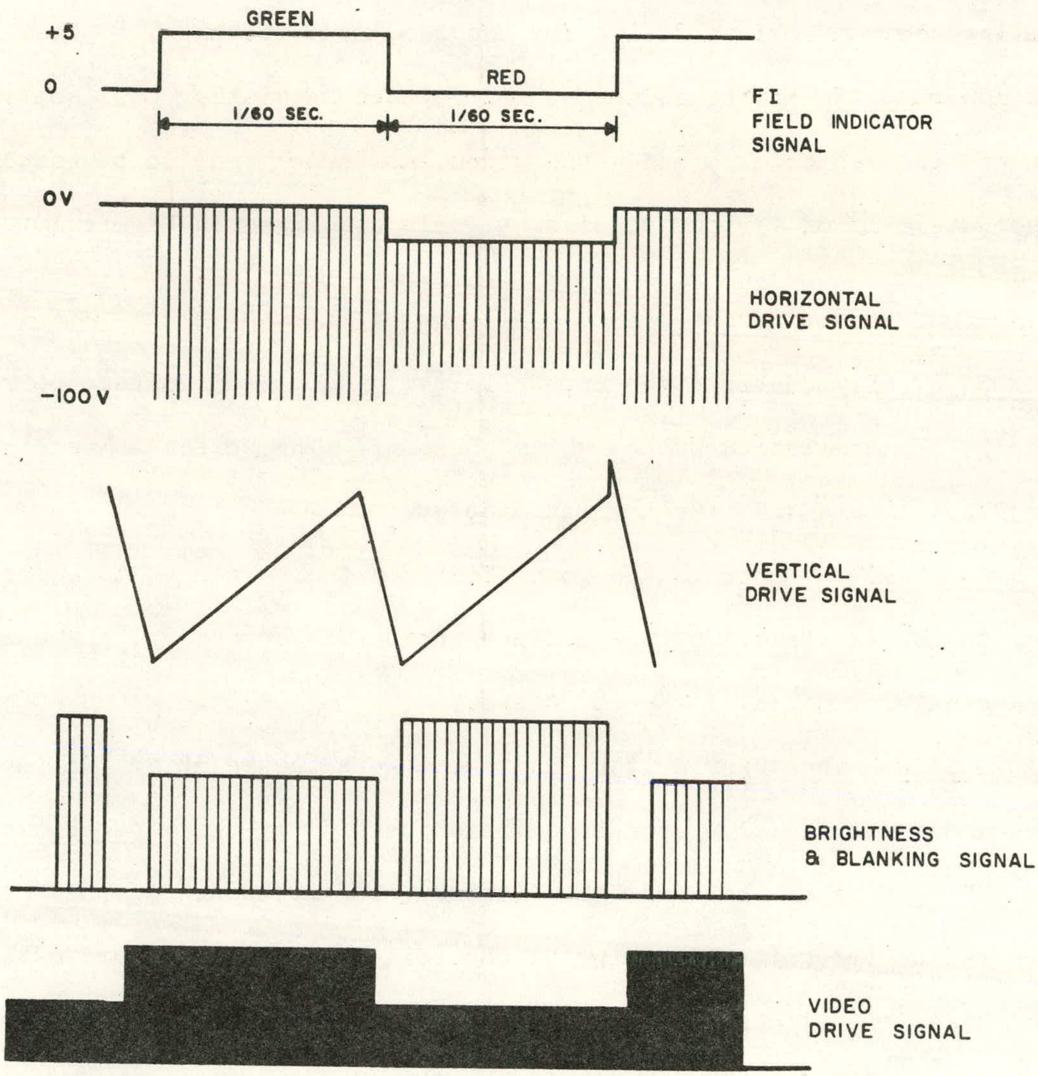


Figure 10.2. Receiver Waveforms

to the excitation of the red phosphor with screen voltage of 11KV. The lower screen voltage should be adjusted around 1500V.

VERTICAL HEIGHT: Controls the height of the red and green fields.

RED VERTICAL GAIN: Controls the vertical size of the red field.

RED VERTICAL CENTERING: Controls in the centering of the red field on the white field by the application of a proper dc correction signal.

BRIGHTNESS FIELD INDICATOR SWITCH: This SPDT switch applies either FI or $\overline{FI}$ to control the relative brightness of the red and white fields. If FI is applied the brightness controls are as indicated below. If FI is applied the red and white controls are exchanged.

BRIGHTNESS RED: This increases the relative brightness of the red field if turned in the CW direction.

BRIGHTNESS WHITE: This increases the relative brightness of the white field if turned in the CCW direction.

BRIGHTNESS SWITCH: This switch applies either the brightness signal derived in the brightness correction circuit or the brightness signal obtained from the Conrac monitor.

CONRAC MONITOR CONTROLS

Most of the Conrac monitor controls are used in conjunction with the PENTECOST Receiver controls. The FOCUS control is not used as a separate high voltage focus supply is used. The focus controls are as described earlier in this section. The BRIGHTNESS and CONTRAST Controls are used along with the PENTECOST Receiver controls to achieve the proper relative brightness and contrast levels. The Conrac monitor controls change both the red and white fields whereas the PENTECOST Receiver controls selectively control the red and white field displays.

It should be recognized that some of the PENTECOST system controls interact with one another. If one adjusts the brightness levels, the screen voltage also changes a little and consequently changes the registration to some extent. Thus, the system parameters should be adjusted for the best performance and left as it is.

10.2 PENTECOST Camera

The picture of the PENTECOST camera is shown in Figure 10.3. The black-and-white camera with the Plumbicon tube and the filter wheel assembly is mounted on a base plate screwed to the tripod. The synchronization and the field indicator circuits are housed in a box mounted below the base plate toward the rear of the camera. The camera system, including the filter wheel assembly and the synchronizing circuits, performs quite reliably. The original vidicon camera did not have any gamma control circuit. The Plumbicon has unity gamma characteristics ($\gamma = \Delta \log V / \Delta \log L$; V = signal, L = Luminance) whereas the cathode ray tube luminance output is proportional to the square of the signal. So the dynamic range of the picture is limited.

The Plumbicon tube is fast enough for this application though there is some carryover from the previous field. This carryover from the previous field tends to mix the red and green camera signals and consequently obscure the Land effect by the percentage of the carryover. The sensitivity of the Plumbicon in the red region is very limited. This reduces the magnitude of the signal when the red filter is in front of the camera. This is compensated at the receiver by switching the amplitude of the video for alternate fields.

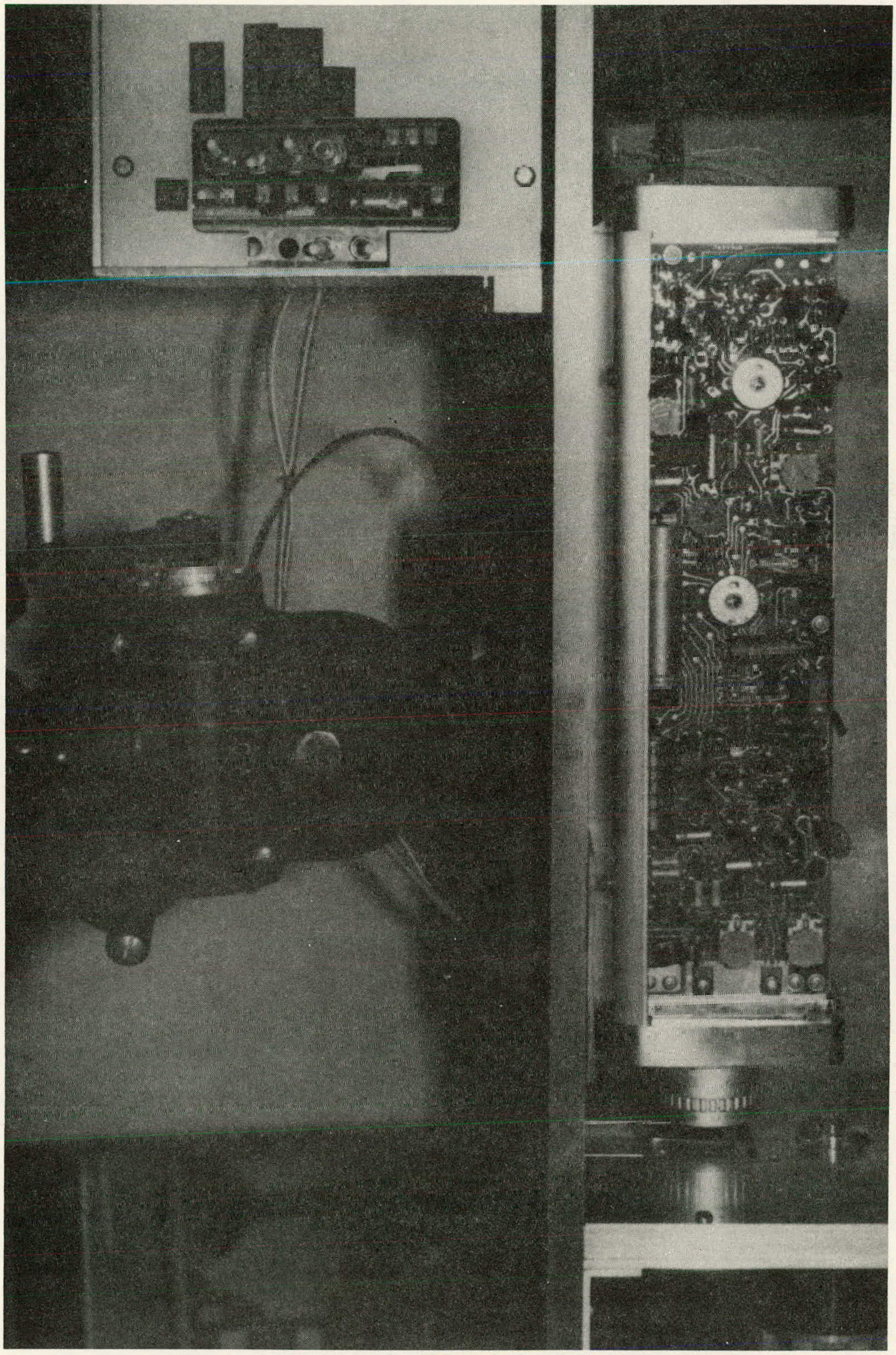


Figure 10.3. Pentecost Camera

There is some halo effect. Total reflection in the glass faceplate of the Plumbicon tube produces an anular brightening of the picture around highlights. The dark current of the Plumbicon is very small. Hence, the noise in the picture is very small even if the video gain is increased to the maximum.

Camera Controls

SYNC ADJUST: Adjusts the synchronization of the camera system with the photodetector signal derived from the position of the filter-wheel.

FILTER SYNC (POWER SYNC): This switch chooses either the sync signal derived from the filter wheel position or the 26 volt AC 60c/s power frequency to synchronize the 2:1 interlace oscillator circuit.

VSBR (CAMERA VSB): This switch chooses either the vertical system blanking derived in the auxiliary synchronization circuit or the one derived in the camera system.

NORMAL (REVERSAL): This switch selects the Field Indicator signal, (FI), or its complement, $\overline{FI}$, to control the receiver switching circuits. In the NORMAL position FI is sent and it displays the camera red field on red phosphor and camera green field on white phosphor. In the REVERSAL position $\overline{FI}$ is sent and it displays the camera red field on the white phosphor and camera green field on the red phosphor. This corresponds to color reversal in the Land color system.

FIELD INDICATOR: This switch selects either the field signal chosen by the NORMAL (REVERSAL) switch or the signal level (+5, or 0) chosen by the SPDT switch above it. By sending either +5V or 0 as the receiver control signal, one displays the picture respectively on the white phosphor or the red phosphor.

10.3 Color Modulator Testing

The color modulators No. 1 and No. 2 were mounted with stands and white light was directed with the help of lenses through the aperture of the modulators. Light coming out of the modulators was projected on a white screen. The driving signals required for the two specimens are shown in Figure 10.4. For static conditions ($\tau > 10$ sec) the value of V is 30V ~ 50V for Modulator No. 1 and 50V ~ 80V for Modulator No. 2. For dynamic switching the amplitude of the signal applied is unrestricted. We apply $\pm$ 50V to Modulator No. 1 and $\pm$ 75V to Modulator No. 2 for d.c. testing. A switching signal of $\pm$ 75V is applied to both the modulators for dynamic switching. The driving circuits are shown in Figure 10.5.

The blue and green colors were fairly good, but the red color obtained was more purple for Modulator No. 1 and yellowish for Modulator No. 2. The transmitted light depends on the angle of incidence. If one looks through the modulator to an incandescent source the color seen is quite dependent on the angle looked at. If a switching signal is applied to Modulator No. 1, one could see the color boundary moving at the transition point. No. 2 was tested for transition between red and green transmittance conditions. An application of a signal of $\pm$ 75V to pin C (A = 75V; B, D = 0V) results in the transmission of either red light or green light. The transition time is in the range of milliseconds. If insufficient time is allowed for the transition from one color to the other, the color remains at a color corresponding to the dc average of the driving voltage.

The specimen filters were not incorporated into the system because of the smallness of their aperture (1cm dia circle) and the consequent need for an optical assembly to match this aperture to the present system.

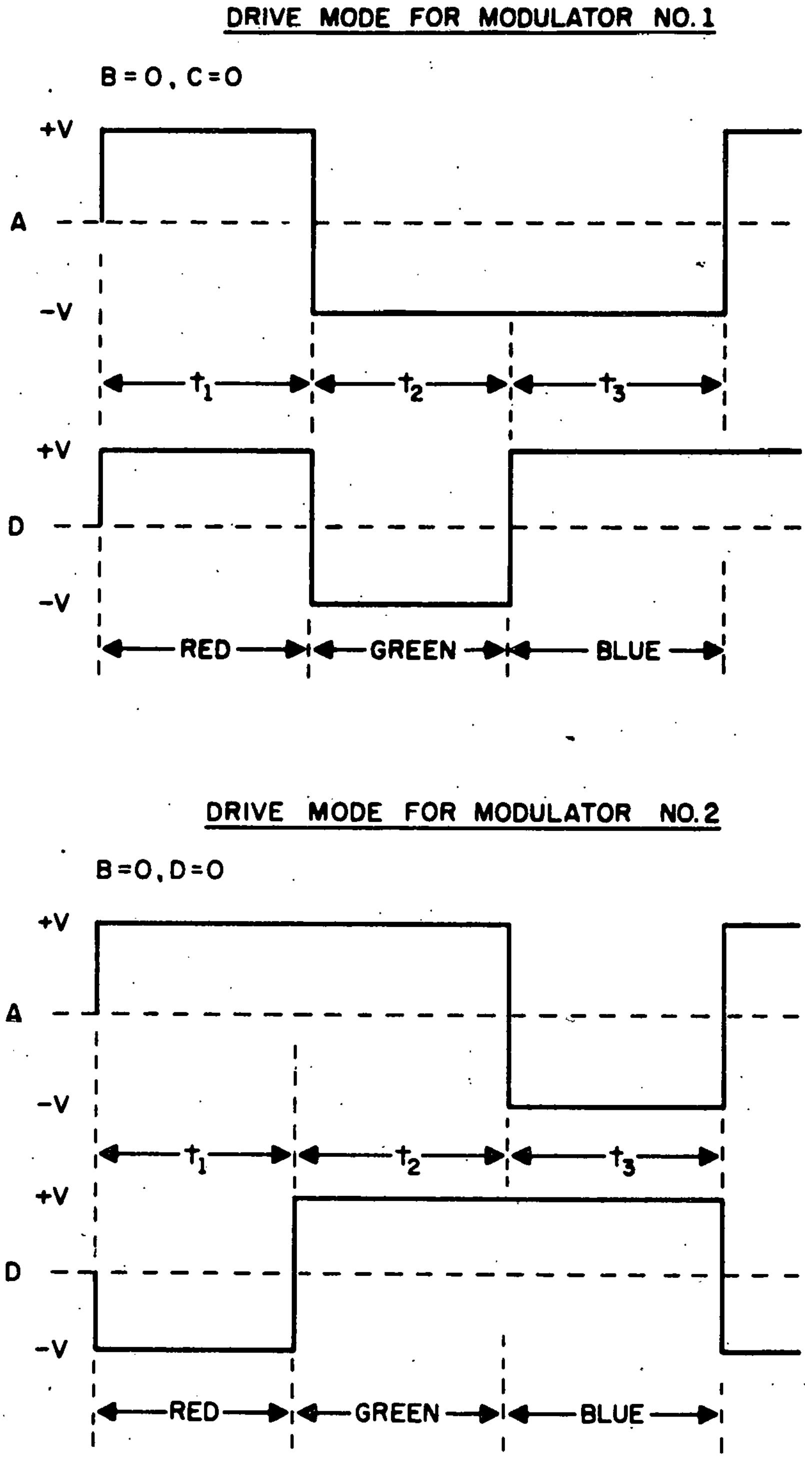


Figure 10.4. Drive Signals for the Color Modulators

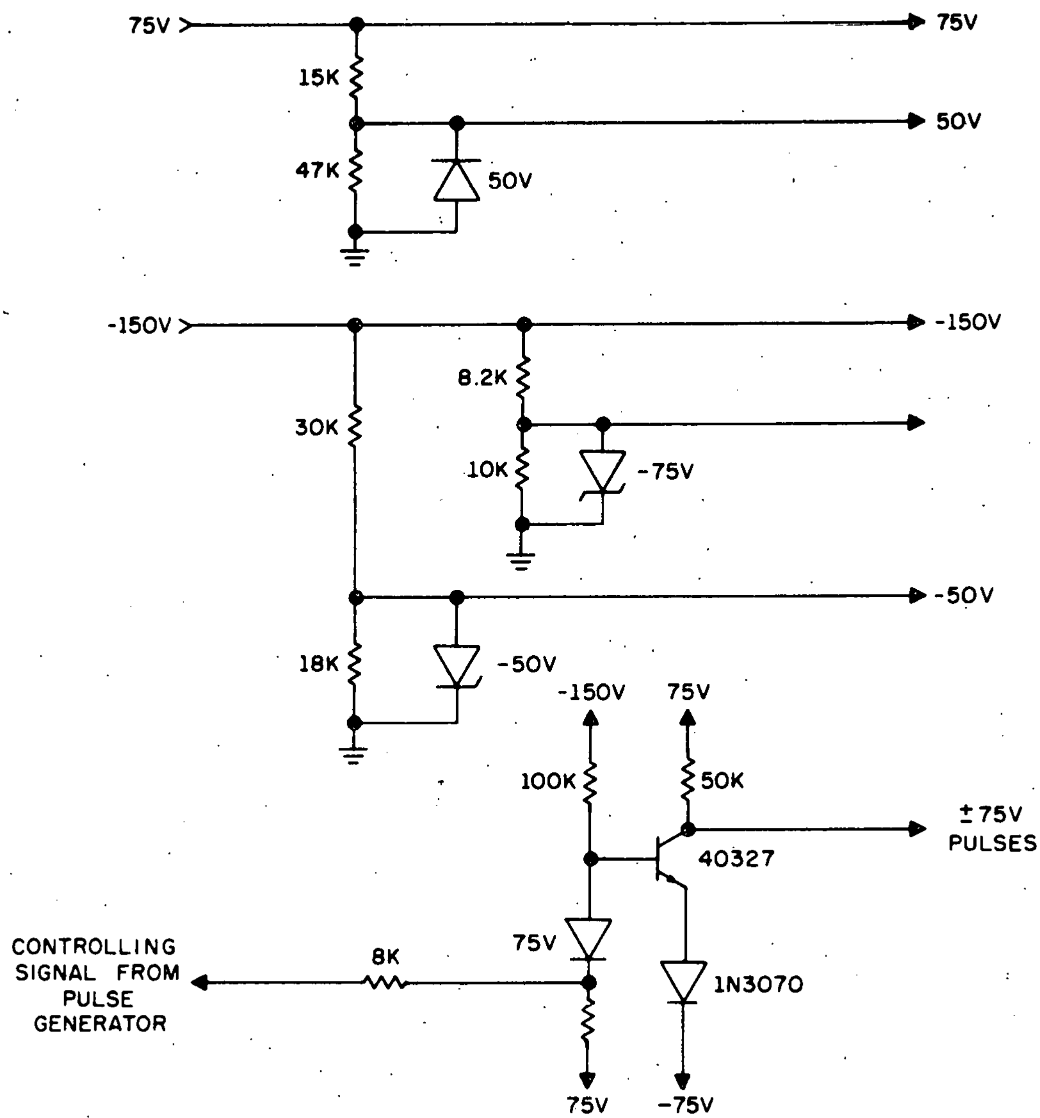


Figure 10.5. Color Modulator Driving Circuits

There will be some loss in the transmission through the optics and the modulator. Since the filter transmission colors (red and green) were fixed and no control over individual colors was provided, there is less flexibility than might be desirable. This is due to the bistable characteristic of the MOG crystal. From this point of view the ferroelectric ceramics offer more flexibility for controling the range of colors. In MOG modulators one needs to have n number of plates to control the color pass band. This decreases the transmission and also necessitates controlling n different plates. Since the ferroelectric ferrostatic modulators are single crystals one expects that modulators of very large aperture will be difficult to make. The ferroelectric ceramic materials should not have this size limitation as they are polycrystalline fine grained materials.

10.4 Land Color Experiments

Various Land experiments were made using the PENTECOST system. The color perceived on the CRT was a strong function of the surrounding illumination near the screen and the illuminating light on the objects and their reflectance. The relative intensity of the two fields had to be adjusted carefully. All of the projection experiments of Section 4.0 were repeated. We observed red, green, and blue colors though the green and blue were not very saturated. The blue perceived was quite grayish and towards the green end of the spectrum. It is extremely difficult to observe yellow. At very low light levels one could see some faint yellow. The color reversal effect was observed by projecting the camera red scene on the white phosphor and the green scene on the red phosphor. One observes blue-green for red objects and magneta for green and blue objects. The blue color was more prevalent in the reverse color display. A neutral density Mondrian kept in front of the camera did not produce significant change in the perceived colors.

Motion in the picture had no detrimental effect. We did not experiment with elaborate moving pictures because of the lack of a proper synchronizing interface with a commerical color TV. However, slightly moving objects were introduced into the scene and they did not obscure the color perceived. Masking different areas of the scene tended to decrease the degree of the Land effect but was not so pronounced as to completely eliminate the effect. The Land effect becomes enhanced when one adapts to the picture. This is particularly true when one knows the colors of the objects. The Land phenomenon is a large field effect where various psychophysical factors interplay. However, it was observed that a decrease in the field size did not degrade the colors too any extent. By using a 4 x 4 checker board pattern, one could observe colors such as green and blue in addition to red by properly adjusting the relative intensity. The color perceived deteriorated for a color grid pattern of 16 x 16. It appeared to be a matrix of different gray squares under these circumstances. For this reason, the pattern display system designed for implementing the 16 x 16 pattern was not employed. There was no means for correlating the color perceived on the screen to real object colors when the pseudorandom patterns were used.

One could not optimize all of the parameters to perceive all the colors equally well. If one adjusted the parameters to get the best yellow effect, the green, blue and red were degraded. In an adaptive Land system, each spatial region must be independently controlled in order to get the best color effect.

Summerizing, the Land color display system provides a fast and flexible tool for conducting various Land two-color experiments but the degree of Land effect is usually less than in the projection set-up. This decrease in the effect is due to non-ideal electronic devices and the need to match the camera and receiver characteristics closely.

11. CONCLUSION

The PENTECOST Land color display system described affords a very convenient set-up for conducting various experiments in two-primary color perception. The receiver spectral characteristics can be controlled to certain degree. If the ferroelectric ferroelastic or the ferroceramic filter is employed, one could electrically control the exact filtering characteristic for the two fields. A good two-color display must employ an optimum choice for the filters, and the receiver characteristics.

The system performance can be improved by incorporating a gamma control to increase the dynamic range. One could also consider a silicon matrix tube for such an application since during the last two years they have been improved to avoid the occurance of black spots. They have a lag response similar to Plumbicons but their sensitivity and spectral characteristics are much better. Their spectral response extends all the way to the far infra-red region.

The Penetron tube is certainly a viable display media but the switching and registration problems still make it troublesome to adjust. The multigun Penetron and the current sensitive multilayer CRT might alleviate some of these problems, though they, too, introduce their own peculiar problems. Penetron color tubes are being increasingly used in information display systems, such as, air-traffic control displays, computer driven displays and computer graphics. In addition to its simple and rugged construction, some important features like the availability of high resolution, freedom from stray magnetic fields, and the insensitivity to shock and vibration make it a very powerful device for information display purposes. The ones most widely used are the red-green and red-white two-layered Penetrons. A red-white Penetron display could produce monochrome pictures in addition to displaying alphanumeric information. One could also employ Land techniques to produce color pictures on such a system. Since low saturation colors abound in information systems, we would have less trouble in reproducing these by Land techniques.

The receiver characteristics, the camera filtering properties, and the relative brightness and contrast levels of the fields should be automatically adjusted to achieve the best Land color effect for widely different scenes. In addition, the camera and receiver characteristics should be spatially optimized so that one may obtain the best color reproduction possible in all regions. This, of course, increases the complexity of the system but this is the way our visual system works--it adapts its capabilities and characteristics to suit different conditions.

Some thorough psychological experiments are required to take care of the difference in observer characteristics. The results can be compared with the results derived from applying the Helson-Judd formulation. It appears that color constancy and the Helson-Judd formulation in fact don't answer all the interesting questions arising from Land effect. We are still far from understanding the visual system and work should be pursued vigorously in this field.

APPENDIX A

CATHODE RAY TUBE SELECTION

Different possible schemes for implementing the receiver of the two-color TV system are described below. A cost comparison of the different schemes is made. Anticipated technical difficulties are noted.

1. Single-gun Penetron: Voltage switching of the beam is employed to change the color. Saturated colors are difficult to obtain. The manufacturers of the Penetron, along with the price and the characteristics of their products are listed below in Table 1.

2. Two-gun Penetron: The main problem with the single gun penetron tube is switching the anode voltage. A multiple gun CRT with the guns held at different potentials obviates the requirement for voltage switching. A partial deflection-yoke-shielding technique on the lower-voltage guns is used to automatically compensate for the increased deflection sensitivity.

The potential suppliers are:

a. Zenith Radio Corporation, Rauland Division (16" flat tube, 12 - 18KV anode voltage, delivery time = 90 - 120 days, price = $1600.00)

b. RCA (in development stage).

Focus voltage switching circuits, video gain change and brightness correction circuits will be, of course, required in this scheme.

3. Current Sensitive Single-gun color CRT: By combining a superlinear phosphor of one color with a linear or sublinear phosphor of a different emission color, a phosphor screen can be obtained which changes color as a function of current density. Two problem

TABLE 1. Comparison of Single-gun Penetrons

a. RCA

	Name	CRT size	Defl. Angle	Sealing	High V	Focus V	Line W.	Luminance		Cost
(1)	Development type C24092	12" dia	70°	with bonded implosion shield 37% transmission	11KV (Red) 16KV (White)	1860-2400V	10 mil	15 fL (Red)	30 fL (White)	$ 225
(2)	Development type	14" dia	70°	supplied with filter glass face plates 66% transmission	"	"	11 mil	24 fL	48 fL	$ 300
(3)	"	17" dia	70°	"	"	"	12.5 mil	21 fL	42 fL	$ 350

Red/Green, Red/White (CIE illuminant C) and Red/White (CIE illuminant A) combination of phosphors also available.
Delivery time: 30 days for all of them.

b. Sylvania

	Name	CRT size	Defl. Angle	Sealing	High V	Focus V	Line W.	Luminance		Cost
(1)	SC4899	8" dia	90°	gray filter glass face plate, 60% transmission	6KV (Red) 12KV (White)	-100 $\pm$400 Volt.	20 mil	4 fL (Red)	50 fL (White)	$ 262
(2)	SC4876	21" dia	72°	gray filter glass face plate, 76% transmission	"	"	25 mil		"	

c. Thomas Electronics

	Name	CRT size	Defl. Angle	Sealing	High V	Focus V	Line W.	Luminance		Cost
(1)	17M19PT322M	17" dia	70°	gray filter glass face plates, 76% transmission	9KV (Red) 17KV (Green)	-100 +400	18 mil	15 fL (Red)	120 fL (Green)	$ 400

d. Electro Vision Industries

	Name	CRT size	Defl. Angle	Sealing	High V	Focus V	Line W.	Luminance		Cost
(1)		17" dia			9KV 18KV					$2500

areas of the present current-sensitive tubes are limited color gamut and simultaneous variation of brightness with color shift. A combination of current-sensitive and voltage-sensitive screen is possible. The manufacturers are:

a. Special Purpose Tube Company: (delivery time--2-4 months, price = $5,000.00)

b. Raytheon (under development).

4. <u>Chromatron CRT</u>: The display screen consists of a series of vertical phosphor strips; in our case, alternating strips of white and red phosphors. Since most of the electrons from the gun impinge on the phosphor screen (unlike the shadow mask tube) the grid type tubes display high brightness color information. Two distinct grid types are used in such color tubes: A 'switching grid' and a non-switching type known as a 'post-focus grid.' 'Switching grid' types employ one electron gun. Depending upon what relative potential is employed between the grid wires, the electron beam is made to converge on either of the two phosphor strips. In 'post focus grid' type color discrimination is achieved by the angle of incidence of the individual electron beams (from two electron guns) with the plane of the post-focus grid. The different chromatron tubes in the market are described below.

a. Electro Vision Industries:

(1) 2-color, 17" dia, price = $5,000, delivery time = 3 months.

(2) 2-color, 12" dia, price = $3,500, delivery time = 3 months.

b. Thomas Electronics:

(1) 2-color, 17" dia, price = $1,000, delivery time = 4 months or longer.

5. Multicolor Storage Tubes: A change in electron landing-energy or viewing screen potential of several kilovolts (10KV and 12KV for red and green) will alter the light output of some phosphors from red to green. In phase with this voltage change and resultant color shift, the backing electrode is varied over a range of one volt. This cycle is repeated at 30 cycles per second.
Hughes Aircraft produces this kind of storage tube. But the price is high. The receiver system must be completely built or a monitor system must be purchased which employs this kind of tube.
6. Entertainment Type Shadow Mask CRT System: Some experiments have already been done with this type of arrangement.[76] Two film tracks corresponding to monochrome pictures through the red and green filters are made. One of the film tracks is used to control all three color channels equally so that a simple black and white picture was produced from it. The signal from the other film track was then added to one of the three color channels (say, red). Mr. Hughs concluded that 'every phenomenon observed with the projected slides was observed with the color television system, although it was more difficult to get saturated colors on television.' This scheme is a simultaneous color system whereas all the previous schemes were field-sequential systems (chromatron CRT and current-sensitive CRT can be adapted for dot-sequential method too).

In Japan they have utilized the color signals from a conventional color TV receiver to check Land's predictions.

One can use just the red and green signals in a color receiver to see the Land phenomena.

Since the objective of the project is to make not simply a two-color TV system but a high resolution two-color TV system (with resolution as good as monochrome tubes), it did not seem appropriate to employ a shadowmask tube in the final project. The chromatron tubes also suffers from this deficiency (though to a lesser extent).

Conclusion: It is apparent from cost comparison that the Penetron is the cheapest of all the available two-color CRT's. Two-color display systems with Penetron tubes have been successfully employed for alpha-neumeric displays. It was hoped that it would work for the Television application. At the present time the anode voltage switching can be accomplished for field-sequential systems. The only objection to the penetron scheme is the need for voltage switching--and the associated correction circuits.

A 'two-gun penetron' or a single-gun current-sensitive' screen would remove some of the difficulties encountered with the 'single gun penetron' scheme. But at the present time they are still in development stage and their delivery time may be quite long. They are also expensive.

APPENDIX B

CAMERA SYSTEM SELECTION

The different forms of camera systems considered are:

1. SEC (Secondary Electron Conduction)
2. Plumbicon
3. Vidicon
4. Silicon matrix

For our system we have the requirements that the camera should have very low lag so that it can be used for a field-sequential system.

1. SEC Camera System

The essential mechanism responsible for this is the secondary electron conduction process: One hundred times multiplication of photo-electrons incident on a special dielectric target.

SEC Tube Characteristics

Target gain: Optimum target potential 10-20 volts for a good target gain of around 100. Target gain varies with primary energy of the photoelectrons for a constant target potential (maxm. value at ~ 8 Kev.).

Transfer Curves: Operation from 10^{-5} to 10^{-2} lumen of illumination. Gamma is close to unity.

Lag: The lag signal is only 5% of the 1st field signal after 50 ms. and is due only to discharge lag.

Sensitivity: ∿ 15,000 μA/lumen

Storage Capacity: Can be good. It is desirable to have a large storage capacitance as long as discharge lag is avoided.

Integration:	Long integration times possible for static, low-light level scenes.
Resolution:	Because of the high resistivity of the target it seems likely that its intrinsic resolution capability will be limited by electron scattering rather than by leakage. Resolution of $3 - 4 \times 10^3$ lines/inch should be possible.
Halation:	Bloom and halation absent.
Additional Char:	Rugged, low power requirements.

SEC Market Possibilities

a. Westinghouse

1.	STV - 706A	Single Piece SEC camera including burn resistant tube with lens.	$ 9,875.00
*2.	STV - 606	2-piece SEC including WL30691 (burn resistant) less lens (25mm SEC tube) (lag 10%), Resolution 500 lines	11,900.00
3.	STV - 609	2-piece SEC including class 2 WL30654 (40mm tube) less lense	14,000.00

* STV - 309H (1" vidicon) or STV - 314H (plumbicon) can be used in STV - 606 with minor modification.

b. CBS Labs

Minicam	Field sequential camera system using SEC 180 fields with lens and tube	$19,500
	For 2-color 120 fields/sec modification cost	5,000
	Total	$24,500

2. Plumbicon Cameras

The Plumbicon is a camera tube of the vidicon type which utilizes a layer of lead oxide (PbO) for the photosensitive target instead of the more usual photoconducting layer of Sb_2S_3.

In the Plumbicon the lead oxide layer acts as a p-i-n diode. The n-region is formed at the PbO - SnO_2 interface. The p-region is a thin layer on the electron gun side of the layer. The bulk of the material behaves as if it is intrinsic. The p-i-n layer is biased in reverse direction.

Characteristics:

Negligibly low dark current.

Temperature independence of dark current.

Unity gamma

Very fast response.

Lag: In the vidicon, lag is mainly due to emptying of carriers from traps which exist in large numbers in the bulk of the photoconductive layer. In the Plumbicon traps only play a minor role. Instead, the time response is generally limited by capacitance of the layer and the effective resistance of the electron beam.

Spectral Sensitivity:

Because of 1.9 ev bandgap of PbO the absorption edge occurs at about 6500°A and the absorption coefficient increases only slowly through the visible region of the spectrum.

Phillips has recently introduced a tube by doping the normal PbO layer with sulfur to form a PbO - S layer--which has a higher absorption coefficient for longer wavelengths.

Disadvantages of Plumbicon

1. The sensitivity is independent of target voltage so that control of signal current at a given light level, usually an excessively bright level, must be controlled by either reducing the face plate illumination by, say, a remote control iris or, if the signal current is not beam-current-limited, by adjusting the gain of one of the video amplifier stages.

2. The unity gamma of the layer makes it difficult to handle a wide range of light levels, more than, e.g., several hundred to one.

3. The resolution of rather thin PbO layer is limited to values of 700 - 800 TV lines.

4. The PbO layer is not airstable and is therefore difficult to manufacture.

5. Spectral response curve is limited in standard Plumbicons.

Plumbicon Camera Market Study

a.	Phillips	LDH 0150/01	Multipurpose Vidicon/Plumbicon Camera 1 inch, 525 line, separate mesh wired, less tube	$ 895
		LDH 0160/02	Multipurpose control unit, Rack mtg. 525 line, less sync. generator	1685
		LDH	Multipurpose sync. generator module, 525 line, 2:1 interlace	220
			Sub-total	$2800
			Tube (CCTV 111, or 16Q)	850
			Total	$3650
b.	Phillips	LDH 0151/01	Plumbicon Camera, 1 1/4" 525 lines, less tube std. mesh wired	$1090
		LDH 0160/02	Camera Control	1685
		LDH 4300/10	Sync generator	220
			Total	$2995

			Tube X Q 1021, 55875, X Q 1024, CCTV101 (30mm)	\$ 850
c.	COHU		3207 Plumbicon Camera with CCTV 101	
			2484-750 dual Camera control	
d.	Westinghouse	STV-711	Single piece Plumbicon camera including Tube and 50mm F/1.8 lens	\$4995
e.	Colorado Video	501/A	with CCTV 111	\$2500

3. Vidicon

Most of the vidicon cameras can accept 1" Plumbicon tube with additional \$1000 for the cost of the tube. All vidicon tubes have 25-40% lag and hence, cannot be advantageously used for our field-sequential system.

The different products considered in this category were from manufacturers like MTI, Cohu, Phillips, Westinghouse, and G. E.

4. Silicon Matrix

Silicon Matrix tubes have an array of Silicon diodes that act as the sensing element. These tubes have many advantages:

Over Sb_2S_3 vidicon tubes: High sensitivity, broad spectral response, low lag, good resolution.

Over Plumbicon: Sensitivity, spectral response and resolution.

In lag characteristics they are slightly inferior to Plumbicons.

The market search revealed the following candidates in this category.

a.	Amperex	S10XQA	Silicon Vidicon Camera tube 10% lag after 50 m.s., electrically interchangeable with any separate mesh 1" vidicon
b.	RCA	C23136 Development type	Silicon diode array, 8% lag 200nA signal

Conclusion

At this time it looks as though a camera system using a Plumbicon tube is about the best that we can have considering the cost and the present state of technology. SEC's don't have better lag characteristics than a Plumbicon--they are rugged and have better versatility in sensitivity range. We rule out SEC system because of price considerations--though CBS lab has developed a field sequential color system employing these tubes for the Apollo program.

A 1" tube should be used since most of the developments and research is concentrated on 1" tube. If we buy a 1" tube we can use it for vidicon, plumbicon or silicon matrix tube (with modifications). Silicon matrix tubes are still in development stages. Though they have better resolution and spectral sensitivity than the Plumbicon, they don't have better lag characteristics.

With the Plumbicon the resolution is limited to about 700 lines which is adequate for our use. The red sensitivity of standard Plumbicon is limited to 6500°A. So we will have less red output.

The Phillips camera system (1" type) seems to be the most versatile. The camera system has dual outputs--it means we can also use this camera control for a dual camera system. We can use vidicon or Plumbicon for a dual camera system using dichroic mirrors. So it will be convenient to buy this vidicon/Plumbicon camera.

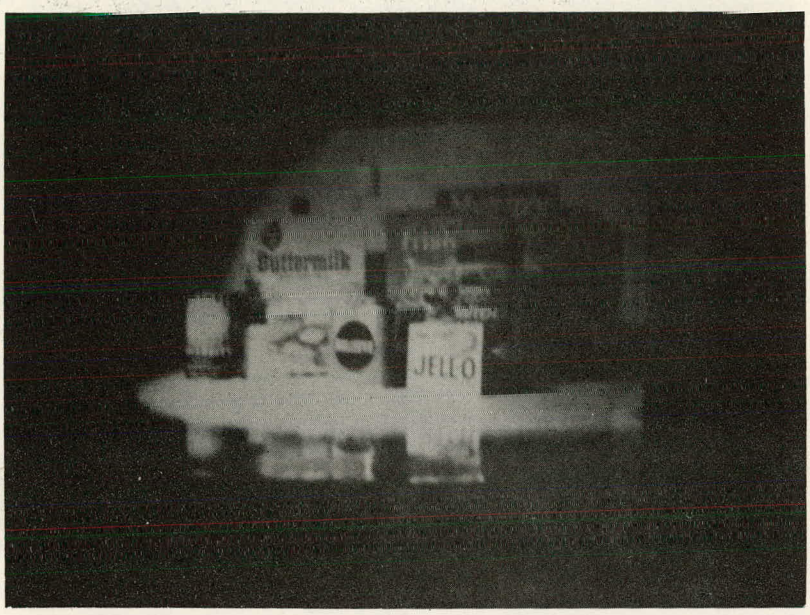
Addendum: Because of financial considerations, the GE fully contained vidicon camera system was purchased and the vidicon was replaced with an Amperex Plumbicon tube with some modifications.

APPENDIX C

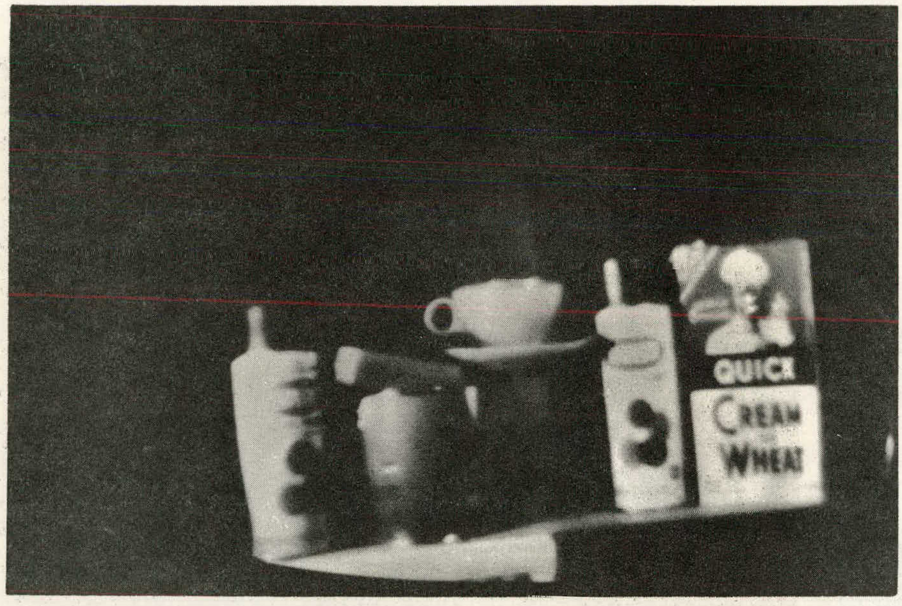
LAND SLIDES AND PHOTOGRAPHS

C.1 Land Black and White Transparency (Longwave Record)

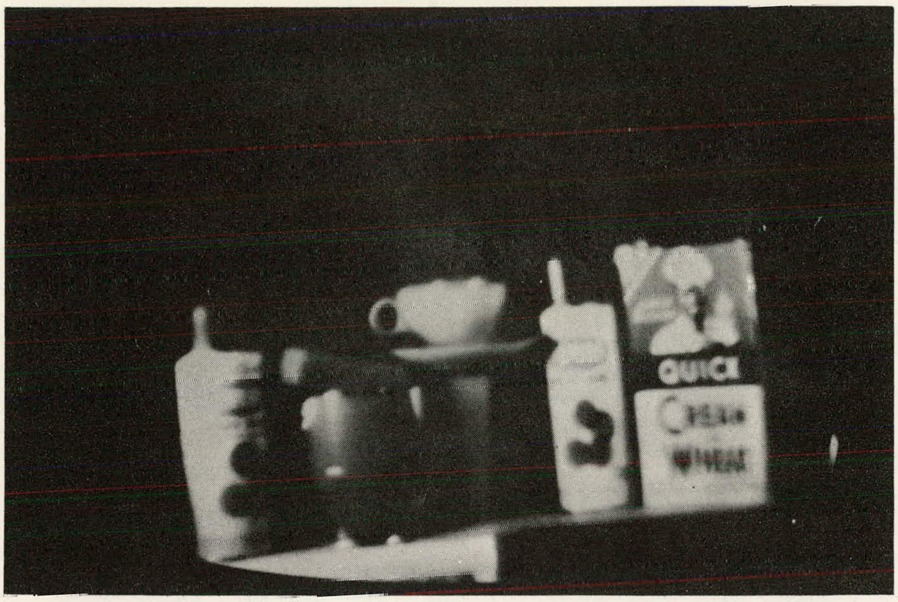
C.2 Land Black and White Transparency (Shortwave Record)



C.3 Land Color Projection of Longwave and Shortwave Records



C.4 Land Color PENTECOST Display



C.5 Land Color PENTECOST Display (Color Reversal)

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In September 1968, he joined the University of Illinois, Urbana as a University of Illinois Fellow in Electrical Engineering and continued in that position until September 1970. He did research on MOS (Metal-Oxide-Semiconductor) Devices in the Solid State Electronics Laboratory and received his M.S. in Electrical Engineering in June 1970. In September 1970, he joined the Computer Hardware and Systems Research Group presently called the Information Engineering Laboratory under Professor W. J. Poppelbaum. He was a Teaching Assistant in the Department of Electrical Engineering from September 1970 to June 1971. He worked the summer of 1971 as a Research Assistant in the Computing Centre of the Department of Psychology. Since September 1971 he has held a Research Assistantship in the Department of Computer Science and has continued to work under Professor W. J. Poppelbaum towards a Ph.D. degree.

He is the author of a paper on Metal-Oxide-Semiconductor Devices in the Electronics Letters, IEE London and the co-author of a paper on the Numerical Solution of Poisson's Equation in Semiconductor Devices in the Journal of Applied Physics. He is a member of the Computers Group and the Electronic Devices Group of IEEE.

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Professor and Principal Investigator

Organization

Department of Computer Science
University of Illinois
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15. Supplementary Notes

16. Abstracts

This work examines the human color vision mechanism in light of Dr. E. H. Land's two-color experiments on color vision. The problem of color perception in machines is looked into. Some of the two-color experiments are described. But the main emphasis has been on the building of a two-color television display system based on the two-color projection experiments.

17. Key Words and Document Analysis. 17a. Descriptors

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17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

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