Section 5

COLOR-TELEVISION FACILITIES

INTRODUCTION TO SECTION 5

This section of the handbook has been reproduced through the courtesy of the Radio Corporation of America who kindly permitted us to use portions of their "Color Television, Manual for Technical Training."

Obviously, the material contained herein is not a complete treatment of the subject but covers only the aspects which are considered to be of fundamental importance to an understanding of the system. Further reference to the RCA "Manual for Technical Training," as well as such publications as "Color Television Engineering," by John W. Wentworth, Manager, Television Terminal Engineering, RCA Engineering Products Division, and other worthy treatises on the subject, is recommended.

In view of the deletion of certain portions of the reference material, minor editorial changes have been made to provide continuity.

Part 1

COLOR FUNDAMENTALS

Color is a new dimension that has been added skillfully to black-and-white television. To the engineering fraternity as a whole it signifies one of the most dramatic technological achievements of this age.

Nearly every branch of science including chemistry and psychology contributes in some way to the reality of color television. Through chemistry, improved phosphors are continually being found for use in color-picture tubes. Psychology enters into the selection of lighting arrangements and picture composition to obtain desirable interpretations by the viewer. But physics plays the leading role with intense application in optics and illumination as well as in the design of electronic circuitry and components for the complete television system.

Two specialized branches of physics, namely, radio and television engineering, are responsible for the electronic techniques which make color television "compatible" with black-and-white, or monochrome, television, marking what is probably the greatest technical advance in television in the past decade.

COMPATIBILITY

The compatible color system offers tremendous economic advantages to the home viewer as well as to the television broadcaster. Because of compatibility, color telecasts can be seen (in monochrome) on existing television receivers without any changes or added devices. Also, color receivers can receive monochrome as well as color telecasts. Since compatible color is transmitted over the same channels as monochrome and within the same framework of standards, the television broadcaster can utilize his monochrome system as the transmitting nucleus when installing equipment to broadcast color. Moreover, he can utilize his color equipment to produce monochrome telecasts.

Another important advantage of the compatible color system is the part it plays in the conservation of the radio-frequency spectrum. Compatible color requires no additional space in the spectrum. However, it employs techniques which make much more efficient use of the standards originally set up for monochrome television.

A brief review of the fundamentals of monochrome television, particularly the areas wherein specialized color methods are employed, is presented in the next few paragraphs as an aid in describing the basic color concepts.[1]

TELEVISION—A SYSTEM OF COMMUNICATIONS

Basically, television is a system of communications consisting of the television station at one end of the system and the television receiver at the other. As such, it is actually one of the highest capacity systems in use today, being able to transmit from station to receiver more than five million "bits" of picture information every second.

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[1] For detailed information on the theory and operation of monochrome television broadcast equipment, reference should be made to the RCA "Manual for Television Technical Training," Form No. 2J 8172.

Very simply, the function of the television station is to divide and subdivide the optical image into over 200,000 picture elements, each of different light intensity; convert these light elements to electrical equivalents; and transmit them in orderly sequence over a radio-frequency carrier to the television receiver.

Reversing this process at the receiver, these electrical signals are each converted to light of corresponding brightness and reassembled to produce the transmitted image on the face of the picture tube.

Scanning

Picture elements to be transmitted in sequence are selected by a process of image scanning which takes place in the television camera focused on the studio scene at the station. Within the camera, an electron beam in a pickup tube scans a sensitive surface containing an "electrical image" of the scene of action. The electron beam successively scans the image at great velocity, beginning at the upper left corner and continuing from left to right in a series of parallel lines to scan the image completely. Movement of the electron beam, which is controlled magnetically by vertical- and horizontal-deflection coils surrounding the tube, is analogous to that of the eye in reading a printed page. The speed of movement is such, however, that 30 complete image frames of approximately 500 lines each are scanned every second. Of course,

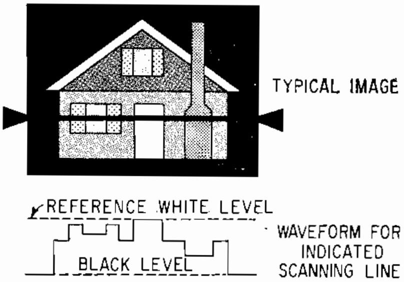

FIG. 1-1. Typical image and camera output waveform produced by light and dark areas during one scan along line indicated by arrows.

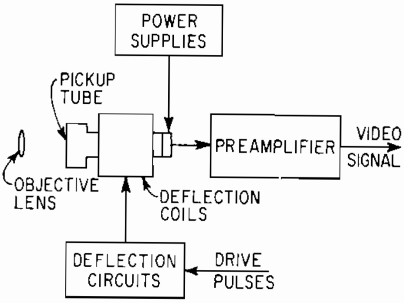

FIG. 1-2. Block diagram of monochrome-camera circuits.

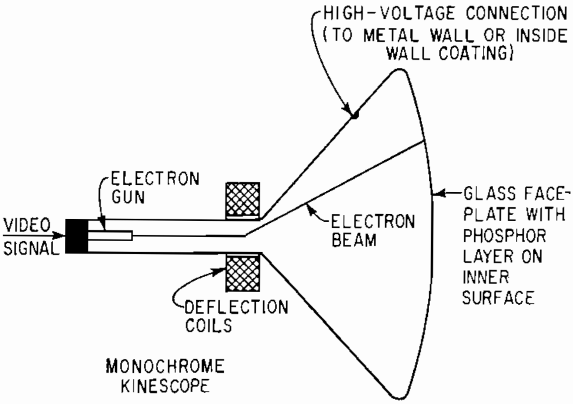

FIG. 1-3. Diagram showing principal elements of the monochrome kinescope picture tube.

at the receiver, an electron beam in the kinescope, or picture tube, moves with the same speed and in synchronism with the camera-tube beam so that the corresponding picture elements appear in the proper relative position on the television screen.

Owing to "persistence of vision" and the speed of scanning, these elements appear to be seen all at once as a complete image rather than individually. Thus, the impression is one of continuous illumination of the screen and direct vision.

Scanning standards have been established in this country to assure that all television receivers are capable of receiving programs broadcast by any television station within range. The scanning pattern adhered to by manufacturers in the design of television receivers and broadcast equipment consists of 525 lines with odd-line interlaced scanning. Interlaced scanning, effective in eliminating perceptible flicker, is a method whereby the electron beam scans alternate rather than successive lines.

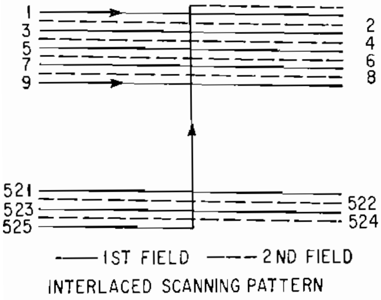

FIG. 1-4. Diagram showing paths of the electron beam in both the pickup tube and kinescope to produce the interlaced scanning pattern.

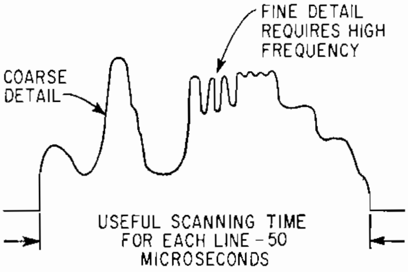

FIG. 1-5. Diagram illustrating the relationship between picture detail and signal bandwidth.

For example, the beam begins by scanning the odd-numbered lines (1, 3, 5, 7, etc.) until it reaches the bottom of the image, whereupon it returns to the top of the image to scan the even-numbered lines (2, 4, 6, 8, etc.). Thus, each scan, or field, comprises only half the total number of scanning lines, and two fields are required to produce the 525-line frame. Each field is completed in one-half the frame time. The vertical scanning frequency is 2 × 30 or 60 cps, and the horizontal scanning frequency is 30 × 525, or 15,750 cps.

Resolution and Bandwidth

The degree of resolution, or fine detail, that can be seen in a televised image depends upon the number of scanning lines used and the bandwidth of the transmitting and receiving system.

The relationship between resolution and bandwidth can be seen by considering the number of picture elements that can be transmitted each second.

The standard 6-Mc broadcast channel provides a video bandwidth of approximately 4.1 Mc (the remaining bandwidth being required for a vestigial sideband plus the sound signal). Since each cycle of a sine wave is capable of conveying two picture elements (one black and one white), the maximum rate at which picture elements can be transmitted is 4,100,000 × 2, or 8,200,000 per second. Since 30 complete frames are transmitted per second, the number of picture elements per frame would be 8,200,000 ÷ 30, or 273,333, if it were not for the retrace blanking problem, which requires interruption of the picture signal periodically by blanking pulses. Since the combination of horizontal and vertical blanking pulses requires nominally 25 per cent of the total time, the maximum number of picture elements per frame is reduced in practice to 0.75 × 273,333, or approximately 205,000.

Synchronizing

In addition to the picture information, or video signals, blanking and synchronizing signals are transmitted by the television station to control the intensity and movement of the scanning beam in the kinescope of the television receiver. Both these signals are in the form of rectangular pulses. Moreover, their polarity and amplitude are such that they are received as "black" signals and therefore do not appear on the receiver screen.

Blanking pulses eliminate the "retrace" lines which would otherwise appear between scanning lines and at the end of each field from the bottom of the picture to the top. Horizontal blanking pulses, transmitted at the end of each line, or at intervals of 1/15,750 sec, blank the beam during retrace periods between lines. Vertical blanking pulses, transmitted at the end of each field, or at intervals of $\frac{1}{60}$ sec, blank the beam during the time required for its return to the top of the picture. Because the vertical retrace is much slower than the horizontal, the vertical blanking periods are longer than the horizontal blanking periods. Vertical blanking pulses are about 20 lines duration, while horizontal blanking pulses have a duration of only a fraction of a line.

Synchronizing signals keep the scanning beam of the kinescope in step with that of the camera tube. These signals consist of horizontal and vertical pulses which are transmitted within the respective blanking periods. Although the sync pulses are of the same polarity as the blanking pulses, they are of greater amplitude ("blacker than black") and thus easily separated in the receiver and fed to the deflection circuits of the kinescope.

Since the vertical sync pulses are quite long compared with the horizontal sync pulses and the two are of the same amplitude, separation at the receiver is accomplished through frequency discrimination. Serrations, or slots in the vertical pulses, prevent loss of horizontal sync during the vertical blanking period.

THE MONOCHROME-TELEVISION SYSTEM

The major equipment in a typical television station consists of the aural and visual units illustrated in the block diagram of Fig. 1-6. In the visual channel, the video signal leaving the camera is passed through processing equipment which inserts the

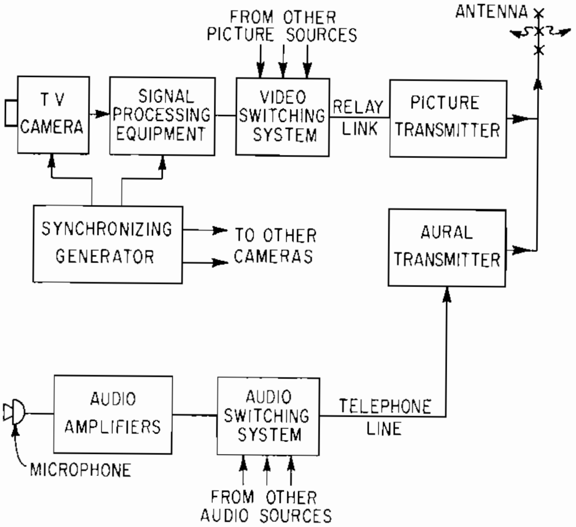

FIG. 1-6. Simplified block diagram of the monochrome-television station.

blanking and synchronizing signals and performs other functions such as aperture compensation and gamma correction. From the processing chain, the video signal is fed to a switching system which provides for selection from a number of video sources. The selected signal is then sent to the visual transmitter through coaxial cable or over a microwave relay link, depending upon the distance between the television studio and transmitter. In the transmitter, the composite video signal amplitude-modulates a carrier in the VHF or UHF range, which is radiated by the television antenna.

In the aural channel, the audio signal is fed from the microphone or other sound source through the switching system and to the aural transmitter. Frequency-modulated output from the aural transmitter is combined with the visual output and radiated from the same antenna.

The Radiated Picture Signal

Amplitude relationships between the synchronizing pulses and the tonal gradations from white to black in the picture are represented in the waveform of the radiated picture signal. From the illustration, it can be seen that modulation takes place in such a way that an increase in the brightness of the picture causes a decrease in carrier output power. Note that the reference-white line indicated on the sketch is relatively close to zero carrier level. Also, the synchronizing pulses are in the "blacker than black" region, representing maximum carrier power. Use of a widely different range of amplitude for the sync pulses makes it possible for home receivers to separate them by a simple clipping technique.

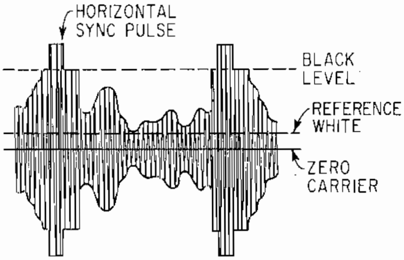

Fig. 1-7. Waveform and radiated picture signal.

Receiver

The basic elements of the television receiving system are illustrated in the block diagram of the television receiver. The radiated television signal is picked up by an antenna and fed to a tuner which selects the desired channel for viewing. Output from the tuner is passed through an intermediate-frequency amplifier which provides the major selectivity and voltage gain for the receiver. A second detector then recovers a video signal which is essentially the same as that fed to the visual transmitter.

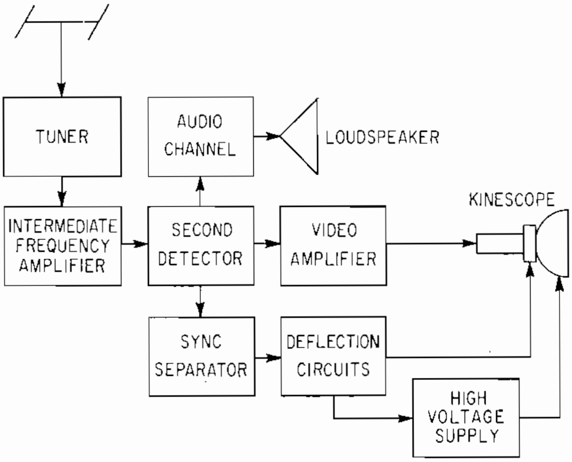

Fig. 1-8. Block diagram of monochrome-television receiver.

The sound signal is usually taken off at the picture second detector in the form of a frequency-modulated beat between the picture and sound carriers. The sound signal is further amplified in a special IF stage, detected by a discriminator or ratio detector, and applied to the speaker through an audio amplifier.

Picture output from the second detector is fed to two independent channels. One of these is the video amplifier which drives the electron beam in the kinescope, and the other is the sync separator, or clipper, which separates the sync pulses from the picture information. The separated pulses are then used to control the timing of the horizontal and vertical deflection circuits. The high-voltage supply, which is closely associated with the horizontal deflection circuit, provides accelerating potential for the electron beam.

THE THREE VARIABLES OF COLOR

Color is the combination of those properties of light which control the visual sensations known as brightness, hue, and saturation. Brightness is that characteristic of a color which enables it to be placed in a scale ranging from black to white or from dark to light. Hue, the second variable of a color, is that characteristic which enables a color to be described as red, yellow, blue, or green. Saturation refers to the extent to which a color departs from white, or the "neutral" condition. Pale colors, or pastels, are low in saturation, while strong or vivid colors are high in saturation.

The monochrome system is limited to the transmission of images that vary with respect to brightness alone. Thus, brightness is the only attribute of a color that can be transmitted over a monochrome-television system. To produce a color image, therefore, provision must be made for the transmission of additional information pertaining to all three of the variables of color. However, since the primary-color process can be employed, it is not necessary to transmit information in exactly the form expressed by the three variables.

Primary Colors in Television

Experiments have proved conclusively that virtually any color can be matched by the proper combination of no more than three primary colors. While other colors could be used as primaries, red, green, and blue have been selected as the most practical for color-television use. A few of the many colors that can be made by mixing lights of red, green, and blue are illustrated in Fig. 1-9. Red and green combined produce yellow, red plus blue gives purple, and green plus blue gives cyan or blue-green. The proper combination of all three of the primary colors produces white, or neutral, as shown at the center of the illustration. By relatively simple optical means, it is possible to separate any color image into red, green, and blue, or RGB, components, as shown by Fig. 1-10.

Generating RGB Signals

Major components of the color-television camera are shown in block-diagram form in Fig. 1-11. Whereas the monochrome camera contains only one pickup tube, the color camera contains three separate pickup tubes mounted in three separate deflection-coil assemblies. An objective lens at the front of the camera forms a real image within a condenser lens which is located where the pickup tube is usually mounted in a mononchrome camera. A relay lens transfers this real image to a system of dichroic mirrors which shunt the red and blue light to the red and blue pickup tubes and permit the green to pass straight through to the green tube. In this manner, the three pickup tubes produce three separate images corresponding to the RGB components of the original scene. These images are scanned in the conventional manner by common deflection circuits.

A single scanning line through the typical color image at the point shown (Fig. 2-6) produces three separate waveforms. It is important to note the correlation be-

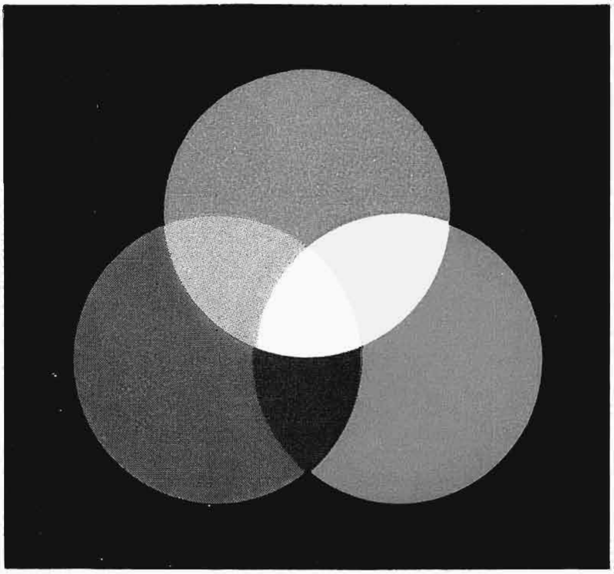

FIG. 1-9. The primary colors of television are red, green, and blue. Virtually any color can be matched by combining proper amounts of these primaries. White is produced by a combination of all three.

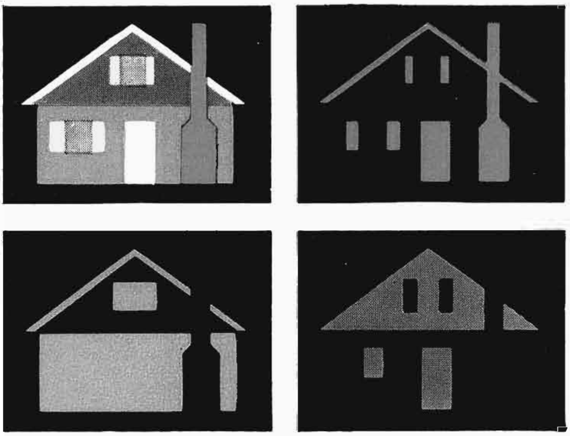

FIG. 1-10. Illustrating how a typical color image (upper left corner) can be separated by optical means into red, green, and blue counterparts.

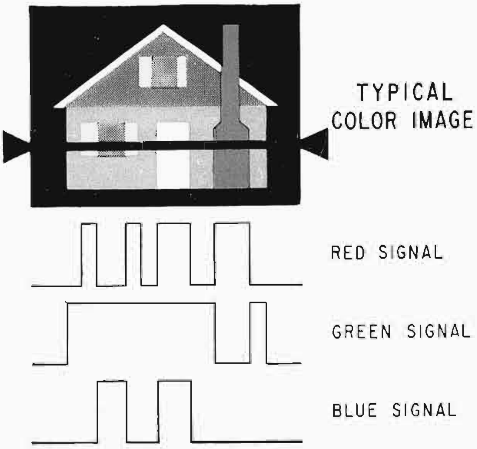

FIG. 2-6. Typical color image and RGB waveforms.

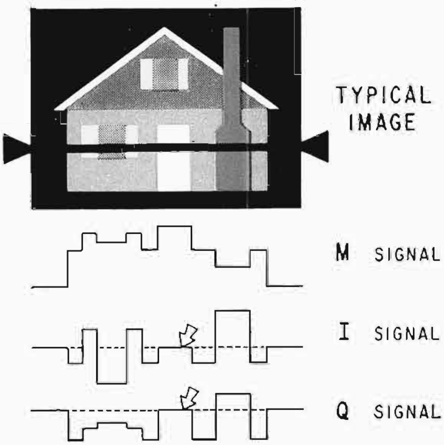

FIG. 2-7. Typical color image and MIQ waveforms.

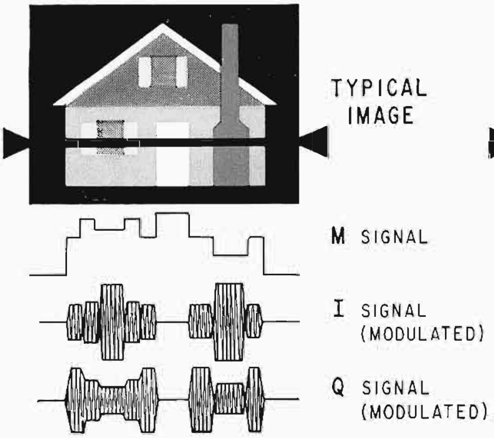

FIG. 2-15. Typical color image and waveforms of the M signal and modulated I and Q signals.

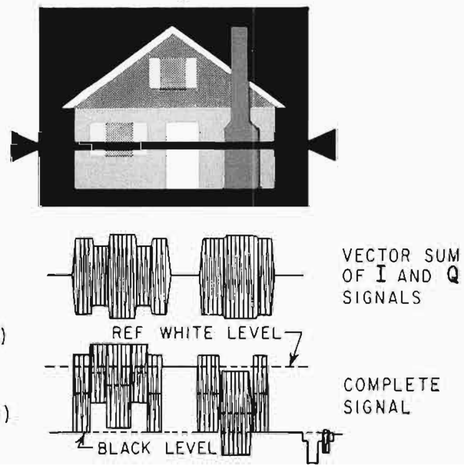

FIG. 2-16. Typical color image with vector sum of I and Q signals together with composite waveform produced by adding all signal components.

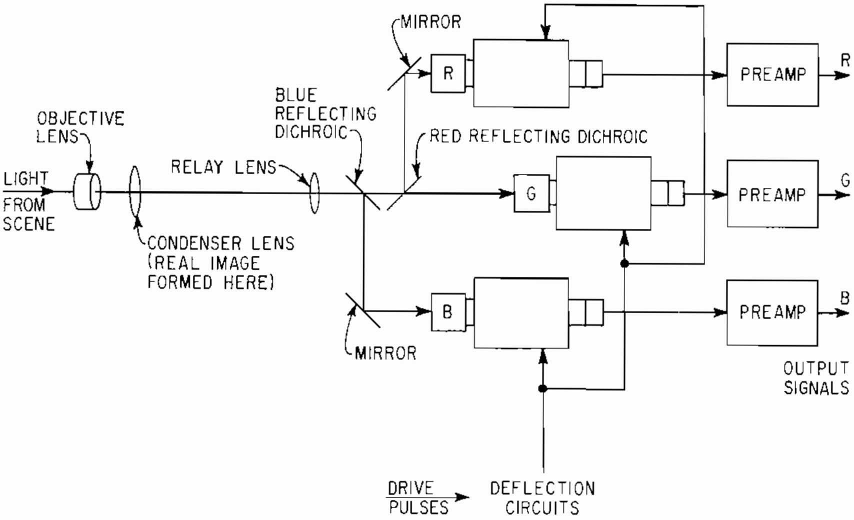

Fig. 1-11. Simplified block diagram of the optical and electrical components of the color camera.

tween these waveforms and the image at the top. The yellow shutters in the image, for example, must be produced by a mixture of red and green, and the blue signal is not required. Thus, at this interval of scanning, the red and green signals are both at full value and the blue signal is at zero. The white door utilizes all three color signals. Of course, similar correlations can be seen for other parts of the image along the scanning line.

Displaying RGB Signals

RGB signals are displayed in color by the tricolor kinescope, the basic components of which are shown in the diagram of Fig. 1-12. Three electron guns produce three beams which are independently controlled in intensity by the red, green, and blue signals. These three beams are all made to scan in unison by deflection coils around the neck of the tube. The three beams converge at the screen owing to the magnetic field produced by a convergence yoke.

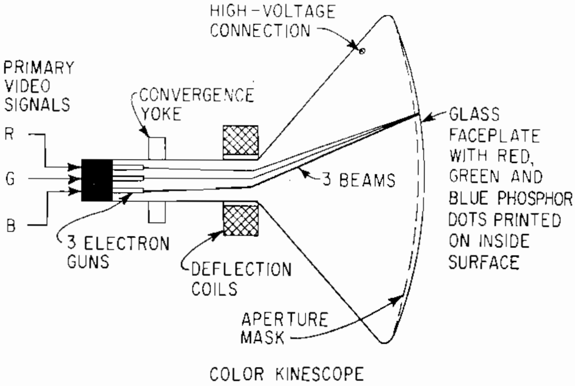

Fig. 1-12. Diagram showing components of the three-gun kinescope picture tube.

The phosphor screen of the color kinescope consists of an array of very small primary-color dots. Approximately ½ in. behind the phosphor screen is an aperture mask which has one very small opening for each group of red, green, and blue phosphors. Alignment of this aperture mask and screen is such that each beam is permitted to strike phosphor dots of only one color. For example, all the electrons emitted by the red gun must strike red phosphor dots on the aperture mask; they cannot strike either the green or blue dots because of the "shadow" effect of the mask. Likewise, the beams emanating from the other two guns strike only green or blue dots.

In this way, three separate primary-color images are produced on the screen of the tricolor tube. But since these images are formed by closely intermingled dots too small to be resolved at the normal viewing distance, the observer sees a full-color image of the scene being televised.

Part 2

ELECTRONIC ASPECTS OF COMPATIBLE COLOR TELEVISION

To achieve compatibility with monochrome television, color-television signals must be processed in such a way that they can be transmitted through the same channels used for monochrome signals, and they must also be capable of producing good monochrome pictures on monochrome receivers. Since color television involves three variables in contrast to the single variable (i.e., brightness) of monochrome television, an encoding process is required to permit all three to be transmitted over the one available channel. Likewise, a decoding process is required in the color receiver to recover the independent RGB signals for control of the electron guns in the color kinescope. Moreover, the process used must enable existing monochrome receivers to produce a monochrome picture from the color information.

Encoding and decoding processes used in compatible color television are based on four electronic techniques known as matrixing, band shaping, two-phase modulation, and frequency interlace. It is these processes which make the color system compatible with monochrome and enable the color system to occupy the existing 6-Mc channel.

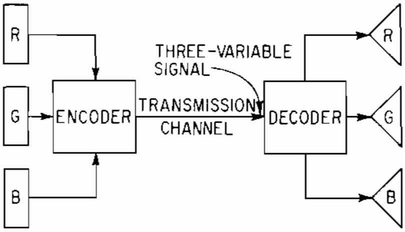

FIG. 2-1. Encoding of the RGB signals provides a three-variable signal which can be transmitted over existing monochrome channels.

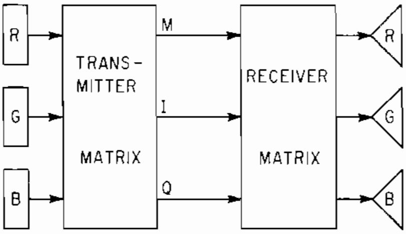

FIG. 2-2. A part of the encoding process is the matrixing of R, G, and B signals to provide M, I, and Q signals.

MATRIXING

Matrixing is a process for "repackaging" the information contained in the red, green, and blue output signals from a color camera to permit more efficient use of the transmission channel. The matrix circuits which perform this function consist of simple linear cross-mixing circuits. They produce these signals, commonly designated M, I, and Q, each of which is a different linear combination of the original red, green, and blue signals. Specific values for these signals have been established by FCC standards.

The M-signal component, or *luminance* signal, corresponds very closely to the signal produced by a monochrome camera, and therefore is capable of rendering excellent service to monochrome receivers. The M component is obtained by combining red, green, and blue signals in a simple resistor network (Fig. 2-3) designed to produce a signal consisting of 30 per cent red, 59 per cent green, and 11 per cent blue.

The I and Q signals are *chrominance* signals which convey information as to how the colors in the scene differ from the monochrome, or "neutral," condition. The component I is defined as a signal consisting of 60 per cent red, −28 per cent green, and −32 per cent blue. Minus values are easily achieved in the matrix circuits by use of phase inverters to reverse the signal polarity (see Figs. 2-4 and 2-5). The Q signal is defined as 21 per cent red, −52 per cent green, and 31 per cent blue.

It can be seen that the quantities are related so that when red, green, and blue are equal, corresponding to a neutral condition, both I and Q go to zero. Thus, when the color camera is focused on an object having no color information, such as a monochrome test chart, the I- and Q-signal components are absent, leaving only the M component, or monochrome signal.

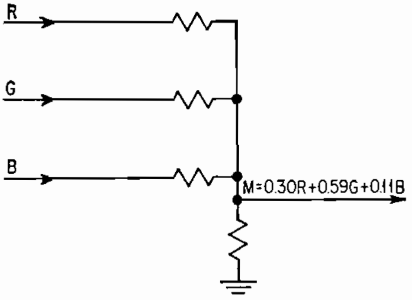

Fig. 2-3. Diagram of resistance matrix circuit used to produce the M luminance signal.

The matrix circuits, therefore, produce a new set of waveforms corresponding to the M, I, and Q components of the image. A comparison of the MIQ and RGB waveforms (Figs. 2-6 and 2-7[*]) obtained from the image illustrates the correlation among the types of signals. It will be seen that the M signal remains in the region between black level and reference white. It is identical with the monochrome signal derived from the monochrome version of the image. The I and Q signals, on the other hand, swing positive and negative around a zero axis.

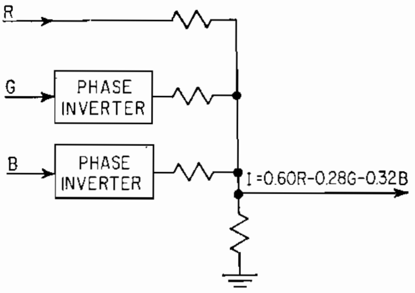

Fig. 2-4. Diagram of I matrix showing phase inverters to produce minus green and blue quantities.

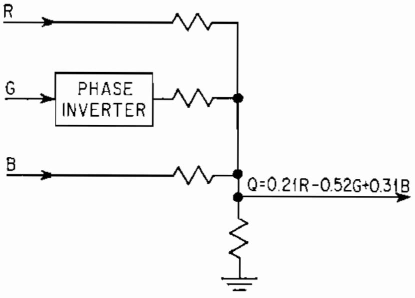

Fig. 2-5. Diagram of the Q matrix showing phase inverter to produce required minus green signal.

BAND SHAPING

The eye has substantially less acuity in detecting variations in color than it has for resolving differences in brightness. This important characteristic of human vision was considered in setting up the I and Q equations because it permitted a significant reduction in the bandwidth of these signals through use of low-pass filters. A bandwidth of approximately 1.5 Mc was found to be satisfactory for the I signal, which corresponds to color differences in the range extending from orange to blue green. For color differences in the range from green to purple, as represented by the Q signal, the eye has even less acuity and the bandwidth was restricted to only 0.5 Mc. The M-signal component, which conveys the fine details, must be transmitted with the standard 4-Mc bandwidth.

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[*] For Figs. 2-6 and 2-7 see the illustrations in color between pages 5-8 and 5-9.

TWO-PHASE MODULATION—GENERATION OF COLOR SUBCARRIER

Two-phase modulation is a technique by which the I and Q signals can be combined into a two-variable signal for transmission over a single channel. This is accomplished by adding the sidebands obtained through modulation of two 3.6-Mc carriers separated in phase by 90°. The resultant waveform is the vector sum of the components. Elements of the transmitting and receiving system are shown in Fig. 2-8. The two carriers, which are derived from the same oscillator, are suppressed by the balanced modulators. Thus, only the two amplitude-modulated sidebands, 90° out of phase, are transmitted. At the receiving end of the system, the I and Q signals are recovered by heterodyning the two-phase wave against two locally generated carriers of the same frequency but with a 90° phase separation and applying the resultant signals through low-pass filters to the matrix circuits. Typical signal waveforms are illustrated in Fig. 2-9.

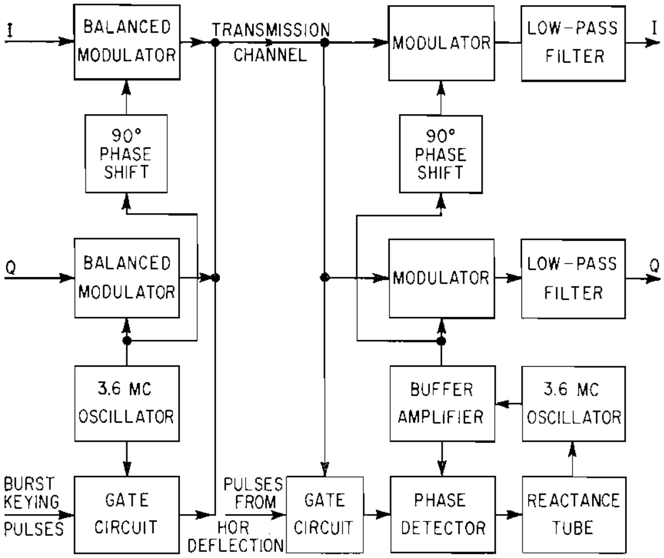

Fig. 2-8. Simplified block diagram showing elements for transmitting and receiving the I, Q, and burst signals.

The 3.6-Mc oscillator at the receiver must be accurately synchronized in frequency and in phase with the master oscillator at the transmitter. The synchronizing information consists of 3.6-Mc "bursts" of at least 8-cycle duration transmitted during the "back-porch" interval following each horizontal sync pulse. The bursts are generated at the transmitter by a gating circuit which is turned "on" by burst keying pulses derived from the synchronizing generator. At the receiver, the two-phase modulated signal is applied to another gating circuit, known as a burst separator, which is keyed "on" by pulses derived from the horizontal deflection circuit. The separated bursts are compared in a phase detector with the output of the local 3.6-Mc oscillator. Any error voltage developed is applied through a smoothing filter to a conventional reactance tube which corrects the phase of the local oscillator.

FCC Standard phase relationships between the I and Q signals and the color synchronizing burst are shown in the vector diagram of Fig. 2-11. The I and Q signals are transmitted in phase quadrature, and the color burst is transmitted with an arbitrary 57° phase lead over the I signal.

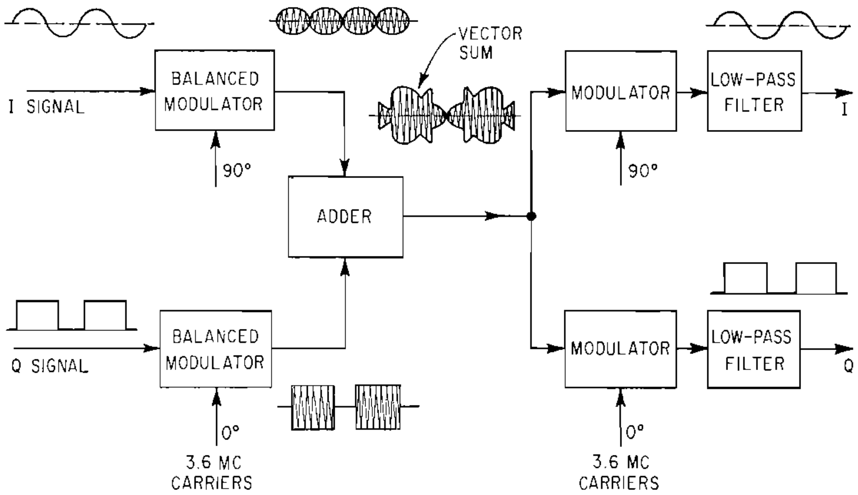

Fig. 2-9. Representative waveforms of the separate I and Q signals and the vector sum of the suppressed carrier sidebands at the modulator output. Original I and Q signals are recovered by heterodyning in balanced modulators at receiver.

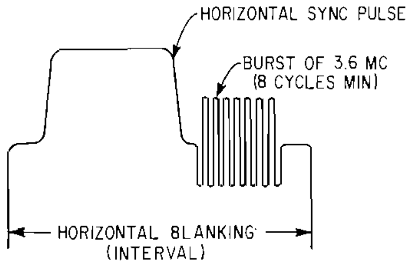

Fig. 2-10. Diagram showing position of subcarrier burst during horizontal blanking interval.

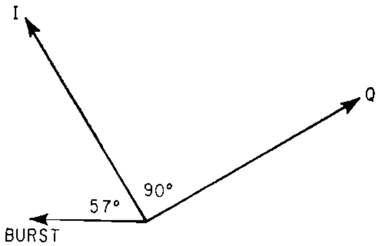

Fig. 2-11. Diagram showing phase relationship of I, Q, and burst signals.

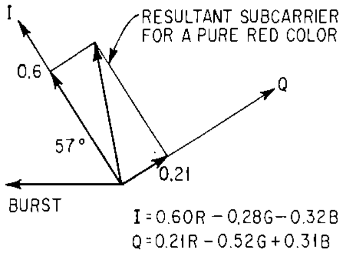

Fig. 2-12. Vector diagram showing phase and amplitude of subcarrier for a pure red signal.

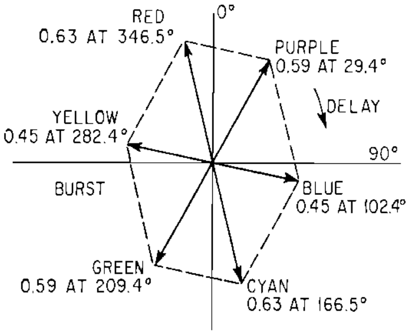

Fig. 2-13. Composite vector diagram showing subcarrier phase and amplitude for each of six colors.

Several interesting properties of the two-phase modulated signal are illustrated by the vector diagrams which represent the resultant signal under known transmission conditions. For example, when a pure red color of maximum amplitude is being transmitted, the green and blue components are at zero and the I and Q signals have levels of 60 and 21 per cent, respectively. When modulated upon their respective carrier, these signals produce the resultant shown in Fig. 2-12. The phase and amplitude shown are characteristic of pure red of maximum relative luminance. Figure 2-13 is a composite vector diagram showing the phase and amplitude characteristics of all three primaries and their 1-to-1 mixtures. This composite diagram indicates that there is a direct relationship between the *phase* of the resultant two-phase modulated signal and the *hue* of the color being transmitted. There is also a relationship (although indirect) between the *amplitude* of the resultant signal and the saturation of the color being transmitted. If the phase of the resultant subcarrier and the level of the monochrome signal both remain constant, then a reduction in the amplitude of the subcarrier indicates a decrease in color saturation. The composite vector diagram also shows an interesting symmetry between complementary colors (colors are complementary if they produce a neutral when added together); the resultants for any two complementary colors are equal in amplitude but opposite in phase.

FREQUENCY INTERLACE

Since the 3.6-Mc carriers, consisting of the I and Q sidebands, fall within the video passband as shown in the diagram of the television channel (Fig. 2-14), they become subcarriers and can be handled in many respects like unmodulated video signals. By use of *frequency interlace* it is possible to add the several components of the chrominance and monochrome signals together without causing objectionable mutual interference.

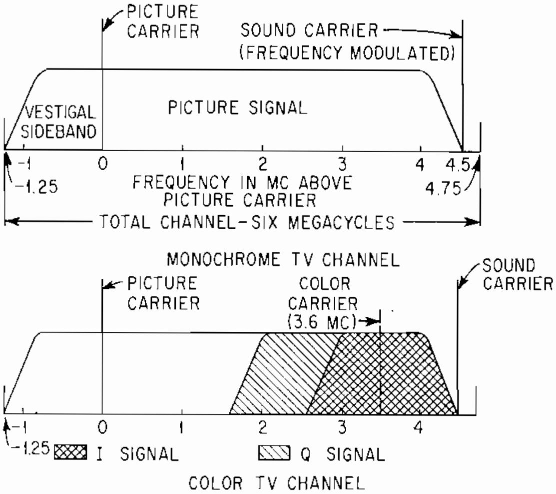

FIG. 2-14. Diagram of television channel showing portions occupied by color and monochrome signal components.

The significance of the straightforward addition of signal components made possible by frequency interlace may be brought out by a study of waveforms derived from a simple color image. Figure 2-15 shows M, I, and Q signals after the latter two have been modulated upon 3.6-Mc subcarriers. Note that both the I- and Q-signal components are at zero during the scanning of the white door, a neutral area. Figure 2-16 * shows the vector sum of the I and Q signals and also the complete compatible

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* For Figs. 2-15 and 2-16 see the illustrations in color between pages 5-8 and 5-9.

color signal formed by adding together all the components, including synchronizing pulses and color-synchronizing bursts. The most significant fact about this signal is that it is still capable of providing good service to monochrome receivers, even though a modulated wave has been added to the monochrome-signal component. Although the modulated wave is clearly a spurious signal with respect to the operation of the kinescope in a monochrome receiver, its interference effects are not objectionable because of the application of the frequency-interlace principle.

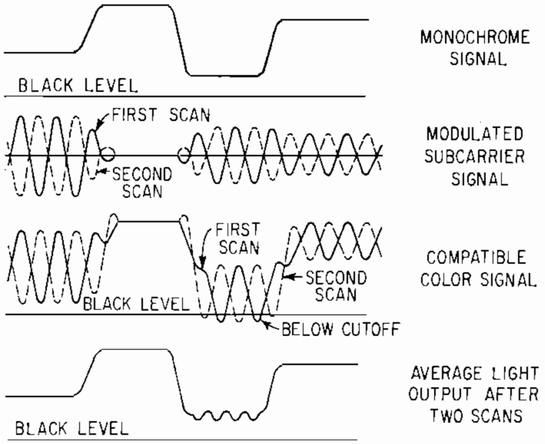

Fig. 2-17. Waveforms showing superposition of modulated subcarrier on scanning signals, compatible color signal, and effect of subcarrier on average light output.

The frequency-interlace technique is based on two factors—a precise choice of the color subcarrier frequency and the familiar "persistence-of-vision" effect. If the color subcarrier is made an odd multiple of one-half the line frequency, its apparent polarity can be made to reverse between successive scans of the same area in the picture. Since the eye responds to the average stimulation after two or more scans, the interference effect of the color subcarrier tends to be self-canceling, owing to the periodic polarity reversals (see Fig. 2-17).

COLOR-FREQUENCY STANDARDS

The relationships among the various frequencies used in a compatible color system are illustrated in the block diagram of Fig. 2-18. The actual frequency of the color subcarrier, which has been referred to as 3.6 Mc, is specified by FCC Standards as 3.579545 Mc, or exactly 455 multiplied by ½ the line frequency.

In broadcast practice, the frequency of the color subcarrier provides a frequency standard for operation of the entire system. A crystal oscillator at the specified frequency provides the basic control information for all other frequencies. Counting stages and multipliers derive the basic frequencies needed in the color studio. A frequency of nominally 31.5 kc is required for the equalizing pulses which precede and follow each vertical sync pulse and for the serrations in the vertical sync pulse. A divide-by-2 counter controlled by the 31.5 kc signal provides the line-frequency pulses at nominally 15.75 kc needed to control the horizontal blanking and synchronizing waveforms. Another counter chain provides the 60-cycle pulses needed for control of the vertical blanking and synchronizing circuits.

The synchronizing waveform adopted by the Television Committee of the Radio Electronics Television Manufacturers Association[1] is illustrated on page 1-233.

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[1] Now known as Electronic Industries Association.

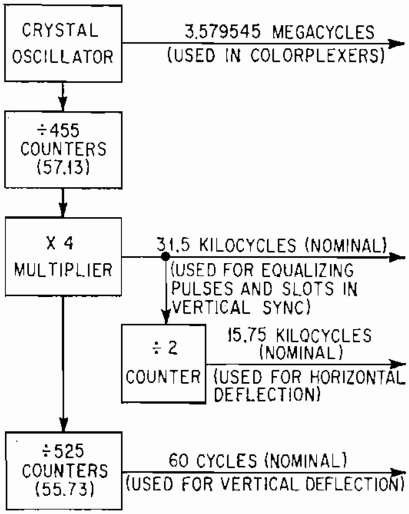

Fig. 2-18. Block diagram showing relationship between various frequencies used in color-television station.

THE OVER-ALL COLOR SYSTEM

The major functions performed in transmitting and receiving color are shown in the over-all block diagrams of the transmitting and receiving systems (Figs. 2-19 and 2-20).

At the transmitting end, camera output signals corresponding to the red, green, and blue components of the scene being televised are passed through nonlinear amplifiers (the gamma correctors) which compensate for the nonlinearity of the kinescope elements at the receiving end. Gamma-corrected signals are then matrixed to produce the luminance signal M and two chrominance signals I and Q. The filter section establishes the bandwidth of these signals. The 4.1-Mc filter for the luminance channel is shown in dotted lines because in practice this band shaping is usually achieved by the attenuation characteristics of the transmitter and the filter is not required.

The bandwidths of 1.5 and 0.5 Mc shown for the I and Q channels, respectively, are nominal only—the required frequency-response characteristics are described in more detail in the complete FCC signal specifications. Delay compensation is needed in the filter section in order to permit all signal components to be transmitted in time coincidence. In general, the delay time for relatively simple filter circuits varies inversely with the bandwidth. The narrower the bandwidth, the greater the delay. Consequently, a delay network or a length of delay cable must be inserted in the I channel to provide the same delay introduced by the narrower band filter in the Q channel, and still more delay must be inserted in the M channel.

In the modulator section, the I and Q signals are modulated upon two subcarriers of the same frequency but 90° apart in phase. The modulators employed should be of the doubly balanced type, so that both the carriers and the original I and Q signals are suppressed, leaving only the sidebands. Some sort of keying circuit must be provided to produce the color-synchronizing bursts during the horizontal blanking intervals. To comply with the FCC signal specifications, the phase of the burst should be 57° ahead of the I component (which leads the Q component by 90°). This phase position was chosen mainly because it permits certain simplifications in receiver designs. Timing information for "keying in" the burst can be obtained from a "burst flag generator," which is a simple arrangement of multivibrators controlled by horizontal and vertical drive pulses.

In the mixer section, the M signal, the two subcarriers modulated by the I and Q chrominance signals, and the color-synchronizing bursts are all added together. Provision is also made for the addition of standard synchronizing pulses, so that the output of mixer section is a complete color-television signal containing both picture and synchronizing information. This signal can then be put "on the air" by means of a standard television transmitter, which must be modified only to the extent necessary to assure performance within the reduced tolerance limits required by the color signal.

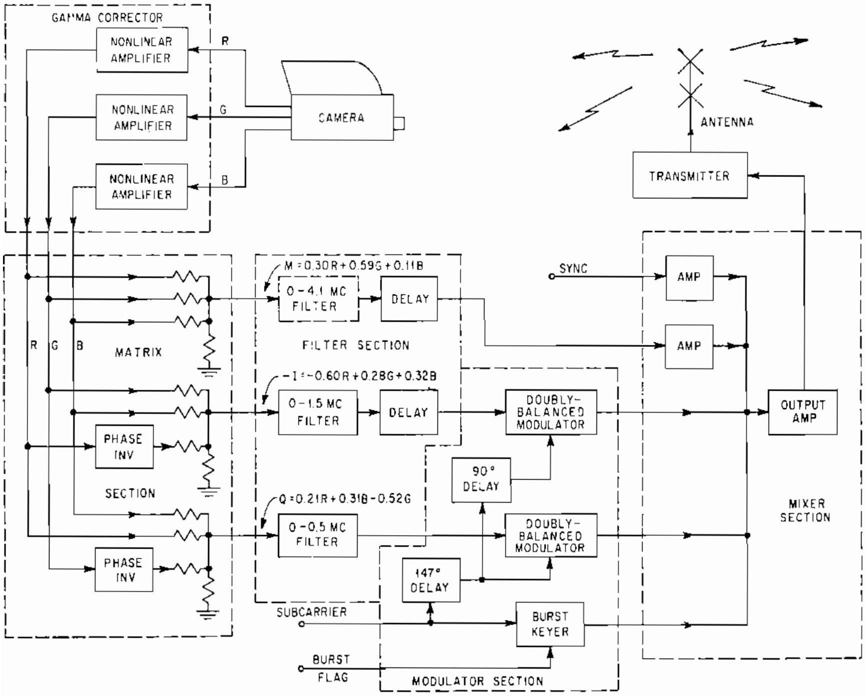

FIG. 2-19. Block diagram showing major functions of color-transmitting system.

(Since the color signal places more information in the channel than a black-and-white signal, the requirements for frequency response, amplitude linearity, and uniformity of delay time are stricter.)

THE COLOR-RECEIVING SYSTEM

In a compatible color receiver, the antenna, RF tuner, IF strip, and second detector serve the same functions as the corresponding components of a black-and-white receiver. Thus, up to the second detector, the color receiver is no different from a black-and-white receiver except that the tolerance limits on performance are somewhat tighter.

The signal from the second detector is utilized in four circuit branches. One circuit branch directs the complete signal toward the color kinescope, where it is used to control luminance by being applied to all kinescope guns in equal proportions. In the second circuit branch, a bandpass filter separates the high-frequency components of the signal (roughly 2.0 to 4.1 Mc) consisting mainly of the two-phase modulated subcarrier signal. This signal is applied to a pair of modulators which operate as synchronous detectors to recover the original I and Q signals. It should be noted that those frequency components of the luminance signal falling between about 2 and 4.1 Mc are also applied to the modulators and are heterodyned down to lower frequencies. These frequency components do not cause objectionable interference, however, because they are frequency-interlaced and tend to cancel out through persistence of vision.

The remaining two circuit branches at the output of the second detector make use of the timing or synchronizing information in the signal. A conventional sync separator is used to produce the pulses needed to control the horizontal- and vertical-deflection circuits which are also conventional. The high-voltage supply for the kinescope can be obtained either from a "flyback" supply associated with the horizontal

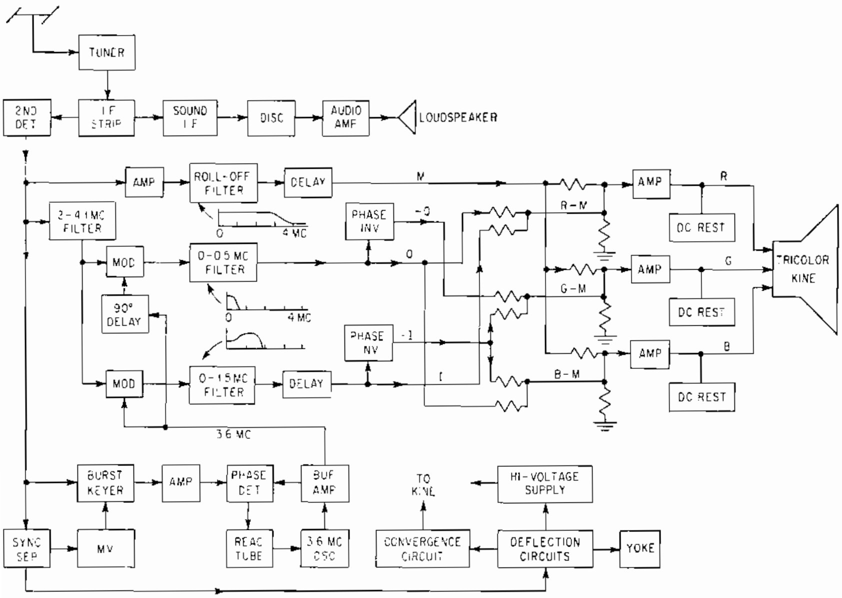

FIG. 2-20. Block diagram showing major functions of color-receiving system.

deflection circuit or from an independent RF power supply. Many color kinescopes require convergence signals to enable the scanning beams to coincide at the screen in all parts of the picture area; the waveforms required for this purpose are readily derived from the deflection circuits.

The final branch at the output of the second detector is the burst gate, which is turned "on" only for a brief interval following each horizontal sync pulse by means of a keying pulse. This pulse may be derived from a multivibrator controlled by sync pulses, as illustrated, or it may be derived from the "flyback" pulse produced by the horizontal output stage. The separated bursts are amplified and compared with the output of a local oscillator in a phase detector. If there is a phase difference between the local signal and the bursts, an error voltage is developed by the phase detector. This error voltage restores the oscillator to the correct phase by means of a reactance tube connected in parallel with the tuned circuit of the oscillator. This automatic-frequency-control circuit keeps the receiver oscillator in synchronism with the master subcarrier oscillator at the transmitter. The output of the oscillator provides the reference carriers for the two synchronous detectors; a 90° phase shifter is necessary to delay the phase of the Q modulator by 90° relative to the I modulator.

There is a "filter section" in a color receiver that is rather similar to the filter section of the transmitting equipment. The M, I, and Q signals must all be passed through filters in order to separate the desired signals from other frequency components which, if unimpeded, might cause spurious effects. The I and Q signals are passed through filters of nominally 1.5- and 0.5-Mc bandwidth, respectively, just as at the transmitting end. A step-type characteristic is theoretically required for the I filter, as indicated in Fig. 2-14, to compensate for the loss of one sideband for all frequency components above about 0.5 Mc. Actually, this requirement is ignored in many practical receiver designs, resulting in only a slight loss in sharpness in the I channel. A roll-off filter is desirable in the M channel to attenuate the subcarrier signal before it reaches the kinescope. The subcarrier would tend to dilute the colors on the screen if it were permitted to appear on the kinescope grids at full amplitude. Delay networks are needed to compensate for the different inherent delays of the three filters, as explained previously.

Following the filter section in the receiver there is a matrix section in which the M, I, and Q signals are cross-mixed to recreate the original R, G, and B signals. The R, G, and B signals at the receiver are not identical with those at the transmitter because the higher frequency components are mixed and are common to all three channels. This mixing is justifiable, because the eye cannot perceive the fine detail (conveyed by the high-frequency components) in color. There are many possible types of matrixing circuits. The resistance mixers shown provide one simple and reliable approach. For ease of analysis, the matrix operations at the receiver can be considered in two stages. The I and Q signals are first cross-mixed to produce R-M, G-M, and B-M signals (note that *negative* I and Q signals are required in some cases), which are, in turn, added to M to produce R, G, and B.

In the outpnt section of the receiver, the signals are amplified to the level necessary to drive the kinescope and the d-c component is restored. The image which appears on the color kinescope screen is a high-quality full-color image of the scene before the color camera.

It should be made clear that the block diagram of Fig. 2-20 is intended only to illustrate the principles used in color receivers and does not represent any specific model now on the market. Design engineers of color receivers have shown great ingenuity in simplifying circuits, in combining functions, and in devising subtle variations in the basic process which have made possible significant cost reductions while maintaining excellent picture fidelity. The principles of compatible color television are firmly established, and it is to be expected that steady progress will be made in the practical application and requirement of those principles.

Part 3

COLOR FIDELITY

"Color fidelity," as used herein, is the property of a color-television system to reproduce colors which are realistic and pleasing to the average viewer.

Although perhaps not apparent at first, color fidelity is analogous to "high fidelity" as applied to sound reproduction. Just as a high-fidelity audio system faithfully reproduces sounds reaching the microphone, the color-television system is capable of faithfully reproducing colors as seen by the television cameraman. In fact, the color-television system is capable of reproducing colors more accurately than techniques presently used in color printing and color photography.

Tests have shown, however, that color-television pictures are generally more pleasing to the viewer when deliberate modifications are made in the reproduced colors to compensate for the surroundings in which they are reproduced. The situation is similar to that experienced in the art of sound reproduction in the case of a symphony orchestra recorded at high sound levels in a large hall and reproduced at lower sound levels in a small room. In this case, a more pleasing effect is obtained if the ear's new environment is taken into consideration and the reproduction modified accordingly. Similarly, in color television, the changed environment of the eye must be considered and the reproduced colors modified accordingly.

Color fidelity, therefore, is a term used to indicate a color reproduction which pleases the viewer esthetically and convinces him that he is viewing an accurate reproduction of the original colors in the scene being televised.[1]

The following describes possible distortions in the color system and their effect on the picture and prescribes amounts or degrees of distortion that can be tolerated without adverse effects on picture quality.

COLOR-SYSTEM ANALYSIS

Individual elements or areas of the complete color system are discussed in the following paragraphs with the aid of the diagrams shown in Figs. 3-1 through 3-5.

Figure 3-1 is a theoretical color system in that it assumes linear camera tubes and kinescope interconnected by a distortionless wire system. The only distortion that can result from this system is a flaw in colorimetry.

Figure 3-2 introduces linearity correctors to compensate for color errors produced by nonlinearities in the transducers.

Figures 3-3, 3-4, and 3-5 successively introduce the complexities of matrixing, band limiting, delay compensation, and the transmission system (shown dotted in Fig. 3-5). These diagrams, each representing a possible color system, introduce techniques used in compatible color television and permit the study of color distortions peculiar to each technique.

The systems diagramed in Figs. 3-1 and 3-2 are described under Possible Distortions

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[1] A detailed discussion of colorimetry and perception, and how these factors affect the viewer, is presented in "Color Television Engineering" by John W. Wentworth, McGraw-Hill Book Company, Inc., New York, 1955.

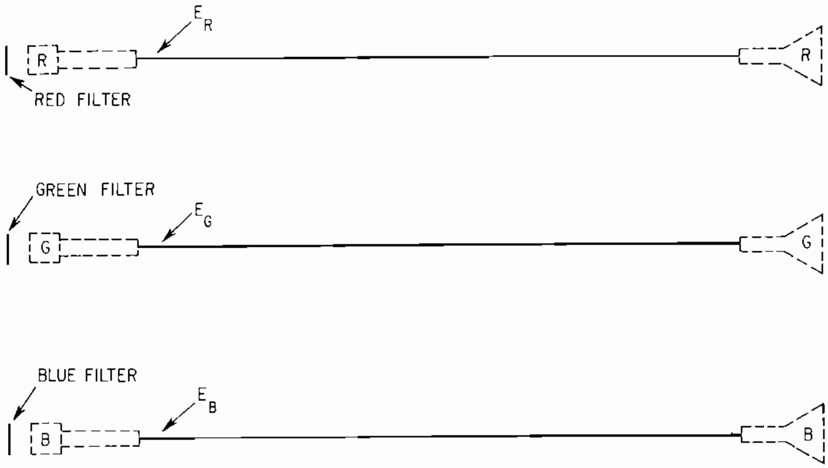

Fig. 3-1. Diagram of a theoretical color system showing linear RGB pickup tubes and kinescopes interconnected by wire.

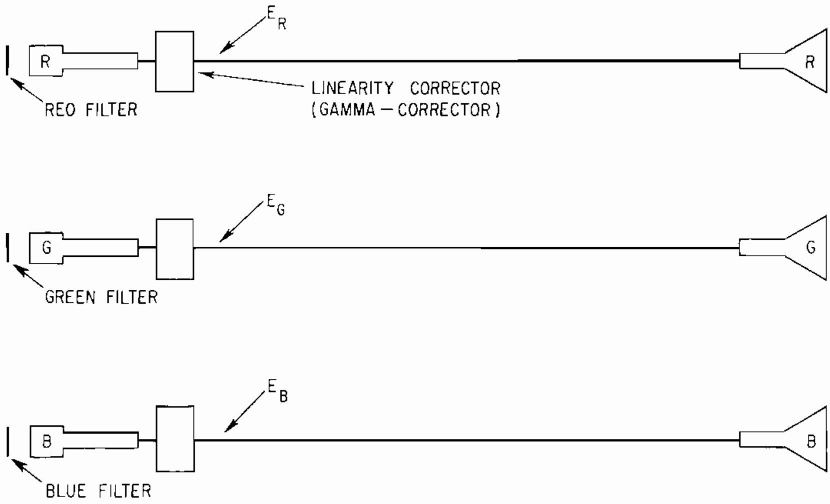

Fig. 3-2. The basic color system shown with necessary linearity correctors to compensate for color errors introduced by the nonlinear transducers.

in Transducers, and those in Figs. 3-3, 3-4 and 3-5 under Possible Distortions in Encoding and Decoding Processes. The system shown in Fig. 3-5 is discussed under Distortions in the Transmission System.

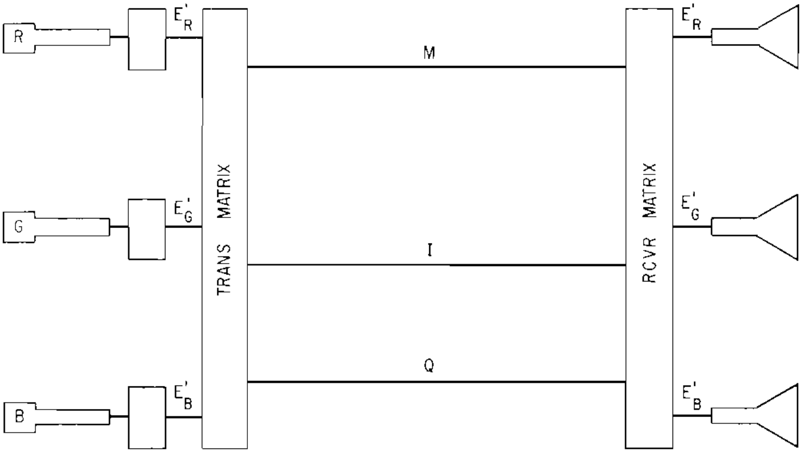

FIG. 3-3. Diagram showing transmitter and receiver matrix functions in the color system.

CHARACTERISTICS OF THE EYE

To appreciate fully the significance of color fidelity, it is helpful to consider some of the characteristics of the eye associated with color perception and to analyze such terms as color adaptation, reference white, and primary colors and determine their relationship to a color-television system.

Color Adaptation

One amazing characteristic of the eye is the phenomenon known as color adaptation. It is this adaptation which enables one to describe accurately the color of an object under "white" light while viewing it in nonwhite light. That is to say, recognition of color is surprisingly independent of the illumination under which an object is viewed. For example, if sunlight at high noon on a cloudless day is taken as "white" light, then, by comparison, the illumination from a typical 100-watt incandescent bulb is very yellow light. Yet it is known that an object viewed under sunlight looks very little if any different when viewed under incandescent light. Moreover, it is obvious to the observer, after a very few minutes in a room illuminated with incandescent lights, that the light is not yellow at all; it is really "white."

It is apparent, then, that the color seen by an observer is dependent upon the illumination to which that observer has been exposed for the past several minutes. This ambient illumination will have a marked effect on his choice of what color he is going to call "white."

This phenomenon can cause a loss of color fidelity under certain conditions. Consider, for example, a theoretically perfect color system with camera viewing an outdoor scene under a midday sun while the reproduced picture is being viewed in a semidarkened room, with what little light is in the room also being derived from the midday sun. Under these conditions, the ambient illuminations at both camera and receiver are identical, so a man standing alongside the camera and a man viewing the receiver would both see the same colors. Now, if a change in the weather at the camera location should cause a cloud to cover the sun, the ambient illumination at the camera location would shift toward a bluer color. This shift would not disturb

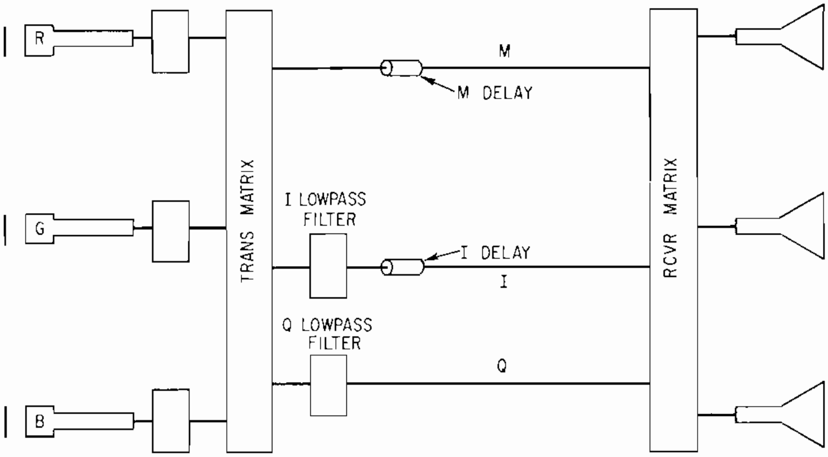

FIG. 3-4. Basic color system with band limiting and delay compensation.

the viewer standing alongside the camera, because his eyes, bathed in the new ambient light, would rapidly adapt to the new viewing conditions and he would perceive the scene as being unchanged.

The man viewing the receiver would not be so fortunate. Assuming that he is far enough away that this same cloud would not affect his ambient, he would observe that everything on his screen had suddenly and inexplicably taken on a bluish cast, which he would certainly find most disturbing.

Such errors in color fidelity can always be corrected by making the camera imitate the human eye in adaptation. The eye adapts to changes in ambient illumination by changing its sensitivity to a certain color. For example, if a light source changes from white to blue-white (as in the above example), the eye reduces its blue sensitivity until the light again appears to be white to the observer. Likewise, a camera operator can correct for the same situation by decreasing the gain of the blue channel of the

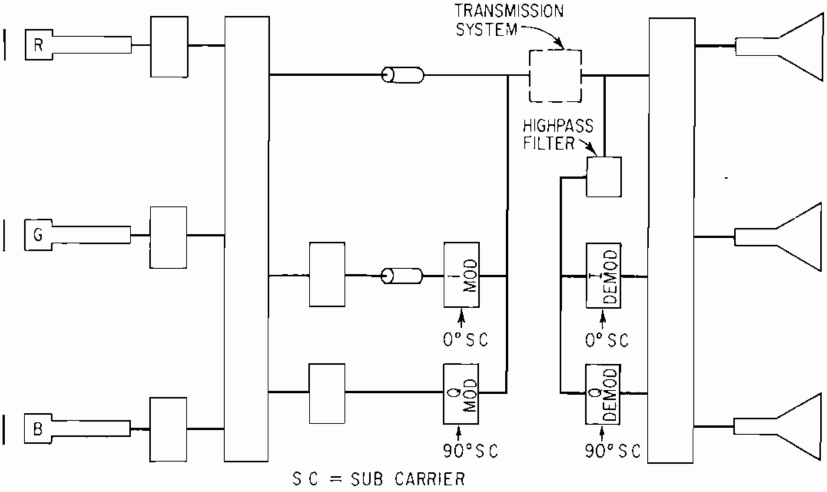

FIG. 3-5. Basic color system showing all major elements, including the transmission system.

camera or by attenuating the light reaching the blue camera tube. In this way, the camera is made to "color-adapt," and the reproduced picture on a receiver loses its bluish cast.

Reference White

Although color adaptation can generate a problem such as the one just described, it also simplifies certain requirements. Specifically, it eases the requirement that white be transmitted as a definite, absolute color, for there clearly can be no absolute white when almost any color can be made to appear subjectively white by making it the color of the ambient illumination to which an observer's eye has adapted.

In color television, we take advantage of this characteristic in the following manner: A surface in the studio which is known by common experience to be white—such as a white shirt or a piece of paper—is selected to be reproduced as white on a home receiver. The relative sensitivities of the three color channels of the camera are then adjusted so that the camera "adapts" to this white regardless of the studio illumination. The home receiver can then be adjusted to reproduce the surface as any "white" which the home viewer prefers, depending upon his surroundings. In the average home-viewing situation, a strong viewer preference has been shown for a bluish-white at the receiver; a subjective effect of freshness, newness, and crispness is conveyed by this white. Therefore, a hue of this type is the common choice for reference white in the home.

It is interesting to note that the studio illumination is commonly the yellow-white of incandescent lighting; hence, a white object in the studio would appear considerably different from its image in the home. It would be possible to adjust the home receiver to reproduce the object with its "proper" whiteness, but this adjustment would result in a yellowish reference white which the viewer would find displeasing. The surprising fact appears, therefore, that absolute color fidelity in a reproduced picture is usually undesirable.

The change in reference white between studio and home must inevitably produce errors in all reproduced colors, but the errors are small and, more important, tend to be subjectively self-correcting, so that any given object will tend to produce the same color sensation whether viewed in relation to the studio reference white or the home reference white.

Consequently, a viewer may become familiar with an object such as a sponsor's packaged product and will recognize it on his television screen, under the fluorescent lighting of his supermarket, or under the incandescent lighting of his home and, furthermore, will note no difference in the colorimetric values of the package under the three conditions, even though the absolute colorimetric values would be appreciably different in the three situations.

Primary Colors

Of all the characteristics of the eye, there is perhaps none more fundamental to practical color television than that characteristic which allows us to choose certain colors, called primary colors, and from these synthesize almost any other desired color by adding together the proper proportions of the primary colors. If it were not for this characteristic, each hue in a color system would have to be transmitted over a separate channel; such a system would be too awkward to be practical. Because of the eye's acceptance of synthesized colors, it is possible to provide excellent color rendition by transmitting only the three primary colors.

POSSIBLE ERRORS IN TRANSDUCERS

The block diagram of Fig. 3-1 shows a fundamental color-television system using red, green, and blue primaries and three independent transmission channels. The camera tubes and kinescopes are shown dotted to indicate that any inherent nonlinearities in these devices are to be disregarded, for the moment, in order to simplify the discussion of the colorimetry of the system.

The general plan in a system such as that of Fig. 3-1 is to provide the three kinescopes with red, green, and blue phosphors, respectively, and to allow the corresponding camera tubes to view the scene through an appropriate set of red, green, and blue filters. If a phosphor and a filter have the same dominant wavelength, that is, if they appear to the eye to be the same color, it might be mistakenly supposed that they would be colorimetrically suited to be used as a filter and phosphor set for the channel handling that color. Actually, the basis for choosing filters and phosphors is much more complex and is based on the shape of the response curve of the filter, plotted against wavelength, and the shape of the light-output curve of the phosphor, also plotted against wavelength. The following paragraphs will discuss briefly a technique which might be used to determine the required relationship between the phosphor curves and the filter curves.

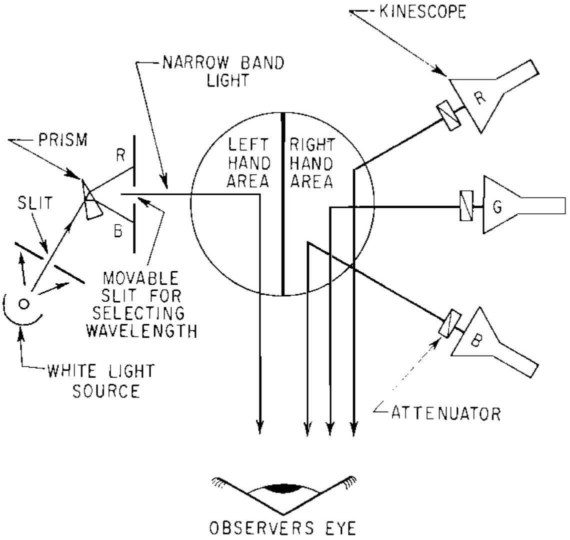

Fig. 3-6. Diagram showing laboratory setup arranged to compare narrow-band light source and R, G, and B light produced by kinescopes to determine proper camera-filter color characteristics.

The color characteristics of the phosphor are generally less easily changed than are filter characteristics; for this reason characteristics of phosphors are taken as the starting point, and characteristics of the filters are determined from them. A laboratory setup which could be used to determine these characteristics is shown in Fig. 3-6. In this figure, an observer (who must have "normal" vision) is viewing simultaneously two adjacent areas, one of which is illuminated by a source of single-wavelength light which can select any wavelength in the visible spectrum, the other of which is illuminated by a red kinescope, a green kinescope, and a blue kinescope. The phosphors of these kinescopes are the phosphors which are to be used in the color system. Starting at, say, the red end of the spectrum, a single-wavelength red is selected to illuminate the left-hand area, and the light from each of the three phosphors is varied until a color match is obtained between the left-hand and right-hand areas. The respective amounts of red, green, and blue lights needed to accomplish this match are recorded. Then another wavelength is chosen, the kinescope outputs varied to produce a match, and the new amounts of red, green, and blue needed for a match are recorded. Similarly, points are obtained throughout the entire spectrum, and a graph is plotted showing the various required outputs vs. wavelength. The shapes of these three curves—one for red, one for green, and one for blue—are the required shapes for the three camera-filter response curves. The resulting curves would in general resemble Fig. 3-7.

(To simplify the above discussion it was assumed that the camera tubes responded equally well to all wavelengths. In practice, camera tubes show higher output at certain wavelengths than at others. The filter-response curves derived by the above technique would have to be modified so that the combined response of filter and camera would be correct.)

Certain practical difficulties could result in errors in the above procedure. For example, if the observer had any deviations from normality in his color-vision characteristics (as most people do), these deviations would result in "nonstandard" matches and, hence, improper camera-filter characteristics. Also, if the phosphors were contaminated in any way during their manufacturing process (as most phosphors are, at least to some small degree), the resulting phosphor characteristics would not be the proper ones and hence would give rise to improper camera-filter characteristics. The observer errors can be normalized out by standard colorimetric procedures, but phosphor errors represent a basic error which may possibly be present not only in the above experiment but also in varying degrees in a large number of receivers. Quality control of phosphor manufacture is sufficiently good, however, to make the net effect unnoticeable in home receivers.

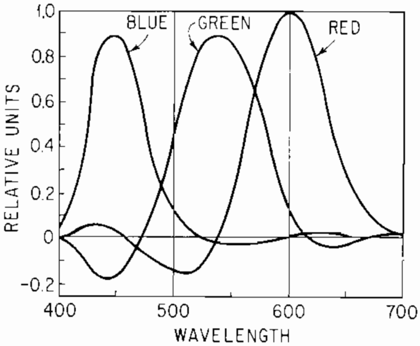

Fig. 3-7. Curves showing relative quantities in camera output required to produce correct kinescope colors over the visible spectrum.

A striking practical difficulty would also arise regardless of observer or phosphor errors. For most wavelengths, no combination of red, green, and blue kinescope outputs could be found which would produce a match. In order to obtain a match at these wavelengths, it would be necessary to move one or two of the kinescopes over to the other side so that they could add their light to the single-wavelength light being matched. This procedure can be described mathematically, for graphing purposes, by saying that adding light to the left-hand area is the same as subtracting that light from the right-hand area. Therefore, the amount of light added on the left would be considered as a negative quantity and would result in a point below the axis on the graph. Since this condition would be found to exist for several successive wavelengths, the resulting graph would show one or more minor lobes below the axis. These are called negative lobes.

These negative lobes represent a need for filters with negative light-transmission characteristics at certain wavelengths. Simple attenuating filters cannot yield such a characteristic; much more elaborate means would be required. However, it has been shown that excellent color fidelity can be obtained by ignoring the negative lobes and using filters which yield the positive lobes only. Positive-lobe processes such as color photography have gained wide acceptance for years. The RCA TK-41 color camera, which also ignores the negative lobes, has shown by its widespread use and approval that this approach to the problem is both practical and sensible. In short, the contribution of the negative lobes is so small that any means for giving effect to them must be comparatively inexpensive to justify its use. Further advances in the art may provide such a device.

Nonlinearities in the Transducers

The assumption made in Fig. 3-1 that a system comprised of perfectly linear devices and circuits was convenient for the discussion of colorimetry, but since any practical system is always found to be more or less nonlinear, further discussion must take into account this nonlinearity. In this section we shall discuss the inherent nonlinearities of camera tubes and kinescopes, the effects of these nonlinearities on the reproduced picture, and the use of conversely nonlinear amplifiers to correct for the camera-tube and kinescope characteristics.

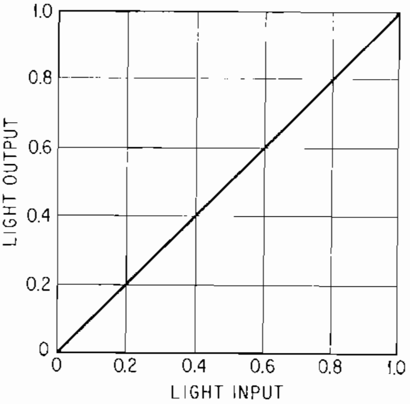

FIG. 3-8. Curve showing light-transfer characteristics of a perfectly transparent piece of window glass.

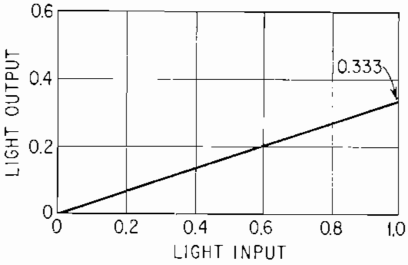

FIG. 3-9. Curve showing transfer characteristic of a neutral density filter with 3-to-1 light attenuation.

Transfer Characteristics

A piece of window glass is perhaps the nearest approach to a perfect video system. For a piece of glass, the light output (to the viewer) is essentialy identical with the light input (from the scene). This fact is shown graphically in Fig. 3-8. This plot could be called the "transfer characteristic" of a piece of glass, since it describes the way that light is transferred through the system.

If the window glass is replaced by a neutral-density filter which attenuates light 3 to 1, the transfer characteristic will then be given by Fig. 3-9. The difference between Figs. 3-8 and 3-9 can he described by these simple relationships:

For the glass:

$$\text{Light output} = \text{light input}$$

For the neutral-density filter:

$$\text{Light output} = k \times \text{light input}$$

where $k = \frac{1}{3}$ in this case.

Both systems are linear; that is, doubling the light input of either will double its light output; tripling input will triple output; etc. A nonlinear system does not exhibit this simple proportionality. For example, consider a system described by

$$\text{Light outut} = k \times (\text{light input})^2$$

Doubling the input to this system will quadruple its output; a threefold increase in input will result in a ninefold increase in output; etc. The transfer characteristic for this type of system is shown in Fig. 3-10. Note that the characteristic is definitely nonlinear; that is, it is not a straight line as were Figs. 3-8 and 3-9.

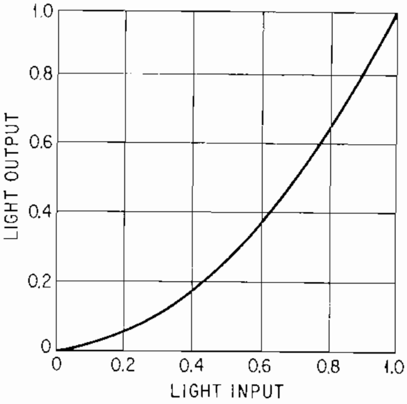

Fig. 3-10. Curve showing a nonlinear transfer characteristic.

In television and photography, nonlinearity is more common than linearity. For example, an ordinary kinescope is a nonlinear device, having a transfer characteristic which can be approximated by the expression

$$\text{Light output} = k\ (\text{voltage input})^{2.2}$$

Camera tubes also are usualy nonlinear devices. For example, the characteristic of a vidicon is approximately

$$\text{Current output} = k\ (\text{light input})^{0.65}$$

The general expression for nonlinear transfer characteristic can be given approximately as

$$\text{Output} = k\ (\text{input})^{\gamma}$$

where the exponent is the Greek letter gamma.

Graphical Displays of Transfer Characteristics

Linear Plots

The first reaction of any person asked to display two variables (like light input and light output) on a set of XY coordinates is to divide X and Y coordinates into equal increments and plot the variables in this manner. A typical result of such a plot has already been described (Figs. 3-8 and 3-9). Such a plot has the advantage of showing at a glance the linearity of the device described by the variables. If the plot is a straight line, we say the device is linear; if curved, we say the device is nonlinear. Moreover, the slope of the line describes the attenuation (or gain) of the device. If the slope is unity (which occurs when the plot makes a 45° angle with the X axis), there is no attenuation; we are dealing with a very good piece of glass. For the neutral-density filter described above, which has the equation (light output) = ⅓ (light input), the line has a slope of one-third (see Fig. 3-9).

Such are the advantages of plotting transfer characteristics with equal-increment divisions of the X and Y axis. However, other advantages—very important ones—can be obtained by dividing up the X and Y coordinates logarithmically. Such a plot is called a log-log plot.

Log-Log Plots

Consider a system which has a transfer characteristic given by $L_0 = (L_{in})^{2.2}$. If this equation is plotted on axes which are divided logarithmically, the resulting plot is the same as though the logarithm of both sides of the equation were plotted on equal-increment axes. Taking the logarithm of both sides, we obtain

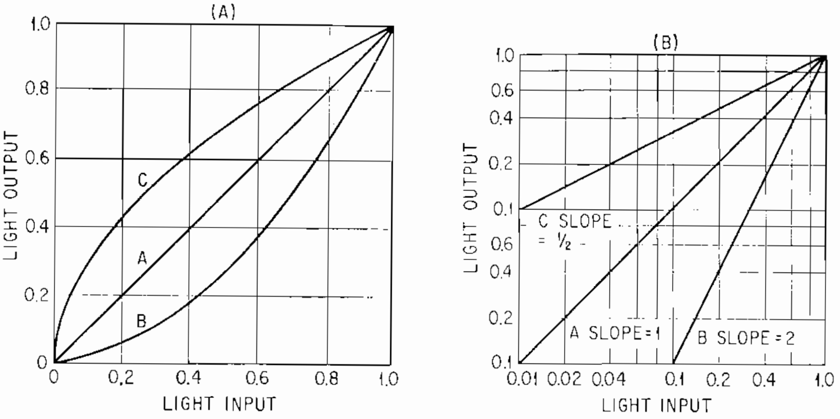

FIG. 3-11. Graphs showing the curves obtained by platting A, B, and C types of transfer characteristics on linear coordinates (A) and on log-log coordinates (B).

$$\log L_0 = \log\ (L_{in})^{2.2}$$

Since $\log\ (L_{in})^{2.2}$ is the same as $2.2 \log\ (L_{in})$, then

$$\log L_0 = 2.2 \log L_{in}$$

Comparing the form of this equation with an earlier equation, light output $= \frac{1}{3}$ light input, we can see that just as the attenuation, $\frac{1}{3}$, was the slope of the earlier equation, so 2.2, the exponent, is the slope of the latter equation. We see, then, that the use of logarithmically divided coordinates yields a plot in which the exponent is given by the slope of the line. Therefore, this plot will show at a glance the magnitude of the exponent and will also show whether or not the exponent of the system is constant for all light levels. It also is advantageous in showing the effects of stray light.

Figure 3-11*a* and *b* compare the two types of plotting for three types of transfer characteristics.

The Effect of a Nonlinear Transfer Characteristic on Color Signals

Effect of Identical Nonlinearities in Each Channel

In monochrome television, some degree of nonlinearity can be tolerated, but such is not the case for a color-television system. It can be shown that a system exponent different from unity must inevitably cause a loss of color fidelity. For an example, consider a situation in which signals are being applied through linear amplifiers to the red and green guns of a perfectly linear (theoretical) kinescope. The green amplifier is receiving 1.0 volt; the red amplifier, 0.5 volt. If everything is perfectly linear, the proportions of the light output should be 1.0G + 0.5R = a greenish yellow. However, if the kinescope has an exponent of 2.0, the light output will be $(1.0)^2$G + $(0.5)^2$R = 1.0G + 0.25R = greenish yellow with an excess of green.

From the above specific case, it may be correctly inferred that in general, a system exponent greater than 1 will cause all hues made of the combination of two or more primaries to shift toward the larger or largest primary of the combination. Conversely, a system exponent less than 1 will shift all hues away from the largest primary of the combination.

In the above example, an exponent of 0.5 would yield $(1.0)^{0.5}$G + $(0.5)^{0.5}$R = 1.0G + 0.707R = a greenish yellow which is just a shade off pure yellow.

In addition, the reader can correctly conclude that white or gray areas, in which all the primaries are equal, will not be shifted in hue by a nonunity exponent.

Effect of Differing Exponents in Each Channel

The preceding discussion assumed that all three channels (in Fig. 3-2) have the same exponent, whether unity or not. In practical systems, however, there is always the possibility that the exponents of the channels may differ from one another. This situation will produce intolerable color errors if the differences become even moderately large. In general, the requirements for "tracking" among the light-transfer characteristics of the individual channels are even more stringent than the requirement for unity exponent.

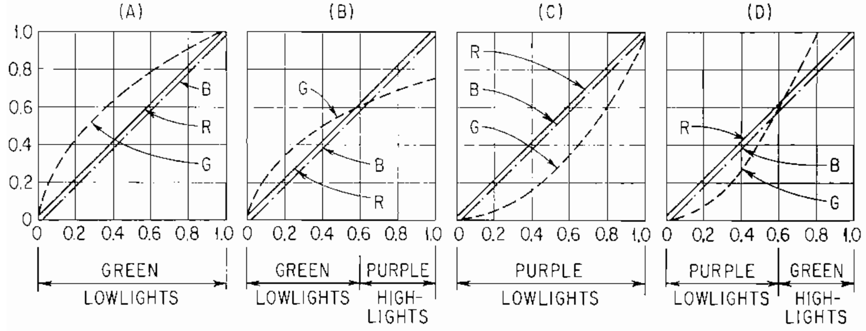

FIG. 3-12. Linear plots showing graphically the effect of unequal exponents in the R, G, and B channels. In all four graphs the R and B exponents are taken as unity. In (*A*) and (*B*) the green exponent is taken as less than 1, and in (*C*) and (*D*), as greater than 1.

Figure 3-12*a, b, c,* and *d* shows graphically the effects of unequal exponents in the three channels. In all four figures, the red and blue exponents are taken as unity; in Fig. 3-12*a* and *b* the green exponent is taken as less than 1, and in Fig. 3-12*c* and *d,* as greater than 1. In Fig. 3-12*a,* the transfer characteristics are shown for the system adjusted to produce peak white properly. It can be seen that the bowed characteristic of the green channel will cause all whites of less than peak value to have too much green. A gray-scale step tablet before the camera would be reproduced properly only at peak white; the gray steps would all have a greenish tinge. Relative channel gains could be readjusted to reproduce one of the gray steps properly (Fig. 3-12*b*), but then all highlight steps would be purplish while lowlight steps would still be greenish.

A green-channel exponent greater than unity would reverse the above results (Fig. 3-12*c* and *d*). With gains adjusted to reproduce peak white properly (Fig. 3-12*c*), lowlights would be purplish; with gains readjusted to provide proper reproduction for one of the lower steps (Fig. 3-12*d*), highlights would be green and lowlights purple.

The Effect of Stray Light

If a kinescope is viewed in a lighted room, there will always be some illumination on the faceplate. Therefore, the eye will always receive some "light output" from the kinescope, regardless of the magnitude of the signal input voltage. Under this condition, a true black is impossible to obtain.

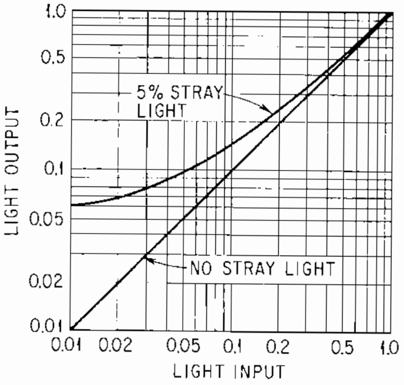

FIG. 3-13. Log-log plot of system with stray light, illustrating change of slope in the lowlight regions.

This condition is reflected in the transfer characteristic of the system. If, for example, the stray light were 5 per cent of the peak highlight brightness of the picture, a linear plot of light output vs. light input would have the entire transfer characteristic shifted upward by 5 per cent. However, the most interesting change is found in the log-log plot, where, as seen in Fig. 3-13, the stray light causes a change in the slope in the lowlight regions. Since the slope is equal to the exponent, this change shows that stray light causes an effective exponent error in the lowlight regions of the picture and hence will cause color-fidelity errors which will be most marked in the lowlight regions.

These errors will be noted by an observer as improper hues and saturations, with the saturation errors—a "washing out" of the more saturated lowlight areas—being the more objectionable to a viewer.

Stray light is not the only cause of errors of this type. Similar effects will be noted whenever the kinescope bias ("brightness") is set too high, if camera pedestal is set too high, or if stray light enters the camera (whether through lens flare or any other source). In general, any condition which prevents the light output of the system from becoming zero when the light input is zero will cause errors similar to those caused by stray light.

Linearizing a System

It can be shown that a system using a vidicon with an exponent of 0.65 to drive a kinescope with an exponent of 2.2 will have an over-all exponent given by the product $0.65 \times 2.2 = 1.43$, assuming that all devices in the system are linear. In general, the over-all exponent of a system is the product of the exponents of the cascaded elements.

This knowledge provides an excellent tool for linearizing a system. For example, a system with an over-all exponent of 1.43 could be linearized by inserting somewhere (in a video path) an amplifier having an exponent of $1/1.43$ ($= 0.7$) so that the product becomes unity: $1.43 \times 1/1.43 = 1$.

In Fig. 3-2, a nonlinear amplifier, or gamma corrector, is shown inserted in each of the three paths.

POSSIBLE ENCODING AND DECODING DISTORTIONS

The second of the two systems discussed in the preceding section bordered on being a practical system but still required three independent 4-Mc/sec channels. A fortunate characteristic of the human eye—the inability to see colored fine detail—allows us to modify this requirement to one 4-Mc/sec channel for monochrome fine detail and two much narrower channels for color information. Before this modification can be made, the red, green, and blue signals must be combined to form three other signals, usually called M, I, and Q, such that the M signal alone requires a 4-Mc/sec channel, and the I and Q channels, which contain the color information, are confined to narrower channels. This rearrangement of red, green, and blue to form M, I, and Q is called matrixing and was described in the previous part. A system which uses a matrix is block-diagramed in Fig. 3-3. The illustration also shows that to recover the original red, green, and blue signals at the receiving end, a "rearranging" device is needed. This device is usually called the receiver matrix.

Matrixing alone offers no advantage unless steps are taken actually to limit the I-signal and Q-signal channels to the narrow bandwidths allowed. Figure 3-4 shows a system employing such band shaping. The band-shaping filters themselves always introduce delay, which must be compensated for by placing delay lines in the wider band channels, as shown in the diagram.

To put both color and monochrome information in the spectrum space normally occupied by monochrome only requires that the color information overlap the monochrome. This overlap can be allowed for both I and Q signals, without incurring visible cross talk, if two techniques, known as frequency interlace and two-phase modulation are employed. A system using these techniques, which were described in Part 2, is block-diagramed in Fig. 3-5.

Possible Errors in the Matrixing Process

The entire matrixing process can be summed up in two sets of equations, the first set describing how the transmitter matrix takes in red, green, and blue and turns out M, I, and Q:

$$\begin{aligned} M &= 0.30R + 0.59G + 0.11B \\ I &= 0.60R - 0.28G - 0.32B \\ Q &= 0.21R - 0.52G + 0.31B \end{aligned}$$

and the second set describing how the receiver matrix takes in M, I, and Q and recreates red, green, and blue:

$$\begin{aligned} R &= 0.94I + 0.62Q + M \\ G &= 0.27I + 0.65Q + M \\ B &= 1.11I + 1.7Q \ + M \end{aligned}$$

Both matrices can therefore be considered as analogue computers which continuously compute the desired output from the given input. The coefficients in the above six equations are usually determined in the "computers" by precision resistors or, in the case of negative numbers, by precision resistors and signal-inverting amplifiers. The basic error that can occur, therefore, is a change in a resistor value or an amplifier gain, resulting in a change in one or more coefficients. In general, the resulting picture error resembles cross talk among the primary colors.

More specifically, the transmitter matrix can have two distinct types of errors. The first type involves the coefficients of the equation for M; the second type, the coefficients for I and Q. An error in an M coefficient will brighten or darken certain areas. In a monochrome reproduction of a color signal, such an error, if small, would not be noticed; if large, it would still probably be tolerated by the average viewer. In a color reproduction, however, even a small error would be objectionable. For example, a reduction of the red coefficient from 0.3 to 0.2 would cause a human face to be reproduced with an unnatural ruddy complexion and dark-red lips.

Note that the sum of the M coefficients is 1. An error in one coefficient would change this sum, so that peak white would no longer occur at 1 volt. An operator could mistake this condition for a gain error and adjust either M gain or over-all gain in an effort to obtain the correct peak-white voltage. Changing M gain would cause errors to occur in all M coefficients; changing over-all gain would put errors in all coefficients. Although such an error is rare in well-engineered equipment, it is a possible source of color error which can be compounded by misdirected attempts at correction.

Note that the sums of the Q and I coefficients are each zero, which means that when R = G = B (the condition for white or gray), Q and I both equal zero. An error in a Q or I coefficient would cause color to appear in white or gray areas and, in addition, would cause general errors in colored areas resembling cross talk among the primaries. Controls are usually provided in the Q and I matrices, called Q white balance and I white balance, respectively, which allow the operator to adjust the sum of the Q or I coefficients by changing the value of one of the coefficients. If the coefficient controlled is the one in error, adjusting white balance restores proper operation. If the controlled coefficient is not the one in error, then adjusting white balance restores the condition that the sum of the coefficients is zero, that is, it removes the color from white and gray objects, but it does so by giving the controlled coefficient an error which just counteracts the error of a nonadjustable coefficient, so that two coefficients are wrong instead of one. Again, such an error is rare in well-engineered equipment, for the adjustable coefficient is usually the one in error. However, the possibility of an error compounded by adjustment should be kept in mind.

A far more likely cause of white-balance error is an error in input level, that is, a discrepancy between the peak white levels of input red, green, or blue. In such a case, an operator can still achieve white balance (Q and I = 0 for white input) but the entire system will be in error. The starting point for all investigations of the cause of white-balance errors should be the levels of the red, green, and blue colorplexer inputs.

In the receiver matrix, only one general type of error can occur instead of two as in the case of the transmitter matrix. This type of error, a general coefficient error, results in cross talk among the primary colors. For example, a change in the I coefficient for the red equation from 0.94 to 0.84 would yield about a 7 per cent reduction in the peak red output available and would also result in unwanted red light output in green or blue areas at about 3½ per cent of the green or blue level.

Gain Stability of M, I, and Q Transmission Paths

In the system of Fig. 3-3, every gain device or attenuating device in the three transmission paths must maintain a constant ratio between its input and output in order to maintain the proper ratios among the levels of M, I, and Q at the input to the receiver matrix. A variation in the gain of one of these paths will result in a loss in color fidelity.

For example, a reduction in M gain must obviously cause a reduction in the viewer's sensation of brightness. Not quite so obvious are the effects of I and Q gain. Since these are color signals, their amplitude would be expected to influence the sensation of saturation, but the manner of this influence is not intuitively obvious until the factors which influenced the selection of I and Q compositions are recalled. It previously was pointed out that the eye has the greatest need for color detail in the color range from orange to blue-green (cyan) and the least in the range from green to purple. Hence I, the wider band signal, conveys mainly orange and cyan information, and Q, the narrower band signal, conveys principally the greens and purples. Therefore, a reduction in I gain could be expected to reduce the saturation sensation for colors in the orange and cyan gamut, leaving the greens and purples virtually unaffected. Conversely, Q gain will influence the greens and purples without causing much change in the appearance of orange and cyan objects.

Modulation and Demodulation

The system of Fig. 3-4, which introduced bandwidth limiting of the I and Q signals in accordance with the capabilities of the eye to see colored fine detail, is a fairly practical and economical system, except for the fact that three individual transmission channels are employed. If we are to have a compatible system, however, these three channels must be reduced to one through some multiplexing technique. The technique used has already been described, and a system employing this technique is blocked-diagramed in Fig. 3-5.

Possible Errors in Modulation

Burst Phase Error

Perhaps the most fundamental error in the multiplexing process would be an error in the phase of the main timing reference, burst. Since the entire system is based on burst phase, an error in burst phase will appear as an opposite error in every phase except burst, because the circuits will insist that burst phase cannot be wrong. The general result will be an over-all hue error in the reproduced picture. This effect can be better visualized by referring to Fig. 3-14.

A phase error in burst produces the same result as holding burst phase stationary and allowing all other phases to slip around the circle an equal amount (but in a direction opposite to the burst-phase error). Each color "vector" then represents a hue other than the one intended.

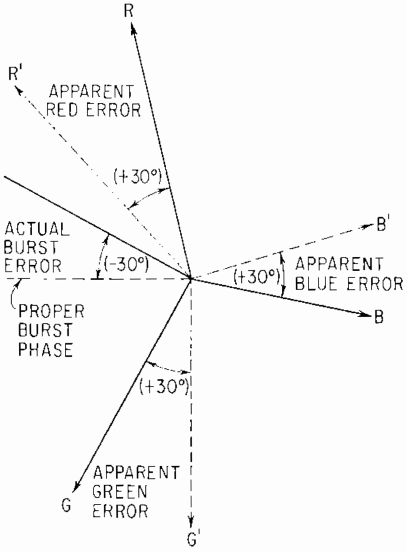

Fig. 3-14. Vector diagram showing how error in subcarrier phase becomes an opposite error in all other phases.

Burst Amplitude Error

In theory, the receiver circuits which extract timing information from the burst are insensitive to variations in burst amplitude as long as the burst is large enough to maintain a respectable signal-to-noise ratio and not so large that some type of clipping or rectification upsets the burst circuitry. But practical receivers always exhibit some degree of sensitivity to burst amplitude, the amount of this sensitivity depending mainly upon the error in the subcarrier oscillator in the receiver. If the free-running frequency of the receiver oscillator is very different from burst frequency—particularly if the difference is so great that the burst is in danger of losing control of the oscillator—then a fairly appreciable amplitude sensitivity will be noted. This sensitivity will take the form of a phase error, and the net result will be indistinguishable from a burst phase error, as discussed above.

Some receivers have a circuit which automatically adjusts the gain of the color-information channels so that the viewer always sees the proper saturations, regardless of errors which might tend either to "wash out" or to oversaturate the picture. Such a circuit, called an automatic chroma control (ACC), derives its control information from the amplitude of burst, which is presumed to bear a constant ratio to the amplitude of chroma. Transmission distortions, for example, might decrease the amplitude of both burst and chroma, but since the ratios of their amplitudes would be preserved, an ACC receiver could automatically modify its chroma-channel gain to compensate for the decreased chroma amplitude. However, if a colorplexer error should cause burst alone to decrease in amplitude, the ACC circuits would increase chroma gain just as in the above case, with the result that a viewer would receive an oversaturated picture.

Two-phase Modulation Errors

The fidelity of color reproduction can be seriously affected if the phase separation of the Q and I subcarriers is not maintained at 90°. It can be shown that a "slip" in the angular position of the Q axis, for example, will result in cross talk of Q and I. The final result will be the same as cross talk among all the primary colors.

Likewise, in a receiver, the phase relationship between the reference subcarriers must be maintained to avoid a similar error. Any deviation from the proper phase relationship will have a result similar to the above, that is, cross talk of I into Q or Q into I, with the net picture result resembling cross talk among all the primary colors.

Carrier Unbalance

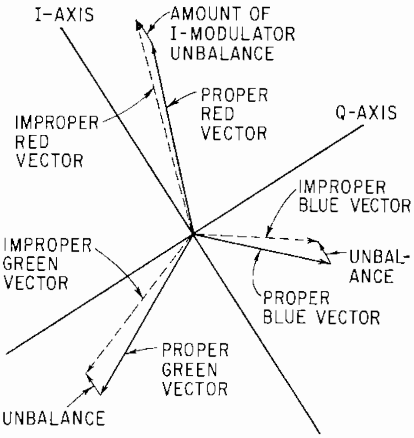

Fig. 3-15. Vector diagram of subcarrier phase and amplitude with positive vectors added to represent carrier unbalance in the I modulator.

In a properly operating doubly balanced modulator, the carrier component of the signal is suppressed in the modulator circuit. If some error in components or operation causes this suppression to be imperfect, the carrier will appear in the output. This condition is known as carrier unbalance.

The effect of carrier unbalance can be evaluated by considering the unwanted carrier as a vector of constant amplitude which adds itself vectorially to every vector present in the colorplexer output. In general, such a vector will shift all vectors and hence all hues seen in the picture toward one end or the other of the color axis represented by the unbalanced modulator. For example, a positive unbalance in the I modulator would shift all colors toward the color represented by the positive I axis, that is, toward orange. A negative I unbalance would shift all colors toward cyan.

To visualize this effect, refer to Fig. 3-15, in which has been added to each color vector a small positive vector which is parallel to the I axis. This small vector represents the amount of carrier unbalance. The resultant vectors will all be rotated toward the positive I axis and changed in amplitude as well. Such changes represent errors in both hue and saturation.

Another error from carrier unbalance occurs in white and gray areas of the picture. In a normally operating colorplexer, a white (or gray) area in the scene causes the Q and I signals to become zero and thereby causes the modulator outputs to become zero. Hence, a white or gray area will normally appear in the signal as an interval of zero subcarrier amplitude. If one of the modulators begins to produce a carrier-unbalance vector, however, a white or gray area will become colored because of the subcarrier which will be added in this interval. Moreover, certain areas which are normally colored may have their subcarrier canceled by the carrier-unbalance vector and become white. Such white-to-color and color-to-white errors are very objectionable.

Video Unbalance

A doubly balanced modulator derives its name from the fact that it balances out or suppresses both the carrier (as described above) and the modulating video (Q or I). If, for any reason, the video suppression becomes less than perfect, the resulting condition is called video unbalance.

Video unbalance will cause unwanted Q or I video to appear in the modulator output, in addition to the desired sideband outputs. This unwanted video signal will be added to the luminance signal, thereby distorting the gray scale of the picture. For example, a slight positive unbalance in the Q modulator would slightly brighten reds and blues and slightly darken greens. A negative unbalance would have the opposite effect.

Subcarrier-frequency Error

The color subcarrier frequency is specified by the Federal Communications Commission to be 3.579545 Mc ±10 cycles. Deviations within this specified limit are of no consequence (provided they are slow deviations). Large deviations, however, can affect color fidelity. The effect does not usually become serious within the possible frequency range of a good crystal-controlled subcarrier source driving a properly designed receiver.

In receivers, the subcarrier timing information is extracted from the burst on the back porch and used to control the frequency of a subcarrier-frequency oscillator in the receiver. As long as the unlocked frequencies of the burst and the receiver oscillator remain the same, the locked phase relationship between the two will remain the same. But if either the burst frequency or the receiver-oscillator frequency becomes different (and the difference between them is not so large that lockup is impossible), then the locked error, which obviously cannot be a frequency error, manifests itself as a phase error. This error can become as large as ±90° before the AFC circuit can no longer hold the receiver oscillator on frequency. The frequency range over which this phase shift occurs depends upon the receiver design.

POSSIBLE DISTORTIONS IN THE TRANSMISSION SYSTEM

Preceding sections have described the processes involved in the generation and display of a color-television signal. Errors in these processes are not the only possible source of distortion; when the signal is transmitted over great distances, the transmission system itself may contribute errors. This section discusses parameters which specify the behavior of a transmission system and describes the effects that errors in these parameters can have on the reproduced picture.

This section is divided into two parts. The first relates to the parameters of a perfectly linear transmission system, while the second part discusses the additional parameters required to describe the nonlinearities that are inevitable in any practical system.

The Perfectly Linear Transmission System

A perfectly linear and noise-free transmission system can be described by its gain and phase characteristics plotted against frequency as the independent variable.[2] Typical plots are shown in Figs. 3-16 and 3-17, respectively. These two characteristics known, it is possible to predict accurately what effect the transmission system will have on a given signal.

Gain Characteristic

Figure 3-16 is usually known as the frequency response or gain characteristic of the system. Ideally, it should be perfectly flat from zero to infinite frequency, but this, of course, is impossible to attain. An amplifier has a definite gain-bandwidth product, depending upon the transconductance of its active elements (tubes or transistors), the distributed capacity shunting these elements, and the types of compensation (peaking) employed. The bandwidth of a given combination of tubes, transistors, stray capacitances, and peaking networks can be increased only by decreasing its gain, or conversely, its gain can be increased only by decreasing its bandwidth.

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[2] If the filters in the system are of the minimum-phase type, only one of the plots is needed, for either plot can be derived from the other for this type of filter. Almost all common interstage coupling networks are of the minimum-phase type.

There is a limitation, therefore, to the actual bandwidth than can be obtained. For a given scanning standard, the bandwidth required in a monochrome-television system is determined by the desired ratio between the horizontal resolution and the vertical resolution. Although nominally a 4.0-Mc/sec bandwidth is required for the monochrome standards, the requirement can be relaxed to the detriment of only the horizontal resolution. The subjective result is a "softening" of the picture in proportion to the narrowing of the bandwidth (neglecting the influence of the phase characteristic in the vicinity of the cutoff frequency). As pointed out in preceding sections, the entire chrominance information of the color system is located in the upper 1.5 Mc of the prescribed 4.0-Mc channel; hence, any loss of response in this part of the spectrum can have a marked effect on the color fidelity of the reproduced picture.

One of the most serious forms of distortion inflicted on a color picture by bandwidth limiting is loss of *saturation*. Consider a case in which the bandwidth is so narrow as to result in no gain at the color subcarrier frequency. The output signal then contains no color subcarrier and hence reaches the color receiver as a monochrome signal, producing zero saturation. Nearly as poor results can be expected from an amplifier with response such that the gain at 3.58 Mc is one-half the low-frequency gain. Since the saturation depends chiefly on the amplitude of the subcarrier, the saturation will be correspondingly reduced. The resultant color picture will have a "washed-out" look.

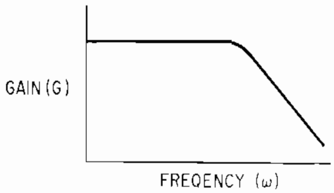

FIG. 3-16. Typical curve showing gain of a system plotted against frequency to determine its gain characteristic.

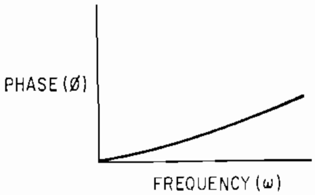

FIG. 3-17. Curve showing phase characteristic of a system plotted vs. frequency.

Loss of high-frequency response, which can be expected to contribute to loss of fidelity, is usually accompanied by phase disturbance, depending on the type of networks employed in the system. The intent in this section, however, is to treat each variable separately. Therefore, discussions are based on the effects of varying only one parameter of a system. It is suggested that the reader can determine the combined effect of two or more variables by comparing the results shown for the individual variables.

Phase Characteristic

An ideal system has a *linear* phase characteristic, as in Fig. 3-18*a*. Such a characteristic implies that all frequencies of a signal have exactly the same *time* delay in passing through this system, since the time delay is given by the phase angle divided by the (radian) frequency. It can be seen in Fig. 3-18 that if three frequencies are chosen arbitrarily, then the corresponding phase angles must have values proportional to their corresponding frequencies (because of the geometric properties of a right triangle). To state it another way, if $\phi_1/\omega_1 = 0.2\ \mu\text{sec}$, then ϕ_2/ω_2 also equals $0.2\ \mu\text{sec}$ and ϕ_3/ω_3, too, is $0.2\ \mu\text{sec}$. Plotting these three values and drawing a straight line through them as in Fig. 3-18*b* will show that the time delay for all frequencies is $0.2\ \mu\text{sec}$.

A signal is not distorted by delay as long as all parts of it are delayed by the same amount. However, when the phase characteristic is nonlinear (as in Fig. 3-19*a*), the time delays for all parts of the signal are no longer equal (see Fig. 3-19*b*). For example, if a complex waveform is made up of a 1-Mc sine wave and its third harmonic, these two components will suffer unequal delays in passing through a system having the characteristics of Fig. 3-19. The resultant distortion can be seen by comparing Fig. 3-20*a*, *b*, and *c*.

Such distortion is detrimental to both the luminance and chrominance of a composite signal. The luminance signal will have its edges and other important details *scattered*, or *dispersed*, in the final image. Such a transmission system is said to introduce *dispersion*. (Conversely, if a system does not scatter the edges and other high-frequency information, it is said to be dispersionless.) The effect of phase distortion on the chrominance information is of a rather special nature and can best be explained by introducing the concept of *envelope delay*.

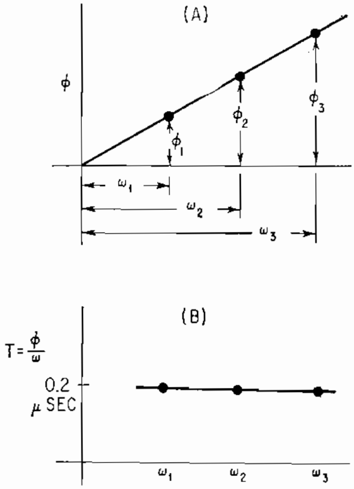

FIG. 3-18. Curves illustrating a system with linear phase characteristics, which will give the same time delay for signals of all frequencies.

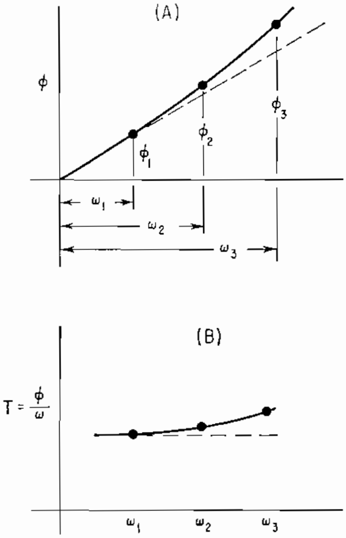

FIG. 3-19. Curves showing the effect of nonlinear phase characteristic on the time-delay characteristic.

Envelope Delay

In the preceding discussion, the time delays ϕ_1/ω_1, ϕ_2/ω_2, and ϕ_3/ω_3 were always determined by measuring the frequencies and the phases from $\omega = 0$ and $\phi = 0$. It might be said that the delay at zero frequency is commonly taken as the reference point for all other delays. This method is usually adequate for determining the performance of systems that do not carry any signals which have been modulated onto a carrier. But a carrier, with its family of associated sidebands (Fig. 3-21*b*), can be thought of as a method of transmitting signals in which the zero-frequency reference is translated to a carrier-frequency reference. This translation can be understood by referring to Fig. 3-21*a* and *b*. To calculate the delay of the carrier-borne signals *after* they have been demodulated, measurements of ϕ and ω must be referenced, not from zero frequency, but from *carrier* frequency.

In Fig. 3-22*a*, an impossible phase characteristic has been drawn to aid in further discussion of this subject. Such a characteristic, consisting of two perfectly straight lines, is never met in practice but makes a very simple system for developing the subject of envelope delay.

First, pass two frequencies ω_1 and ω_2 through this system. Let ω_1 be a carrier and ω_2 a sideband which might be, for example, 1,000 cycles higher. If ω_1 and ω_2 fall on the characteristic as shown in Fig. 3-22*a*, the delay which the 1,000 cycles will show after demodulation can be found putting new reference axes (shown dotted) with ω_1, the carrier, at zero on these new axes. Now, when ω_s and ϕ_s are measured as shown, the time delay after demodulation is ϕ_s/ω_s. In this case, the delay of the 1,000 cycles after demodulation is the same as it would have been had it been passed through the system directly.

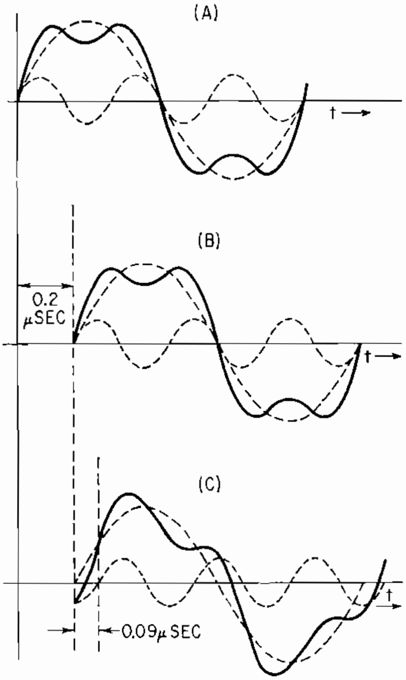

Fig. 3-20. Curves showing that a complex wave (*A*) is not distorted by time delay (*B*) when both components (shown dotted) are delayed by the same amount. Unequal delays (*C*), however, cause distortion.

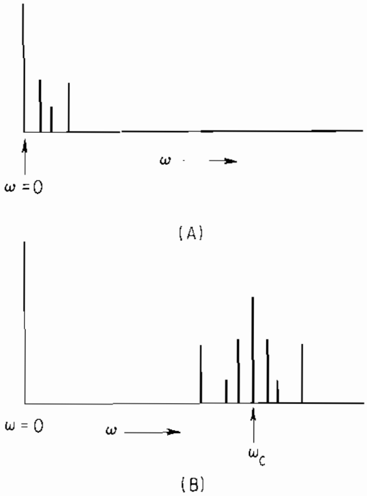

Fig. 3-21. Sketch showing how a group of frequencies near $\omega = 0$ [see (*A*)] can be translated by modulation onto a carrier to a group of sidebands near ω_c – a carrier frequency (*B*).

Second, pass two other frequencies ω_3 and ω_4 through this system as redrawn in Fig. 3-22*b*. This time drawing in the new axes at ω_3, it can be seen that although ω_s is still 1,000 cycles, ϕ_s' is larger than ϕ_s. Therefore, it can be concluded that the time delay ϕ_s'/ω_s for this second case is greater than for the first case. The 1,000 cycles, when demodulated, will show a considerable error in timing.

Stressing the phrase "delay after demodulation" should not be taken to mean that the demodulation process produces this delay or even makes it apparent where it was previously not detectable. Any delay that a demodulated wave shows was also present when the wave existed as a carrier having an envelope. In short, the delay of the demodulated wave appears first as a delay of the envelope, hence the phrase "envelope delay."

Envelope delay does not constitute a distortion. If a system such as the one shown in Fig. 3-22*a* introduces a delay of 0.2 μsec to the 1,000-cycle wave (measured after demodulation), then the *envelope delay* of the system is 0.2 μsec. However, it was shown that a 1,000-cycle signal passed directly through the system (without first being modulated into a carrier) would also suffer a delay of 0.2 μsec. As long as the envelope delay ϕ_s/ω_s is the same as the time delay ϕ_1/ω_1, the envelope delay introduces no timing errors. But in the second system (Fig. 3-22*b*) the demodulated 1,000-cycle wave suffered a *larger* delay, say 0.29 μsec. A 1,000-cycle signal passed directly through this system, however, would still be delayed only 0.2 μsec. Therefore, the second system has an *envelope delay* of 0.29 μsec and an *envelope-delay distortion* of 0.09 μsec.

It is probably wise to point out that the time delay ϕ_3/ω_3 in Fig. 3-22*b* is considerably less than the 0.29 μsec estimated for the value of envelope delay. Although ϕ_3/ω_3 would be greater than 0.2 μsec (say, for example, that ϕ_3/ω_3 is 0.22 μsec), the value would be optimistic about the amount of timing error that would be shown by the demodulated 1,000-cycle signal. The need for a knowledge of the envelope delay ϕ_s/ω_s of the system is therefore obvious.

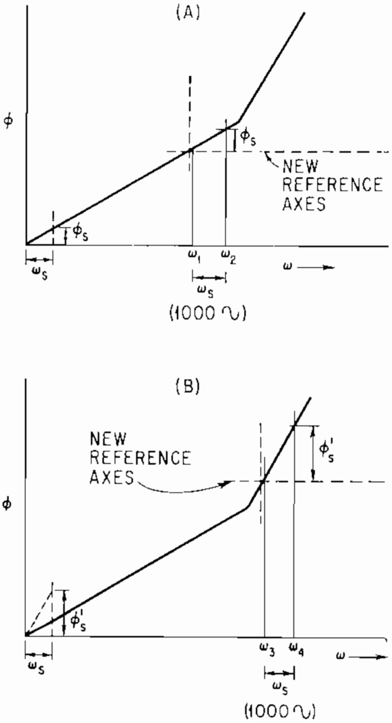

Fig. 3-22. Idealized straight-line phase characteristics showing how a carrier-borne 1,000-cycle signal can be delayed excessively when the carrier and sideband fall on a steeper portion of the phase characteristic.

Effect of Envelope-delay Distortion on a Color Picture

A transmission system which exhibits envelope-delay distortion will destroy the time coincidence between the chrominance and luminance portions of the signal. This will result in misregistration between the color and luminance components of the reproduced picture. The following paragraph explains briefly how envelope-delay distortion causes this error.

Any colored area in a reproduced picture is derived from two signals—a chrominance signal and a luminance signal. Since these two signals describe the same area in the scene, they begin and end at the same time. The chrominance signal arrives at the receiver as a modulated subcarrier; the luminance signal does not. Therefore, as shown above, the delay of the chrominance signal is determined principally by the envelope delay of the system and the delay of the luminance signal is determined principally by the ordinary time delay ϕ/ω. If the two delays are not identical (that is, if there is envelope-delay *distortion*), then the chrominance signal does not coincide with the luminance signal and the resultant picture suffers *color-luminance misregistration* in a horizontal direction.

For example, in a system having the characteristic of Fig. 3-22*b*, the luminance signal is delayed by 0.2 μsec but the chrominance signal is delayed by 0.29 μsec. The error in registration then amounts to 0.09 μsec, or about 0.2 per cent of the horizontal dimension of the picture, which is about 0.3 in. on a 21-in. (diagonal) picture.

Although the subject of compatibility is outside the scope of this part, it is worth noting in passing that envelope-delay distortion adversely affects compatibility, since it causes wideband monochrome receivers to display a misregistered dot-crawl image in addition to the proper luminance image.

General Method for Envelope Delay

The specific cases described above (Fig. 3-22*a* and *b*) made use of simple, idealized straight-line approximations to develop the concept of envelope delay. Practical circuits are not so simple. For example, a simple *RC* network has a ϕ vs. ω plot as in Fig. 3-23. Finding the envelope delay of this curved-line plot will clarify what is meant by envelope delay.

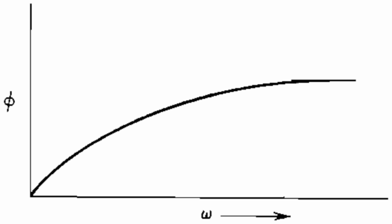

Fig. 3-23. Phase characteristic of an *RC* network.

Referring back to the plots of Fig. 3-22*a* and *b*, it can be seen that the characteristic of the plot that determines the value of envelope delay is its *slope*. The larger envelope delay, which was suffered by the ω_3-ω_4 pair (Fig. 3-22*b*), was a result of their lying on the steeper slope. The envelope delay of *any* system is equal to the slope of the phase-vs.-frequency characteristic. If this characteristic is a curved line (as for the *RC* network, Fig. 3-23), then the slope is different at every frequency and, therfore, the envelope delay is different at every frequency.

The slope of a curved line can be found by the methods of the differential calculus or to a good approximation by breaking up the line into a number of straight-line segments, as in Fig. 3-24. If the slope of each of these straight lines is then plotted against its corresponding frequency (that corresponding to the center of the line), the resulting curve will be approximately the envelope-delay characteristic.

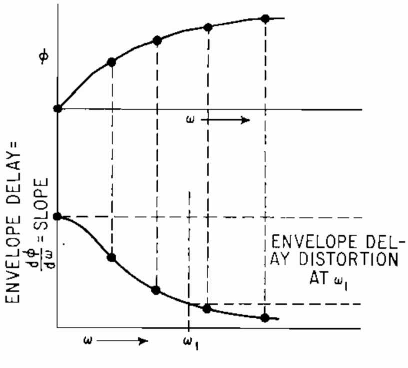

Fig. 3-24. Graphs showing how a series of straight-line segments can be used to approximate the smooth curve of Fig. 3-23 (top) and how the slopes of these segments may be plotted to approximate the envelope delay characteristics (bottom).

Nonlinearities of a Practical Transmission System

It is important to emphasize that the effect of nonlinearities in a color-television system depends upon whether these nonlinearities precede or follow the matrixing and modulation sections of the system. Nonlinearities in transfer characteristics detract from color fidelity; the same degree of nonlinearity after matrixing and modulation also affects color fidelity although in a different way. The purpose of the following paragraphs is to discuss how a nonlinear transmission system affects a *composite* color signal. It is assumed that all other nonlinearities in the entire system either are negligible or have been canceled by use of nonlinear amplifiers such as gamma correctors.

The major sources of nonlinearity in a transmission system are its amplifying devices.[3] These devices—tubes and transistors—have a limited dynamic range. For example, if too much signal is supplied to them, an *overload* results. The transfer characteristic of such a system can be sketched as in Fig. 3-25*a*.

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[3] FM systems can have nonlinearity as a result of *passive* networks, but this case is not considered here.

Such a nonlinearity is one of three types commonly encountered in video transmission systems. These three types are:

1. Incremental gain distortion
2. Differential gain
3. Differential phase

The paragraphs below will show that type 2 is merely a special case of type 1.

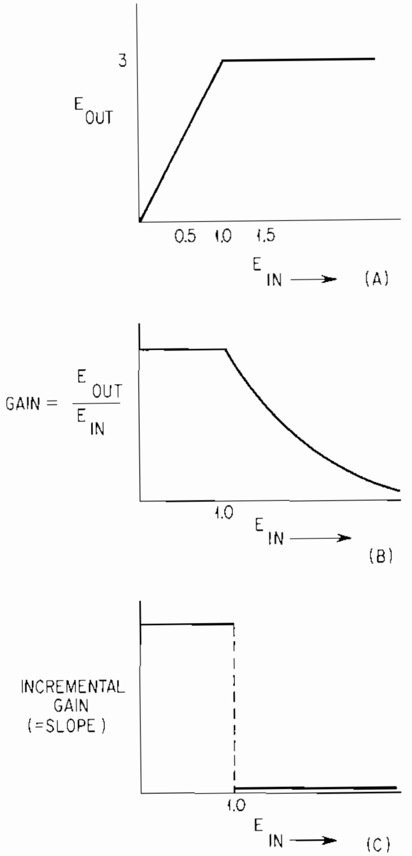

Fig. 3-25. Idealized straight-line plots showing (*A*) output voltage of an amplifier vs. input voltage, (*B*) gain of the amplifier vs. input voltage, and (*C*) incremental gain of the amplifier vs. input voltage. Curve (*C*) is the slope of curve (*A*).

Incremental Gain

The concept of the slope of a plot, developed in the discussion of envelope delay, will be useful here as well. Consider a plot as in Fig. 3-25*a* which shows output voltage of an amplifier plotted against input voltage. Idealized straight-line plots are shown for simplicity. It can be seen that the amplifier has a maximum output of 3 volts for 1-volt input. Larger input voltages result in no more output; the amplifier *clips* or *compresses* when inputs larger than 1 volt are applied.

The gain of the amplifier is

$$\text{Gain} = \frac{E_0}{E_{in}} = \frac{3 \text{ volts}}{1 \text{ volt}} = 3$$

The gain is obviously constant below the clip point. For example, an input voltage of 0.5 volt gives

$$\text{Gain} = \frac{1.5 \text{ volts}}{0.5 \text{ volt}} = 3$$

But at an input of 1.5 volts, the output is still 3 volts, so the "gain" is only 2. (The word "gain" is of doubtful use here because of the clipping involved.) The gain, defined as E_0/E_{in}, is plotted against E_{in} in Fig. 3-25*b*. It can be seen in this figure that the gain is constant only as long as the *slope* of Fig. 3-25*a* is constant.

It is useful, then, to establish a new term, called *incremental gain*, which will be defined as the *slope* of a plot such as Fig. 3-25*a*. For the particular plot of Fig. 3-25*a*, the slope is constant up to $E_{in} = 1$ volt and then suddenly becomes zero. The corresponding plot of slope vs. E_{in} is shown in Fig. 3-25*c*.

The importance of incremental gain in color television can be assessed by applying the input signal shown in Fig. 3-26 to the distorting system of Fig. 3-25*a*. Before being applied to the distorting system, such a signal could be reproduced on a monochrome receiver as a vertical white bar and on a color receiver as a pastel-colored bar, say, for example, a pale green. After passing through the distorting system, the signal would still be reproduced as a white bar on the monochrome receiver with the only apparent error being a luminance distortion, that is, a slight reduction in brightness, which, for the magnitudes shown here, would probably pass unnoticed. The color receiver, however, would receive a signal completely devoid of any color information and would reproduce a white bar in place of the former pale-green one.

A less extreme case is shown in Fig. 3-27. For the system represented by this characteristic, the slope (incremental gain) does not become zero for inputs above 1 volt but instead falls to one-half its below-1-volt value. The color signal of Fig. 3-27 would not lose all color in passing through this system, but the amplitude of the subcarrier would become only one-half of its proper value. Since saturation is a function of subcarrier amplitude, the pale green of the undistorted reproduction would, in this case, become a *paler* green. The luminance distortion would also be less than in the extreme (clipping) case.

It can be seen, then, that unless the incremental gain of a system is constant, that system will introduce compression, which will distort the saturation and brightness of reproduced colors. Usually, the error is in the direction of *decreased* luminance and saturation. For certain systems, however, exceptions can be found. For example, the effect that the system represented by Fig. 3-27 will have on a signal depends on the polarity of the signal. For the signal as shown, the usual *decrease* in luminance and saturation is exhibited. For an inverted signal, however, the subcarrier amplitude would not be reduced, but the luminance signal would still be diminished. The subjective result of this distortion would be an *increase* in saturation. The unusual behavior of this particular system is attributable to its peculiar transfer characteristic, which was drawn with curvature at one end only to simplify the discussion. Most practical system-transfer characteristics exhibit curvature at both ends and therefore have an effect on the signal which is essentially independent of polarity.

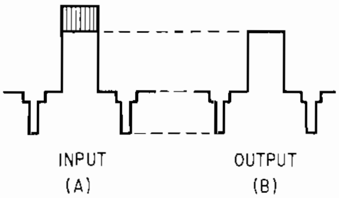

Fig. 3-26. Extreme case of distortion resulting from passing signal at left (*A*) through the amplifier represented by Fig. 3-25. The output (*B*) has no color information remaining.

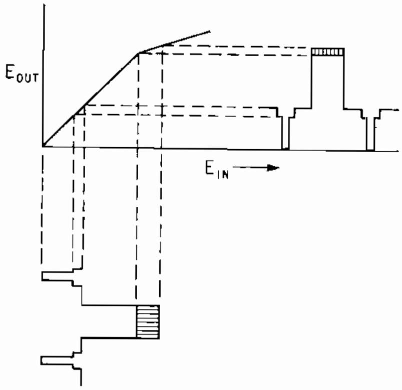

Fig. 3-27. Diagram showing effect of incremental gain distortion in reducing amplitude of color portion of signal.

Incremental gain can be measured in two ways, the first of which stems from its contribution to luminance distortion and the second, from its contribution to chrominance distortion.

In the first method, an equal-step staircase waveform such as shown in Fig. 3-28*a* is applied to the system to simulate a signal having equal luminance increments. If the system has constant incremental gain, the output will, of course, also have equal-step increments. But if the system does not have constant incremental gain, certain of the steps will be compressed, as in Fig. 3-28*b*. If the compression is as in the figure, the *incremental gain distortion* (IGD) is indicated by the distorted amplitude of the last step. Numerically, it can be stated as a percentage:

$$\text{IGD} = 1 - \frac{S_{\text{distorted}}}{S_{\text{undistorted}}} \times 100\%$$

where S is a step amplitude.

For example, if an undistorted step is 0.1 volt and the distorted one is 0.075 volt, then the incremental gain distortion would be 25 per cent.

Using the other (chrominance distortion) technique, an input signal consisting of the step wave plus a small, high-frequency sine wave, as shown in Fig. 3-28*c*, is applied to the system. After the signal has passed through the system, it is fed through a high-pass filter which removes the low-frequency staircase. The incremental gain distortion then is indicated by the differences in the amplitude of the high-frequency sine waves (see Fig. 3-28*d*). In this case, the high-frequency sine wave associated with the top step is shown as having 75 per cent of the amplitude of the sine waves associated with the lower steps, which are assumed to be undistorted. Again, the incremental gain distortion is 25 per cent.

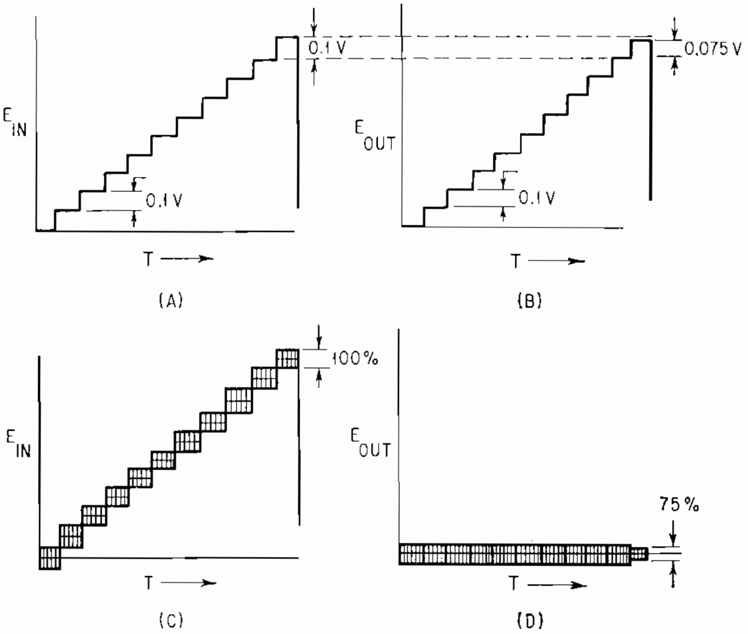

Fig. 3-28. Diagrams showing two methods of measuring incremental gain distortion, namely, in (*A*) and (*B*) by its contribution to luminance distortion and in (*C*) and (*D*) chrominance distortion.

A most important point must be made regarding the equivalence of these two techniques. Certain systems which show incremental gain distortion when tested by the luminance-step technique may or may not show the same distortion when tested by the high-frequency and high-pass-filter technique. Moreover, a system which shows distortion by the second technique may or may not show distortion by the first. In other words, the incremental gain distortion may be different for different frequencies. Such differences are frequently found in staggered amplifiers, feedback amplifiers, or amplifiers having separate parallel paths for high and low frequencies, such as might be found in stabilizing amplifiers.

A thorough test of a system, therefore, should include tests of its incremental gain by both techniques. The staircase-plus-high-frequency waveform can be used to provide *both* tests by observing the system output (for this test waveform input) first through a low-pass filter and then through a high-pass filter. The first test will show low-frequency distortions; the second, high-frequency distortions.

Differential Gain

On the basis of the above discussion of incremental gain distortion, the extremely important concept of *differential gain* can be presented merely as a simple definition. Differential gain is identical with incremental gain distortion when the latter is measured by observing ". . . the difference in the gain of the system for a small high-frequency sine-wave signal at two stated levels of a low-frequency signal upon which it is superimposed."[4] In other words, differential gain is a special form of incremental gain distortion which describes the IGD of a system for the superimposed high-frequency case only.

One of the reasons for selecting the high-frequency aspect of incremental gain distortion for the IRE definition of differential gain was applied in Fig. 3-26, when the ". . . high-frequency sine wave . . ." of the definition was made equal to color subcarrier. This special case of differential gain explores the system gain linearity in the vicinity of this particularly important frequency. The definition of differential gain was purposely made in the broad terms of a ". . . high-frequency sine wave . . ." to allow the greatest possible versatility in devising methods of measurement. In present color-television practice, however, the ". . . high-frequency sine wave . . ." is always color subcarrier and the low-frequency signal mentioned in the definition is a 15,750-cycle staircase, sine-wave, or sawtooth. The complete specifications for the signal presently used in this measurement will be found elsewhere in this manual.

Another reason for emphasizing high-frequency IGD was implied previously by the sentence ". . . the signal . . . would . . . be reproduced . . . with the only apparent error being a luminance distortion . . . which, for the magnitudes shown here, would probably pass unnoticed." The magnitude shown was a 25 per cent IGD, which is passing unnoticed, indicating that large incremental gain distortions usually cause no detectable luminance errors. Incremental gain distortion is almost too sensitive a tool to measure luminance distortions. For this purpose, simple gain distortion (compression) is more useful. Therefore, the luminance-distortion aspect of IGD was deliberately omitted from the definition of differential gain.

Incremental Phase and Differential Phase

The phase characteristic sketched in Fig. 3-17 indicates that the system described by this plot will introduce a certain amount of phase shift for any given frequency. For example, it might be found that a certain system would introduce a phase shift of 60° at 2 Mc/sec. If the system in question were perfectly linear, this 60° phase shift would be produced regardless of how the 2-Mc/sec signal might be applied to the system.

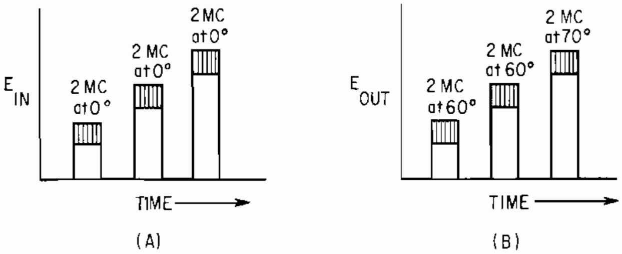

FIG. 3-29. Graphs illustrating how a signal (*A*) may undergo different phase shifts (*B*) depending upon where the zero axis at the sine wave falls on the system transfer characteristic. This distortion is called differential phase.

It can be shown, however, that some systems, when presented with a signal of the type shown in Fig. 3-29, will introduce a delay *different* from 60°, depending on where the zero axis of the sine wave falls on the transfer characteristic of the system. For

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[4] From the definition of differential gain by IRE Subcommittee 23.4.

the case sketched in the figure, a phase shift of 70° is drawn for the largest zero-axis displacement.

By analogy with the incremental gain and differential gain arguments above, it is possible to define three quantities which pertain to this type of distortion. These quantities are *incremental phase, incremental phase distortion,* and *differential phase.* It can also be shown that of the three, differential phase is the most important quantity.

Incremental phase is the least exact analogue, since it is not very similar in form to incremental gain. Incremental *gain* is a *slope;* incremental phase is simply the absolute value of phase shift. In the above system, the incremental phase was 60 or 70° (or somewhere in between), depending upon the location of the zero axis.

Incremental phase distortion, like its analogue *incremental gain distortion,* depends upon the magnitude of the error. It should be zero for a perfect system. In the system of Fig. 3-29 the 2-Mc/sec signal with 70° incremental phase would be said to have 10° incremental phase distortion, so it is clear that the difference between two phases (one of which is assumed to be "correct") gives the incremental phase distortion.

As previously stated, *differential gain* is identical with *incremental gain distortion* for the superimposed-high-frequency case only. Similarly, *differential phase* is identical with *incremental phase distortion,* but there is no need to limit the definition to the superimposed-high-frequency case, since there is no other case which is meaningful for phase distortion. Without the superimposed sine wave, no phase measurement is possible. Therefore, differential phase is identical with incremental phase distortion. In practical work, the first two terms are seldom used, for the last, differential phase, has been found completely adequate to describe this aspect of a system.

In summary, the differential phase of a system is ". . . the difference in phase shift through the system for a small high-frequency sine-wave signal at two stated levels of a low-frequency signal on which it is superimposed." [5]

It is important that the phrases "differential phase *distortion*" and "differential gain *distortion*" be avoided because differential phase *is* distortion as is differential gain, since they are defined as being identical with incremental phase distortion and incremental gain distortion, respectively. To add the word *distortion* to either is redundant. A sample of proper usage is "this amplifier has a differential gain of 1.5 per cent and a differential phase of 0.5°."

Effect of Differential Phase on a Color Picture

The phase of subcarrier in a composite signal carries information about the *hue* of the signal at that instant. If the signal passes through a system which introduces differential phase, the subcarrier phase (and hence, the hue) at the output will become dependent upon the amplitude of the luminance associated with the hue, since it is the luminance signal which determines the location of the zero axis of the subcarrier. For example, a system introducing 10° of differential phase might be adjusted to reproduce properly a low-luminance hue such as saturated blue or a high-luminance hue such as saturated yellow, but *not both.* One or the other would have to be in error.

STATE OF THE ART

The preceding portions of this part have discussed in general terms the possible sources of color errors in a color-television system. In no practical system can any of these errors be reduced to zero; therefore, anyone working with practical systems should know how nearly perfect any given parameter should be to be considered acceptable according to the present state of the art.

System Colorimetry

Talking qualitatively about colorimetric accuracy is one thing; assigning numbers and magnitudes is quite another. For the practical purposes of this part, however,

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[5] From the definition of differential phase by IRE Subcommittee 23.4.

we are spared the need of digging deeply into the quantitative aspects of colorimetry by one simple fact: At the present time, color errors attributable to phosphor errors, filter errors, and other basic colorimetric errors are negligible in comparison with other sources of error.

System Exponent

At the present state of the art, adjusting a system to precompensate for a kinescope exponent of 2.2 is not enforced by the Federal Communications Commission, since this parameter is not yet well established. Adjusting the system to precompensate for this median value, however, can be done with precision. A gamma corrector which uses four or five diodes to make a series of straight-line approximations to a 0.7 exponent can be made so as to have a maximum error of less than 2 per cent of the peak signal amplitude. The exponents of the three channels can be made to match within 1 per cent of the peak signal amplitude.

Matrix Coefficients

A high-quality matrix, such as would be found in a well-engineered colorplexer or studio monitor, uses 1 per cent precision resistors for all resistances which will influence the values of the coefficients, while inverters and amplifiers are either stabilized by feedback or made adjustable. Errors of greater than 2 per cent are rare in such circuits.

White balance in the transmitter matrix, which is a special case of the subject of matrix coefficients, can usually be adjusted and held to a tolerance of the order of ½ per cent of peak white.

Phase Accuracies

Adjustment of Q subcarrier, I subcarrier, and burst to within 1° of their proper relative phases is easily accomplished using standard commercial equipment and techniques. This accuracy is ten times that required by the Federal Communications Commission.

Subcarrier-frequency Accuracy

Subcarrier frequency can be easily adjusted to within ±1 cycle, the real limit on the accuracy of the adjustment being in the inherent accuracy of the standard used for frequency comparison. Long-term stability of well-engineered equipment should be easily within the required limits of ±10 cycles.

Transmission Characteristics

A single amplifier should have a gain characteristic with less than ±½-db variation out to 8 Mc. Its envelope-delay error should be of the order of 0.001 μsec at 3.58 Mc, relative to 200 kc. Differential gain of ½ per cent and differential phase of 0.25° represent good performance.

TOLERABLE COLOR ERRORS

The eye's sensitivity to color errors depends upon the manner in which two colors—the original and the reproduction—are compared. For example, if the two colors are placed side by side, the eye becomes a very sensitive indicator of color errors. However, if the comparison is made only by color memory, the eye is far more lenient in its requirements of perfect reproduction. Furthermore, if the reproduced color is one that the eye has never viewed before, the eye requires only that the color relayed to the brain be plausible, that is, that it be a reasonable color for the object concerned.

Fortunately, side-by-side comparison of colors never occurs in home viewing of color television. However, the system is frequently called upon to reproduce objects whose colors may be well known to the viewer, such as flesh tones or a sponsor's packaged product. The reproductions of these objects must be accurate enough to satisfy the viewer's color memory. And if the system can satisfy the color memory of the viewer, the color-plausibility requirement will be easily met.

Several investigations have been made to determine the sensitivity of the eye to color errors expressed as burst phase errors, Q amplitude errors, etc. The results of two of these investigations [6] are summarized briefly in the following paragraphs:

Above all, it must be borne in mind that the following information represents the effect of changing only the parameter specified while every other parameter in the system remained constant and as nearly perfect as possible. In all cases, the data resulted from subjective tests of a fairly large number of viewers, and almost every viewer used flesh-tone reproduction as the criterion of acceptability. All but the phase data below are from the second reference. The error magnitudes indicated resulted in marginal pictures; larger errors caused the average viewer to class the pictures as "not quite passable."

The amplitudes of the three primary colors themselves proved to be the most critical, in general, of all the variables measured. A −27 per cent change in green could be tolerated; a −28 per cent change in red was found allowable. The permissible positive changes in these colors were 40 and 32 per cent, respectively. Tolerable blue changes were −35 and +53 per cent. Subcarrier amplitude, it was found, could vary ±45 per cent before the pictures were objectionably degraded. A comparatively small negative change in M amplitude, −30 per cent, raised viewers' objections, but a fairly large position error, −72 per cent, could be tolerated. The amplitude of I could fall only 34 per cent before the pictures were rejected, but it could rise 70 per cent before the reproductions were classed as definitely below par. The least sensitivity was shown by Q (namely, −94 and +135 per cent), but the reader should again be reminded that observers admitted using flesh-tone reproduction as the criterion of acceptability, and Q contributes very little to flesh tone.

Also of interest are the approximate variations allowed before the reproductions were downgraded from "excellent" to "good." The three primaries were allowed approximately a ±20 per cent variation: subcarrier amplitude, about a ±30 per cent variation; M and I both about +40, −20 per cent; and Q about +60, −55 per cent.

Both of the investigations referred to agree that the maximum phase error for tolerable picture reproduction was about ±20° for the average observer. The first investigation reported, in addition, that although this figure represented the numerical average, a phase tolerance of about ±11° was all that could be tolerated by 90 per cent of the observers.

If the reader finds these tolerances to be large in comparison with the magnitudes discussed before, he is reminded that a number of cascaded elements in a system may provide an appreciable fraction of these magnitudes and that furthermore, the errors in a typical operating system will include simultaneously *several* of these degrading factors. Also, the subcarrier amplitude and phase in the receiver are under the control of the viewer, who sets them without the aid of any measuring device other than his eyes' judgment. Therefore, careful attention to all parameters at the point of origin is essential to the production of good pictures in the viewer's home.

Conclusion

Although this part may appear to be negative in its approach to the subject of color fidelity, the reader should bear in mind that, in spite of these seemingly unfavorable descriptions of what *might* happen in a system, the picture quality at the output of a *properly adjusted* color-television system is excellent. The apparent pessimistic attitude results, of course, from the need for defining the boundaries of system performance. Therefore, in conclusion, let it never be forgotten that, within these boundaries, there lies one of the best commercial color-reproducing systems that has ever been devised.

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[6] Pritchard, "Visibility of Hue Change versus Overall Phase Error in N.T.S.C., Proposed Color Television Specifications," RCA Internal Report. Weiss, Significance of Some Receiver Errors to Color Reproduction, *Proc. IRE*, vol. 42, no. 9, September, 1954.

Part 4

THE COLORPLEXER

The RCA colorplexer performs the required encoding and processing of RGB signals emanating from the color camera and produces a color video signal conforming to FCC specifications.

As the "heart" of the color system, the colorplexer centralizes a number of very important operating adjustments. Figure 4-1 shows the functional location of the equipment in the basic color-television system.

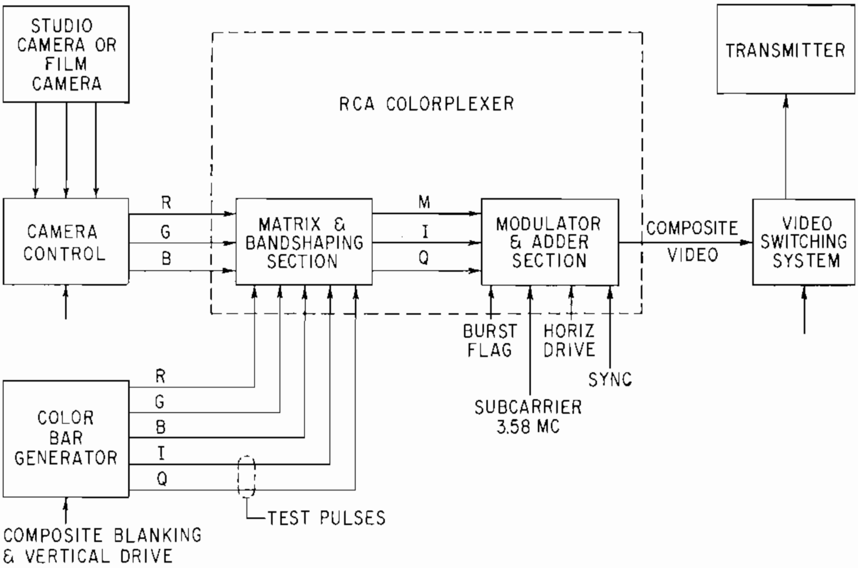

Fig. 4-1. Basic color-television system showing functions and major components of the colorplexer.

BASIC FUNCTIONS

The principal operations and functions performed by the colorplexer include:

1. Matrixing of RGB video signals to produce luminance and chrominance signals
2. Filtering of chrominance signals to required bandwidth
3. Delay compensation to correct for band limiting
4. Modulation of 3.58-Mc carriers by chrominance signals
5. Insertion of color sync burst

6. Aperture compensation of luminance signal
7. Optional insertion of sync
8. Addition of signal components to form a complete color signal

Derivation of luminance and chrominance signals and the principles of matrixing, bandwidth limiting, and color subcarrier modulation are described in Part 2. Aperture compensation is employed to boost the amplitude of the high-frequency component of the video signal, improving the over-all video-response characteristic. This technique is desirable because the finite size of the camera scanning beams, together with the limited resolving power of lenses, produces a video signal with deficient contrast range in picture areas with fine detail. The aperture compensation circuit, which is described in later paragraphs, is of a type that boosts high-frequency components without distorting their phase.

DESIGN FEATURES

The RCA colorplexer, type TX-1, consists of three chassis units designed for installation in a standard 19-in. rack, requiring a total height of only 26 in.

Several features are incorporated in the colorplexer circuits to facilitate operation and to enhance picture quality.

Provision is made for shifting the phase of the incoming 3.58-Mc carrier through 360° to permit signals from several colorplexers to be lined up with respect to subcarrier phase at some common point, such as the output of the switching system.

An automatic-balance-control circuit for the carrier provides instantaneous correction voltages for maintaining carrier balance in the modulators at all times, although manual balance adjustments are provided in the modulators to permit both differential gain and a-c impedance measurements to be made.

A selector switch in the colorplexer gives the operator a choice of two inputs—camera signals or test signals from a color-bar generator. The color-bar generator provides a total of five signals. These signals consist of the RGB video signals plus special test pulses which are very useful in checking phase adjustments of the I and Q modulators. I and Q test pulses are inserted directly into the I and Q channels as shown.

Operating controls for the various functions are mounted on the front of the chassis. Test jacks installed at several points in the circuits provide for observation of waveforms. A few of these waveforms are discussed later, under Colorplexer Operation.

Circuit Description

To aid in describing the circuits, the colorplexer has been divided into two sections in accordance with their functions. In the matrix and band-shaping section, the red, green, and blue signals are transformed into M, I, and Q signals, which are then adjusted with respect to bandwidth and delay. The multiplexing operations required to produce a composite signal from the M, I, and Q signals take place in the modulator and adder section.

Matrix and Band-shaping Section

With reference to the basic circuit arrangement for the matrix and band-shaping section of the colorplexer, RGB signals at 1-volt levels are fed through coaxial jacks and applied through the matrix resistor network to the grids of separate M, I, and Q pentode amplifiers.

In the M amplifier, sync is combined with the matrixed RGB signals to form the composite monochrome signal, which is fed through a coaxial delay line to amplifiers in the modulator-adder section.

The I signal is developed in the I amplifier by application of a red signal to the control grid and blue and green signals to the cathode. This I signal is then fed through a coaxial delay line, a 1.5-Mc band-limiting filter, and a phase splitter to the I modulator tubes. It so happens that the signal produced by the I channel is inverted in polarity relative to the M and Q signals, but this poses no problem in view of the fact that the polarity is readily corrected by proper connections in the modulator which follows.

The Q signal is obtained by applying the green signal to the control grid of the Q amplifier and the red and blue signals to the cathode. The Q signal then passes through an 0.5-Mc filter, amplifier, and phase splitter to the Q modulators. Delay networks, which compensate for band-limiting of the chrominance signals, consist of specified lengths of high-impedance delay cable. A sync delay line is not required, since sync is added to the monochrome signal ahead of the delay line.

Aperture Compensation

As previously mentioned, the aperture compensator is employed to compensate for the finite size of the electron scanning beam in color studio or film cameras. The aperture compensator is connected electrically to the colorplexer, and no other aperture compensation is necessary in the system.

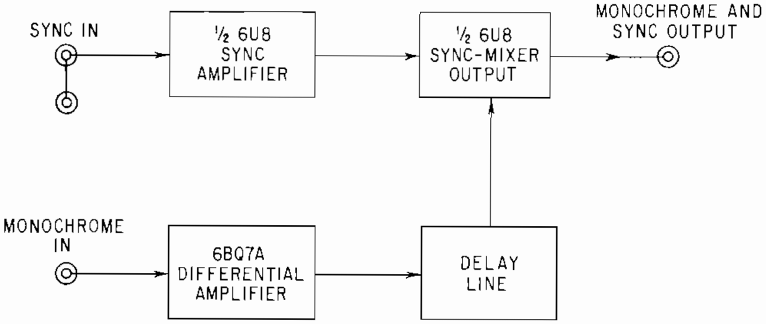

FIG. 4-2. Simplified block diagram of aperture compensator.

Since the monochrome channel is a wideband channel and the I and Q channels are narrow band, it is necessary to apply compensation to only the monochrome channel. It is not desirable to aperture-compensate the sync signal; therefore provision is made for adding sync after compensation.

Circuitry of the aperture compensator is shown in the simplified block diagram of Fig. 4-2. The circuit consists of a differential amplifier which feeds an open-circuited delay line. The open-circuited end of the delay line is connected to the grid of an output amplifier which drives the monochrome delay line. Part of the plate load of the output amplifier is common to the sync amplifier; thus sync can be added at this point if desired.

Modulators and Automatic Carrier Balance

Circuits required to produce the I and Q color subcarrier, insert the color burst, and multiplex the monochrome and color video signals are shown in simplified form in Diagram B. The basic components consist of two pairs of balanced modulators, amplifiers for the 3.58-Mc carrier with provision for 90° phase displacement, "adder" stages for combining the composite M signal with the color and burst signals, and automatic-balance-control circuitry for the carrier to maintain complete 3.58-Mc carrier suppression in the output of the modulators.

I and Q signals developed in the matrix and band-shaping sections of the colorplexer are applied through tube-type phase splitters (in phase opposition) to the control grids of the balanced modulators, while 3.58-Mc carrier voltages with a 90° phase difference are applied to the suppressor grids. Since the plates of the modulators are in parallel, the carrier voltages in each pair of modulators cancel out, leaving only the signal which is the vector sum of the I and Q sidebands in phase quadrature.

The composite color signal from the output of the adders is applied to a two-stage gate in the automatic-balance-control unit for the carrier (see Fig. 4-3). This gate is normally biased in the "off" condition, but it is keyed by horizontal drive pulses, which make it conduct only during the horizontal blanking time (prior to color sync burst) so that only the signal components of the unbalanced subcarrier are amplified. Output from the gated amplifier is fed to two bridge-type diode discriminators through tuned circuits. Reference subcarrier signals are applied in phase quadrature to the two discriminators in such a way that each develops an output voltage proportional to the carrier unbalance in either the I or the Q channel. These correction voltages are then applied as bias voltages to the I and Q modulators to maintain a state of proper balance.

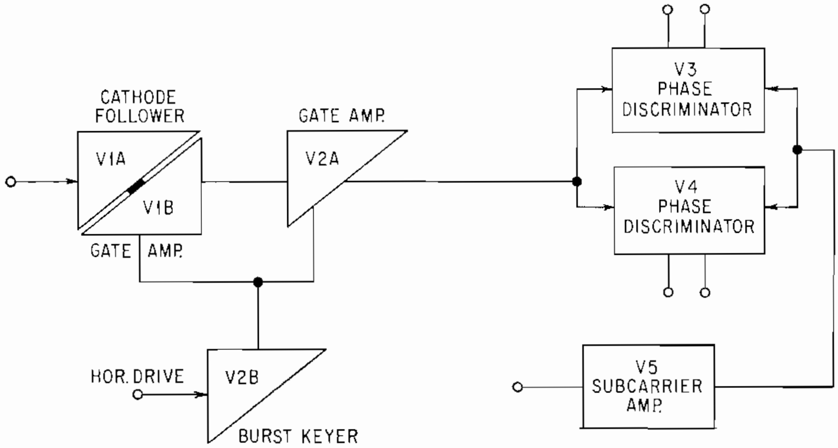

FIG. 4-3. Block diagram of automatic carrier-balance control circuits.

Adders and Output Amplifiers

The complete color signal is formed in the common plate circuits of the monochrome, chroma, and burst adder stages. From these stages the color signal is passed through two feedback amplifiers. The first of these provides most of the required voltage gain and contains a low-impedance video gain control. The second feedback amplifier is the output stage which has sufficiently low output impedance to permit the connection of three separate 75-ohm outputs with a high degree of isolation. The composite color signal is clamped at the proper level in the first feedback amplifier by a clamp tube driven by horizontal drive.

The subcarrier signal, supplied from a frequency standard operating at 3.579545 Mc, is applied through an amplifier and adjustable phase-shifting network to phase-displacement networks that provide subcarrier signals of correct phase displacement for the burst gate, modulators, and automatic carrier-balance circuits. A keying signal from tbe burst flag generator is applied through an inverter tube to the suppressor of the burst gate. The 57 and 33° delay elements shown in the block diagram provide the necessary phase relationship between burst and I and Q signals as described previously.

OPERATION OF THE COLORPLEXER

Correct settings for the operating controls of the RCA colorplexer are obtained by following a step-by-step procedure described in the "Colorplexer Instruction Book."

Thereafter, tests verifying proper adjustment are usually made at the beginning of each operating day. Personnel soon become familiar with the controls and their effects on the output signal, and the detailed initial adjustment procedure then resolves itself to a few routine steps.

Colorplexer setup involves adjustment of signal amplitudes and phase with the aid of test equipment, some of which is designed especially for color use. Actual reproductions of waveforms displayed by an oscilloscope connected to significant points in the circuitry are presented in this section to assist the reader in visualizing colorplexer operation (see Fig. 4-6).

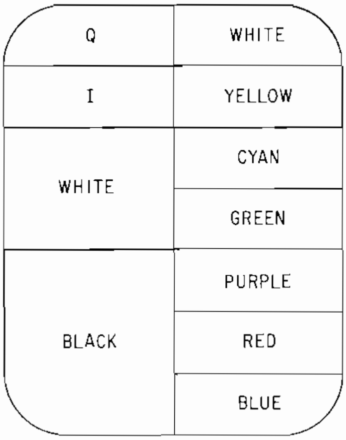

FIG. 4-4. Diagram showing color monitor display of color and test bars electronically produced by RCA color-bar generator.

Test equipment required to produce these waveforms consists of a color-bar generator and an oscilloscope. The color-bar generator is capable of producing on the screen of a color monitor all the signal bars illustrated in Fig. 4-4. Colors in the top portion of the pattern are arranged from left to right in their order of luminance. The lower portion of the pattern contains, from left to right, a special I signal, a special Q signal, a white signal, and a black signal. The special I and Q signals simplify subcarrier phase adjustments, and the white signal facilitates white-balance adjustment. Limiting action assures constant level output of 1 volt, peak to peak, for all signals. The generator requires input signals consisting of composite blanking and vertical drive, both at standard 4-volt peak-to-peak levels. The oscilloscope should have a bandwidth of 10 Mc together with excellent transient response which is required in making accurate waveform analyses.

Waveforms

The composite color waveform obtained at the output jack of the colorplexer can serve to verify all adjustments of the colorplexer excepting the phase of the color burst. Colors from left to right, in descending order of luminance, are white, yellow, cyan, green, purple, red, and blue. Correct amplitudes for these bars and other signal components in the waveform, expressed in IRE scale units (1 volt peak to peak equals 140 IRE scale units), are given in the corresponding line diagram of Fig. 4-5. The photograph shows only the waveforms corresponding to the sequence of color bars shown on the top half of the raster in Fig. 4-4, but the line diagram in Fig. 4-5 also shows the test bursts produced by the special I and Q test pulses adjacent to the color sync burst. As seen, the yellow and cyan bars should be adjusted to coincide at 133

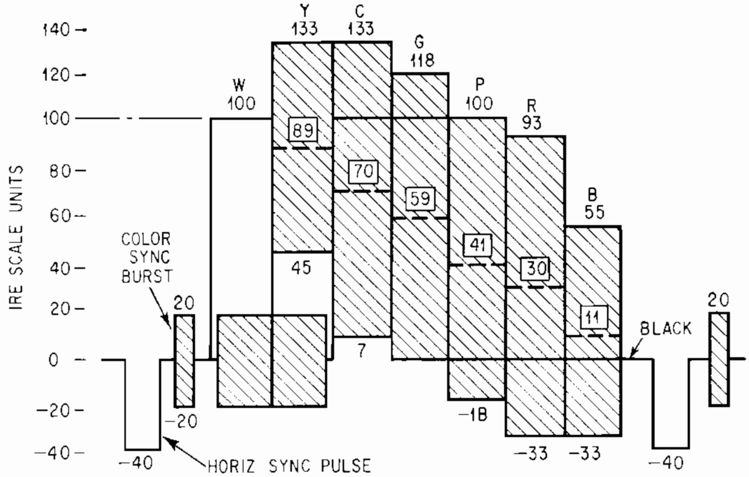

Fig. 4-5. Correct relative amplitudes for color bars, burst, and sync pulses, expressed in IRE scale units (1 volt peak to peak equals 140 IRE scale units).

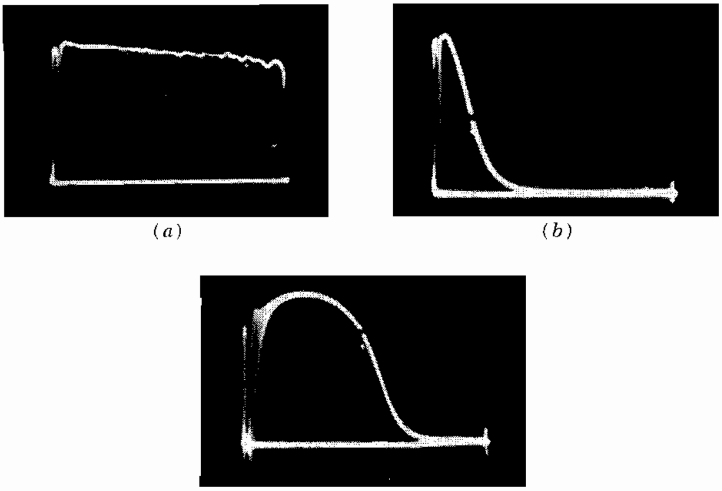
(a)
(b)
(c)

Fig. 4-6. Waveforms showing response characteristics of colorplexer monochrome, I and Q channels. (a) Response of monochrome channel without aperture correction, marker at 8.0 Mc; (b) output of I filter, marker at 2.0 Mc; (c) output of Q filter, marker at 500 kc.

units, and the red and blue bars should coincide at −33 units. The bottom edge of the green bar should just touch the black level, and the top of the purple bar should meet the reference-white level.

Other output waveforms include that of the monochrome signal, obtained by switching out the I and Q amplifiers, and the separate I and Q waveforms obtained with the monochrome switched out. The monochrome signal contains the luminance information of the color-bar signal and hence produces the descending step pattern shown. The I and Q waveforms are useful in setting the proper peak amplitudes for these signals as well as the 90° phase separation. The slow rise time apparent in components of the Q waveform is due to the 0.5-Mc Q-channel filter. The effects of the I filter are not so pronounced and are barely visible in the I waveform.

The special I and Q test bursts shown in Fig. 4-5 can be used to check phase adjustments of the I and Q modulators relative to each other and the burst gate. The instrument used for the purpose is a color-signal analyzer.

Bandpass characteristics of the colorplexer are illustrated by the waveforms shown in Fig. 4-6. These waveforms are typical for a properly adjusted colorplexer and were obtained at the output jacks of the colorplexer.

Part 5

FACTORS AFFECTING COLOR-CAMERA PERFORMANCE

The following general principles underlying proper alignment and operation of the color camera, as they differ from those for monochrome cameras, are presented to assist the station engineer in understanding the effect that each adjustment can have on the composite picture. No attempt is made to present step-by-step alignment procedures.

Although the controls for the three image orthicons in the color camera are similar to those of the monochrome camera, a few additional controls and new alignment techniques are required to permit registration of the images and proper level control of the three signals.

It is important to point out that color-camera setup should be made by viewing the proper test chart. This is the only tool for a true indication of the required camera adjustments. The practice of making indiscriminate adjustments during a scene to "paint" a pleasing picture should be avoided in color-camera setup. It is successful for only the specific scene, and there is too little time during programming to make the required readjustments for subsequent scenes. Also, certain controls of the camera when improperly set give false indications that other controls are misaligned. Therefore, maximum effort should be given to correct alignment of the controls before program time. During operation, a properly aligned camera requires no more than routine adjustments of the master gain control and an occasional adjustment of the master pedestal.

"Q" AND "SKEW" CONTROLS

The "Q" controls, one for the horizontal and one for the vertical, are interconnected to the individual deflection circuits and are utilized to affect the linearity in order to match the scans over the entire raster. A change in the settings of the individual height and width controls changes the reactance-to-resistance ratio in the deflection circuits, affecting the linearity of the channel. Adjustment of the Q control keeps the ratio and linearity the same in each channel.

The "skew" controls, which are connected in the red and blue channels, introduce a small amount of sawtooth waveform at a vertical rate into the horizontal deflection yoke to center the horizontal scan by different amounts at the top and bottom of the raster. This serves to compensate for normal manufacturing tolerances in the axial placement of the yokes. This variation results in a slightly rhomboidal-shaped raster, different in each channel. This amounts to only a degree or two and is not noticeable in monochrome cameras, where only one signal is used. The need for skew adjustment is seen on the kinescope when the vertical lines of two superimposed channels are not parallel after the horizontal lines have been made parallel with yoke rotation.

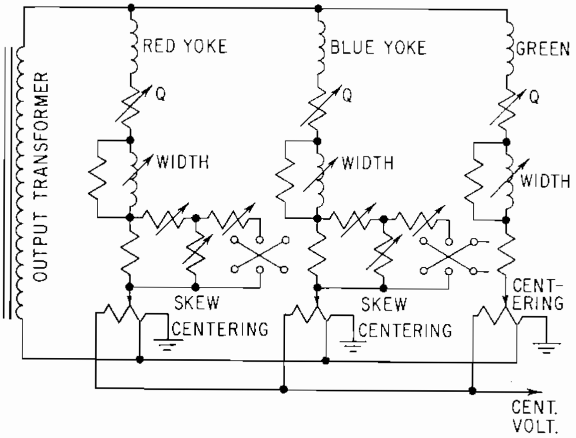

FIG. 5-1. Schematic diagram of horizontal scanning circuit showing location of Q and skew controls.

TEST-CHART LIGHTING

It is already apparent to monochrome-television broadcasters that good lighting techniques are of utmost importance in obtaining good picures. This holds true for color operation, where requirements are even more stringent. A very important phase of aligning television cameras, often overlooked by the engineer, is that of lighting the test pattern. The amount of light is not important provided the level is at least high enough to bring the highlights a little above the "knee" of the image-orthicon transfer characteristic when the remote iris is wide open. Of utmost importance, however, is the placement of lights.

An evenly lighted pattern with a minimum of surface reflectance can be obtained with two equal-size scoops equidistantly placed at 45° angles to the chart. For angles less than 45°, a large amount of surface or direct reflection may enter the camera lens. The image on the photocathode then contains excessive ambient light that gives a distorted gray scale and upsets the true black level. The scoops should also be at the same height as the chart. Direct light from all other scoops and spots should not be allowed to fall on the chart. If the pedestals are first matched with the lens capped, and if no surface reflectance is present, very little adjustment of the individual pedestals should be required to match the black levels of the test chart. If the knees and pedestals have been matched when an improperly lighted test chart was viewed, the color balance will be distorted in both highlights and lowlights when the scene is shifted to the studio set.

OBJECTIVE-LENS IRIS SETTING

When more than one lens iris is contained in an optical system, the over-all aperture and depth of field are defined by the lens that is stopped down to the greatest *f* number. Since the remotely controlled iris is in the relay lens, which has a speed of *f*-4, the objective lens should be set to *f*-4 so it will not limit the maximum over-all aperture. Opening the objective lens greater than *f*-4 will only add flare light to the picture.

IMAGE-ORTHICON OPERATION

The color image orthicon is designed especially for color work. The alignment techniques for this tube follow very closely in accordance with best monochrome practice using the type 5820 image orthicon; however, the nature of the color signal, composed of the mixed outputs of three image orthicons, requires a more precise degree of signal uniformity and freedom from spurious signals. Manufacturing tolerances have therefore been tightened for the color tube, and each image orthicon is system-tested to rigid specifications in order to assure uniform characteristics of the tubes. This eliminates the necessity of buying image orthicons for the color camera in matched sets of three and allows any tube to be replaced by another without replacing the entire set.

It is common monochrome practice to operate the image orthicon above the knee of its transfer characteristic, since this offers a better signal-to-noise ratio and partially corrects gamma in the signal; also the redistribution effect of secondary electrons on the target preserves the fine detail in the highlights. For color operation, however, the image orthicon must be free of any random redistribution that will distort the color information. Furthermore, it must also be operated below the knee over a constant gamma range.

The capacity of the target assembly has been increased in the color version over that of the 5820 by reducing the screen-to-target spacing. This extends the contrast range and improves the signal-to-noise ratio below the knee. The closer spacing allows the screen to collect more of the secondaries from the target. This eliminates random secondary redistribution of the target and "ghost" and "halo" effects. It has been found that the color tube is difficult to handle for large changes of light level reaching the photocathode, so the 5820 is still preferred for monochrome operation where the highlights are allowed to extend above the knee.

An important consideration when a color camera is initially aligned is that all image orthicons should be operated at about the same conditions. Targets should be maintained at 2 volts above cutoff, and the G-4 (Orth Focus) potentials set about equal.

Shading

Extreme care should be taken to obtain the best shading characteristics from the image orthicons rather than correcting later in the system with the shading signals provided in the processing amplifier. These shading signals superimposed on the video signal are fixed-amplitude waveforms and therefore can correct properly at only one video-amplitude level. At other video-amplitude levels the same amount of shading signal is superimposed, but the shading component originating in the image orthicon may vary as a function of the video amplitude.

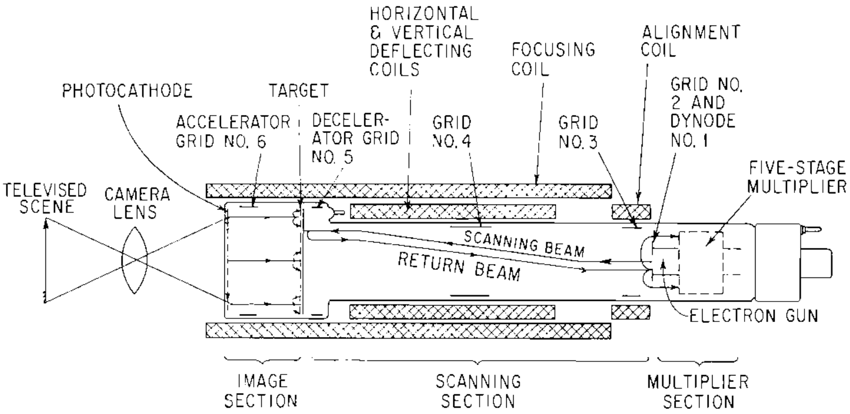

Fig. 5-2. Diagram showing elements of the image-orthicon pickup tube.

The shading component is due mainly to a change in the current amplification in the multiplier section as the return beam scans a small area of the first dynode. The effect of any variations of the secondary-emission ratio over the first dynode will be amplified in the other dynode sections. Therefore, special care is taken in manufacturing the color tube to assure the most uniform and stable secondary-emission characteristics of the first and second dynodes and uniform collection of the secondary electrons.

The color camera requires careful adjustment for best shading because slight differences in the shading components from the three image orthicons will result in severe color distortion, especially in the lowlights. This is seen as spurious changes of hue superimposed over the dark areas of the color picture.

The amplitude of the shading component is a function of the return beam. Therefore it is greatest in the dark areas, where the retnrn beam is maximum, and decreases toward the highlight areas, where the return beam is decreased. All operation on the shading characteristics of the image orthicon should be made with the lens capped. This represents the worst case of shading, since the beam is then completely returned to the first dynode.

The shading generator in the processing amplifier inserts a constant wave shape into the video signal which adds the same amplitude to the dark areas as to the highlight areas, so that the shading-generator signal does not completely cancel the shading component over the entire gray scale. For this reason the best shading possible should first be obtained out of the image orhicon with the shading generator cut off. The necessary shading-generator signal should then be added to give the flattest waveform as seen on the CRO. This adjustment is also made with the lens capped, since in dark areas of the picture a given shading component represents a larger percentage of the signal than in the highlight areas.

G-5 Control

Reducing the potential on G-5 (decelerator grid) decreases the area scanned by the return beam on the first dynode. This potential should be set as high as possible in order to avoid burning the first dynode. G-5 also serves to cause the beam to approach the target perpendicularly at the edges. This eliminates "portholing" a dark ring around the edges. Portholing is introduced as the G-5 potential is reduced. The proximity of G-5 to the target corners causes the potential on G-5 to influence the scanning geometry at the corners of the picture.

Because of the three effects mentioned above, G-5 should be run as far clockwise as possible consistent with good shading. It is decreased to reduce any shading component in the corners due to variation in the secondary-emission ratio over the first dynode. It is also decreased to scan the first dynode inside any burned areas which appear as "clouds" or white streaks when the lens is capped. If difficulty is experienced in registering the corners of the three image orthicons, it may be necessary to decrease the G-5 potential on one or both of the other image orthicons if the third G-5 has been reduced for shading considerations.

The area of the first dynode scanned by the return beam is also directly controlled by the deflection field. The centering and over-all size controls can therefore be used to improve shading, but it is usually desirable to set these controls to scan as large an area of the target as possible.

Multiplier Focus

The potential on G-3 (multifocus) influences the shape of the electrostatic field between the first and second dynodes. This field, in combination with the magnetic focus field, serves to collect the secondary electrons emitted from the first dynode and attract them toward the second dynode. It is essential for good shading characteristics that this field be uniform over the area scanned on the first dynode by the return beam. The G-3 potenital will affect the peak video amplitude by collecting more or less of the total secondary electrons. In the case of the color camera the G-3 potential should be set for best shading rather than for maximum amplitude.

Beam Alignment and Landing

The alignment controls are initially set with the lens capped in order to cause the first dynode aperture spot to go in and out of focus without swirling when the orth focus control is rocked back and forth slightly. This orth focus adjustment indicates that the beam is leaving the electron gun along the axis of the tube normal to the target. As the beam scans across the target, the decelerator grid (G-5) serves to keep the beam normal to the target over the entire raster; the variation in angular velocity of the beam as it approaches the target is therefore held to a minimum. The electrons drawn from the beam to the target should then be entirely a function of the stored charge and not of the angular velocity.

The principle of the return beam being partially a function of the angle at which the beam approaches the target can be utilized by displacing the beam from scanning symmetrically about the tube axis. This displacement can compensate for any slight nonuniformity of target sensitivity or for slight angular assembly of the target. The need for correcting the beam landing is seen on the color monitor when the color balance in the highlights is not uniform over the entire raster. When a resolution chart or a gray card is viewed, the amplitude of the video signal in the highlights as viewed on the CRO will slope to one side or the other at either a horizontal or vertical rate. This should not be corrected by the shading generator for reasons pointed out earlier. This slope can be corrected without affecting the shading in the lowlights by displacing the alignment controls slightly from optimum.

Image Accelerator

The image accelerator (G-6) is set in the same manner as in monochrome operation. However, like the other controls, it is more critical for the color camera, because the result must be matched by all three image orthicons. G-6 should be set for minimum S distortion of horizontal lines when viewing the registration chart. S distortion can be more critically detected by superimposing a grating generator signal of horizontal bars or by panning the camera slowly back and forth. If S distortion of horizontal lines cannot be eliminated entirely in all three channels, the final criterion for setting the image accelerator should be for best registration of the horizontal lines.

Registration

Final registration adjustments should be made only after all image orthicons have been individually aligned for best picture. Besides those controls already mentioned that affect the geometry of the picture, there are several others that the operator may have a tendency to touch up that would cause misregistration. These are orth focus, image focus, and the alignment controls. These are adjusted in much the same manner as in monochrome-camera operation. If any of these are changed after the camera has been registered, registration should be rechecked.

The best registration of the three images occurs when both the electrical and optical registration adjustments are individually set to optimum conditions. The operator should avoid using one adjustment to compensate for misalignment of another. It is difficult to set the front surface mirrors properly in the blue and red channels if the electrical images are not of approximately the same size and linearity, and likewise it is sometimes impossible to match the three scans if the mirrors are not aligned.

Centering

It is important to remember that it is always desirable to scan the largest possible area of proper aspect ratio within the target ring. After this is done, the electrical centering controls are then held fixed and the centering positioning of the red and blue picture to match the green is achieved with the front surface mirrors. The tilt adjustment of the mirrors (for vertical optical centering) should always be set before the rotational adjustment of the mirror (for horizontal optical centering) because a tilt of the mirror also produces some effective rotation of the image. Any image rotation introduced by tilting the mirrors can be corrected by rotating the deflection yokes.

Focus Tracking

The three yoke assemblies are positioned after the mirror adjustment to cause proper focus tracking. This should be done with the remote iris control set wide open (*f*-4) for minimum depth of field, or the most critical focus to be encountered. To be able to make optical focus from extreme close-in shots to infinity for all objective lenses, it is necessary that the image stay in focus at both the focal plane of the field lens and the photocathode of the image orthicons. It is possible when viewing a distant object to position the yoke assemblies to obtain focus on the photocathodes without the image being in focus exactly at the focal plane of the field lens. However, under these conditions, a point may be reached as the camera is moved very close to the subject where it will become impossible to make optical focus.

Amount of Scan

The individual heights and widths should be matched, and the over-all height and width set for proper size and aspect ratio. The proper amount of scan for new image orthicons is that which will just show the target corners when in the OVERSCAN position. All corners should disappear when the overscan switch is thrown to NORMAL. The overscan position does not apply maximum scan but is designed to increase the preset amount of scan by about 15 per cent. When looking for the target corners care should be taken not to confuse corners that may be inserted owing to misalignment of the field lens mask or to excessive compression of the sponge-rubber light-shield bellows. As the image orthicons age, it may be desirable to reduce the scan in order to obtain better shading characterisics.

After the sizes have been matched and the individual linearities adjusted (with the Q controls) for an approximate match over the entire raster, the superimposed pictures will be in better condition to see the need for finer mirror adjustments. Again set the electrical centering controls to scan the center of each target, and then make final adjustments on the front surface mirrors.

In order to see the amount and direction of electrical misregistration more clearly, the two superimposed pictures of the registration chart should be displaced slightly by electrical centering, because a difference in line separation is easier to detect than differences in overlapped lines. The individual height and width controls can then be operated to make the separation of the lines equal around the edges of the raster, and the horizontal Q and vertical Q used to separate the lines in the center by an amount equal to that at the edges. The horizontal lines should be made to be parallel with yoke rotation before paralleling the vertical lines with the skew controls.

Color Balance

The *shapes* of the spectral responses in the color camera are fixed by dichroic mirrors and trimming fitters to conform to the color-mixture curves for the primaries standardized by the FCC. However, the relative *amplitudes* of the primary colors can be controlled by use of the individual gain controls and individual pedestals. The relative amplitude of each primary-color signal to be transmitted is established by the fact that reference white must be transmitted with no color information; i.e., the subcarrier must vanish during the transmission of a neutral color. Since the colorplexer is designed to cancel out the color subcarrier when all three inputs are equal, the gains and pedestals on the camera should be set for equal outputs from all channels when a neutral surface is viewed. Since a neutral object reflects light into the camera of the same spectral quality as the illuminant, it is apparent that the relative gains to which the three channels are adjusted will depend on the spectral quality of the illuminant being used. The pedestals are, of course, set for equal black-level information. When gain and pedestal are properly set for highlights and lowlights, respectively, maintenance of a proper gray scale in between these two levels depends on how well the transfer characteristics are matched.

The transfer characteristic of the kinescope is for all practical purposes assumed to be fixed. However, that of the image orthicon is a function of the potential above cutoff on the target. A potential of 2 volts above cutoff on the target gives the most constant gamma characteristics. The gamma-corrector amplifiers are therefore designed to correct for image orthicons operated at 2 volts above cutoff on the target. The target test switch on the control panel is provided for setting the target at 2 volts above cutoff. When the target is set to cutoff with the switch in TEST position, the pedestal should be raised and the brightness on the monitor increased so that the signal is not clipped. When all targets are operated at 2 volts above cutoff, they all have the same gamma characteristics below the knee. Therefore, in order to match the three transfer characteristics, it is necessary, then, to match the knees.

Matching Transfer Characteristics

If the iris is opened from a closed position when viewing the gray scale chart, three factors will determine which image orthicon reaches the knee first: the spectral quality of the illuminant, the relative light-transmitting efficiencies of the three channels, or the relative image section sensitivities of the image orthicons. In order that all three image orthicons can be operated over the same portion of their transfer characteristics, neutral density filters are inserted in the "hottest" channels just ahead of the image orthicons. This reduces the peak highlights to a point on the transfer characteristic of the hottest channels to that of the least sensitive channel.

It is desirable to attenuate the incident light with the least possible amount of neutral density filters in order to keep the over-all sensitivity of the camera as high as possible. The least sensitive image orthicon should be placed in the most sensitive channel, and vice versa.

When looking for the knee care should be taken to have the beam sufficiently high that a fold-over due to the target not being completely discharged is not mistaken for a compression due to the knee. Too much beam, of course, will add noise and shading to the signal, and the highlights will not be clearly defined. The dynode gains should be held so the highlights do not exceed about 0.3 volt on the master monitor CRO when the "input" signal is punched up on the processing amplifier. This is to be sure that no amplifiers are overloading.

A suggested method that will reduce the trial-and-error time required for selecting the proper neutral density filters when viewing the gray scale chart is as follows:

1. Consider only one channel at a time.
2. Set the iris so the highlight of one channel is at the knee.
3. Set the dynode gain of that channel so the highlight falls at about 0.3-volt input to the processing amplifier.
4. Set the processing amplifier gain of that channel so the highlight falls right at the 0.7-volt calibration mark when the processing amplifier is on the OUTPUT position. (The 0.7-volt level then marks the knee for that channel regardless of where the iris is set, provided the pedestal is not changed.)
5. Repeat the above for each of the other two channels.
6. Set the iris so the highlight in the least sensitive channel falls at the knee, or 0.7-volt-output level.
7. Hold neutral density filters in front of the objective lens to determine the amount required for each of the more sensitive channels, so that highlights can be brought to the 1-volt level, the knee for that channel.
8. Remove the light shield, and insert the neutral density filters into their proper channel.

Gain Controls

The importance of operating with an over-all linear system in order to reproduce colors faithfully over the entire luminance range stresses the fact that the image orthicons must not be operated above the knee of their transfer characteristics. For the greatest contrast range and best signal-to-noise ratio, the brightest highlight should be allowed to fall just at the knee by operation of the remote iris control (master gain). Since the colorplexers are designed for a peak input signal of 0.7 volt, it would be desirable to have the knee represent 0.7 volt out of the processing amplifier. If the gains of each channel are adjusted for 0.7 volt out of the processing amplifier when the highlight is just at the knee, the 0.7-volt calibration mark on the master monitor CRO will then serve as a reference for the position of the knee.

Pedestals

The 0.7-volt level at the knee is set with the individual gain controls after the pedestals have all been adjusted to about a 5 per cent setup. If the pedestal is changed after the 0.7-volt output level has been set, the reference black will be changed from its 0.7 volt below the knee position and the 0.7-volt calibration on the CRO will no longer represent the knee. For this reason the gray-scale chart should have a contrast range similar to that of the scene to be televised, or about 30 to 1. Standard gray-scale charts fulfill this requirement. In order to keep the knee at the 0.7-volt output position, the master pedestal should be touched as little as possible during operation.

It is often necessary to adjust the master pedestal for a more pleasing picture, however, such as in extreme close-ups where the darkest video level may actually be quite high; but it should be kept in mind that if the pedestal is lowered (blanking decreased), the knee will fall below the 0.7-volt level and, if the pedestal is raised (blanking increased), the knee will fall above the 0.7-volt level. During operation of the camera the iris is adjusted so that the highlight in the channel with the greatest peak video amplitude is held as high as possible, for best signal-to-noise, without exceeding either the knee or the 0.7-volt-output level.

Final Color Balance

When the output of the colorplexer is observed on a CRO when viewing the gray-scale chart or the resolution chart, no subcarrier should be present (seen as a thickening of the lines) if the transfer characteristics of the three channels are perfectly matched and the colorplexer is perfectly balanced. The individual pedestals and gains on the processing amplifier should be touched up to cancel the subcarrier in the lowlights and highlights, respectively. Another check for proper color balance is to switch the CHROMA on the color monitor on and off while viewing the signal from the camera focused on the gray-scale chart or the resolution chart. No change in the color balance of the monitor should take place if the camera chain is properly balanced.

LIGHTING AND SUBJECT MATERIAL

The most carefully aligned camera chain cannot give an accurate reproduction from a poorly lighted scene or from a poor selection of subject material. The most important aspect of studio lighting and material selection peculiar to color television is to restrict the reflected light contrast of the scene to the contrast capabilities of the system. For an average scene being reproduced on the kinescope under typical viewing conditions, the contrast between the brightest and darkest areas cannot exceed about 20 or 30 to 1. This is restricted at the high end owing to the limited luminance capabilities of the kinescope and at the low end owing to stray light and "spillover" in the kinescope and the ambient illumination.

Since the iris at the camera is adjusted so the brightest area in the scene is set at the knee, or the maximum transmitted level, the areas with luminance values less than one-twentieth the luminance of the brightest area will become desaturated or be lost in the black level. Very bright areas allowed in the scene may therefore cause some critical colors, such as flesh tones, to be forced far down in the luminance range with the result of color distortion at the kinescope. If the iris is opened to improve the flesh-tone reproduction, then the highlights will extend over the knee, the brightest colors will become desaturated, and some amplifiers will overload. For large, dark areas in a scene where the contrast range exceeds 20 to 1, the shading component of the image orthicons becomes an appreciable amount of the signal and the reproduced colors will be distorted in the lowlights.

Flourescent lights should not be used where color fidelity is important. The spectral distribution is broken by excessive radiation over certain narrow bands of the spectrum.

The amount of light entering the camera lens depends, of course, on both the illumination on the subject and its reflectance value. All material to be used in the scene that has excessive reflectance and very low reflectance should be screened out before going on the air. A light gray shirt, for instance, will be reproduced as a white, when the iris is properly set, without forcing the other colors down in luminance value. The white areas in show cards that contain color should also be grayed down. Observation of the CRO waveform will give an indication of which subjects are exceeding the desired contrast range. The scene contrast can also be checked with a comparison-type light meter such as the Luckiesh-Taylor brightness meter, or the McBeth illuminometer.

Part 6

COLOR TEST EQUIPMENT

High-quality test and monitoring facilities are important and necessary to the color-television station in maintaining desirable standards of performance and to ensure compliance with FCC regulations.

Equipment used for *monitoring* color transmission is almost the same as that used for monochrome, except for the color monitor and the high-quality demodulator needed for color. The color monitor sets the standard of system performance, serving not only in monitoring functions but also as a vital unit of test equipment. In contrast to modest monitoring requirements, however, color operation has introduced new *test and measuring* techniques, as well as a number of test equipments developed especially for color use.

Test equipment for the color station can be listed in two general categories: (1) equipment needed to evaluate the studio installation and (2) equipment required to test transmitter performance. Since requirements differ still further, depending upon whether the station originates color or merely participates in color-network shows, two additional lists are possible. To assist the reader in visualizing the equipment in each case, typical test equipment lists are presented in Tables 6-1 and 6-2. Equip-

Table 6-1. Studio Test and Measuring Equipment

Equipment	*Purpose*
	For Network Participating Stations
Linearity checker	Differential gain measurement
Color signal analyzer	With linearity checker provides differential phase measurement
Color stripe generator (optional)	Provides color test signal for home-receiver adjustment
	For Color Originating Stations (All items listed above plus the following equipment)
Color bar generator	Provides standard color signal for aligning colorplexers and monitors
Calibration pulse generator	Provides standard signal voltage for calibration of waveform monitors and setup of processing amplifier

Table 6-2. Transmitter Test and Measuring Equipment (For Color Originating and Network Participating Stations)

Equipment	*Purpose*
Linearity checker Color signal analyzer	Measuring transmitter amplitude and phase response
VHF or UHF sideband response analyzer	Measuring frequency response of transmitter
VHF or UHF sideband demodulator	Checking and monitoring characteristics of transmitted RF signal
Square-wave generator	Adjustment of phase equalizer
Dummy load and wattmeter	Power-output measurements

ment groups selected for these tables are capable of providing sufficient information to ensure that the installation will meet the operating standards established by the FCC.

COLOR STUDIO TEST EQUIPMENT

Most color video signal tests can be performed by use of standard monochrome test items such as wideband oscilloscope, sweep generator, and suitable test charts, in conjunction with a linearity checker, color-signal analyzer, and color-bar generator. Detailed information on the use of this equipment in measuring the transfer characteristics of color-television equipment is contained in the equipment manuals. Reference should be made to them for actual procedures to be followed in making measurements.

WA-9 Calibration Pulse Generator

The WA-9 calibration pulse generator produces a precise video signal voltage of either 0.7- or 1.0-volt amplitude. These voltage standards can be used for setup of the processing amplifier in film and live camera chains, as well as for accurately calibrating waveform monitors so that video signal amplitudes can be established. The 0.7-volt output serves as a reference standard for noncomposite video signals, and the 1.0-volt output for composite signals. It is common practice to make these voltages available at jack panels and in switching systems so that the entire distribution system can be aligned conveniently for proper levels.

The WA-9 provides a square pulse at horizontal frequency. The output impedance of approximately 0.6 ohm is sufficiently low to permit feeding several circuits with negligible change in level. In addition, the square wave is timed so that it appears as a positive half cycle centered between horizontal sync pulses. Thus, the signal will readily pass through any clamp circuits in the system without disabling them. Horizontal drive from the sync generator is amplified and used to trigger a stabilized, cathode-coupled multivibrator which places the calibrated pulse between the horizontal sync pulses. The output pulse is produced by a square-wave multivibrator. Output of this stage is clipped by a current-regulating circuit controlled by a voltage reference tube, and the resultant calibrated pulse drives a feedback amplifier with highly stabilized gain.

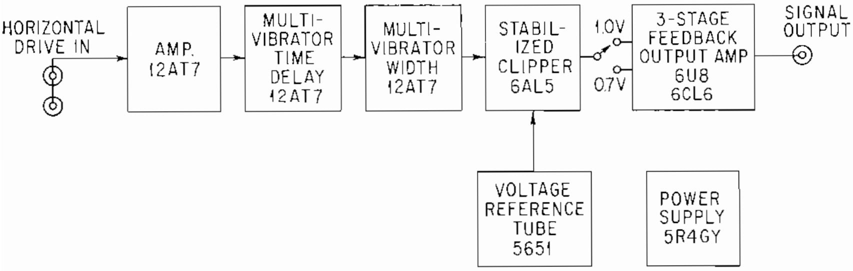

FIG. 6-1. Block diagram of WA-9 calibration pulse generator.

Circuits of the generator, shown in the simplified block diagram of Fig. 6-1, feature extreme stability. With line voltage changes from 110 to 125 volts, output level will vary no more than 1 per cent. Output voltage variations are held to 0.5 per cent in changing from no termination to one 75-ohm termination or from one to two 75-ohm terminations. Pulse width is 31.75 μsec, with a rise time of less than 1 μsec and tilt less than 1 per cent.

All components of the WA-9 are mounted on a recessed-type chassis designed for standard rack mounting. Controls are located on the front of the chassis for the following functions: pulse position, pulse width, voltage calibration, 0.7/1.0-volt selector, and power switch. Output can be controlled by a locking-type screwdriver adjustment.

WA-1 Color-bar Generator

The WA-1 color-bar generator supplies a synthetic signal which permits precise alignment of the colorplexer and provides a standard for measuring color-camera performance. Use of this signal in the color system is analogous to the use of the monoscope camera in monochrome operations.

The WA-1 generates rectangular pulses which when fed to the red, green, and blue input circuits of the colorplexer produce a color-bar test signal at the output of the colorplexer. In addition, the generator is capable of providing a split-field color-bar pattern on the color monitor, displaying standard color bars in the upper half of the raster and a white bar together with the Q and I test bars in the bottom half of the raster, as recommended by the Electronics Industries Association.

Circuits of the color-bar generator are shown in the simplified block diagram of Fig. 6-3. All components are mounted on a recessed-type chassis designed for standard rack mounting. An integral regulated power supply and conservative circuit design assure stability in operation. Limiting action ensures constant output level of 0.7 or 1.0 volt peak to peak for all the color-bar signals.

In operation, the trailing edge of the horizontal blanking pulse triggers the green multivibrator which is adjusted to produce a pulse long enough to include the first four bar intervals. The green multivibrator triggers the red multivibrator from both its leading and trailing edges, so there are two red pulses per line period, each one-half as long as the green pulses. The red multivibrator in turn triggers the blue multivibrator from both its leading and trailing edges to produce four pulses, each one bar interval wide.

Formation of the Q, I, and white pulses is as follows: The trailing edge of the horizontal blanking pulse initiates the I pulse, the trailing edge of the I pulse triggers the white pulse, and the trailing edge of the white pulse triggers the Q pulse. The manner of triggering as well as the amplitude and time relationships of these pulses are shown in the diagrams of Fig. 6-2.

WA-6 Color-signal Analyzer

The WA-6 color-signal analyzer is designed to permit the study of the composite color video and subcarrier signal. The WA-6 facilitates adjustment of the colorplexer and, when used in conjunction with the color-bar generator and an oscilloscope, permits accurate measurement of phase relationships existing between the subcarrier burst reference and various components of the composite color signal. The instrument is also used in conjunction with the linearity checker for making differential-phase (phase intermodulation) measurements.

In all cases a source of subcarrier is required in the operation of the color-signal analyzer. This can be obtained from the linearity checker which contains a generator for this purpose, or it can be obtained from the output of the frequency standard. The color-signal analyzer is a null-indicating-type instrument for measuring phase at subcarrier frequency. It contains self-calibrating facilities and is capable of measuring phase differences of the order of 0.5°.

WA-8 Color-stripe Generator

The WA-8 color-stripe generator is an inexpensive color-signal generator designed to produce a color test stripe on color home receivers. Use of the generator makes it possible for the viewer or receiver service personnel to determine that a particular color-receiver installation is capable of reproducing color programs, even though at the time only monochrome programs are being broadcast.

Any station which is equipped to transmit network color can use the color-stripe generator to add a narrow color stripe to the monochrome signal. The stripe signal

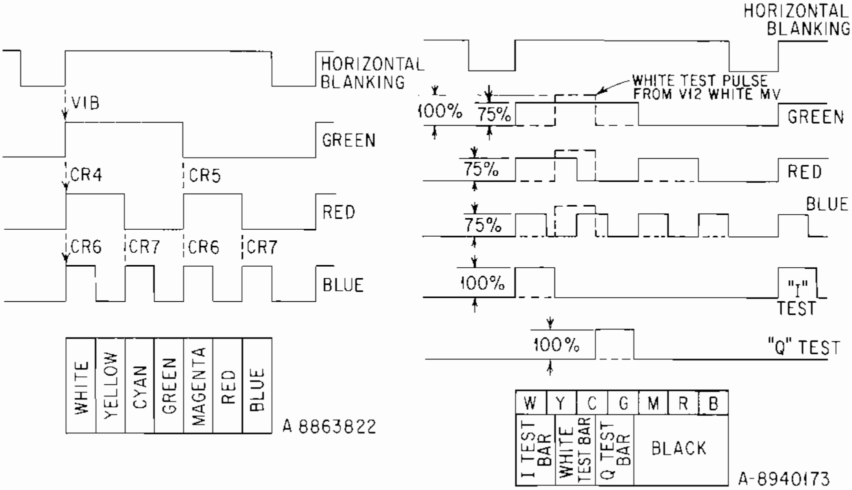

Fig. 6-2. Diagram showing derivation of R, G, and B color bar pulses and time and amplitude relationships in the composite bar signal.

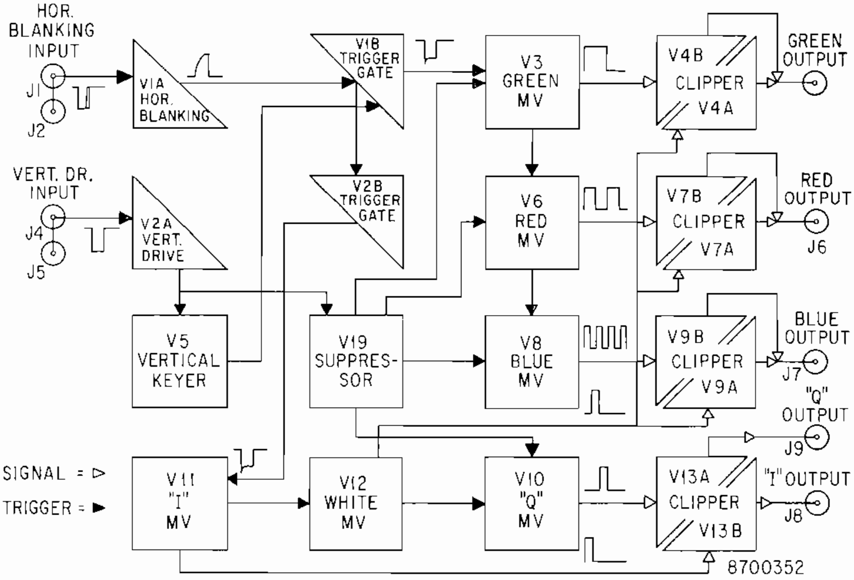

Fig. 6-3. Simplified block diagram of WA-1 color-bar generator.

is normally unnoticeable on either monochrome or color receivers, but the technician installing a color receiver can use the signal to produce a stripe of yellow-green color (when color reception is normal) by making a deliberate temporary misadjustment of the horizontal-deflection oscillator. The generator is loosely coupled to the video line feeding the transmitter in such a way that normal system operation is not changed.

Information added by the stripe generator to the composite monochrome signal consists of two bursts of 3.58-Mc subcarrier frequency. The first burst is positioned immediately following horizontal blanking, or 9.2 μsec (+0.6, −0.0) following the leading edge of horizontal sync. In this location, it is just outside the period normally "sampled" by the burst gate of a receiver, so it does not activate the color circuits in the receiver. If the horizontal phasing circuits of the receiver are deliberately misadjusted, however, the burst sampling pulse can be moved over to pick up the first burst of the stripe signal. When this happens, the color receiver responds as if the signal had a normal color sync burst (i.e., the color circuits are activated). The second burst is positioned so that its leading edge is 3 μsec preceding the leading edge of horizontal picture blanking. This burst produces the color on the kinescope of a properly adjusted color receiver. Since these signals are devoid of any luminance component, they are positioned on the average of the luminance value present in the monochrome signal at the time. When a color program is broadcast, however, the stripe generator should be turned off so as not to cause color interference.

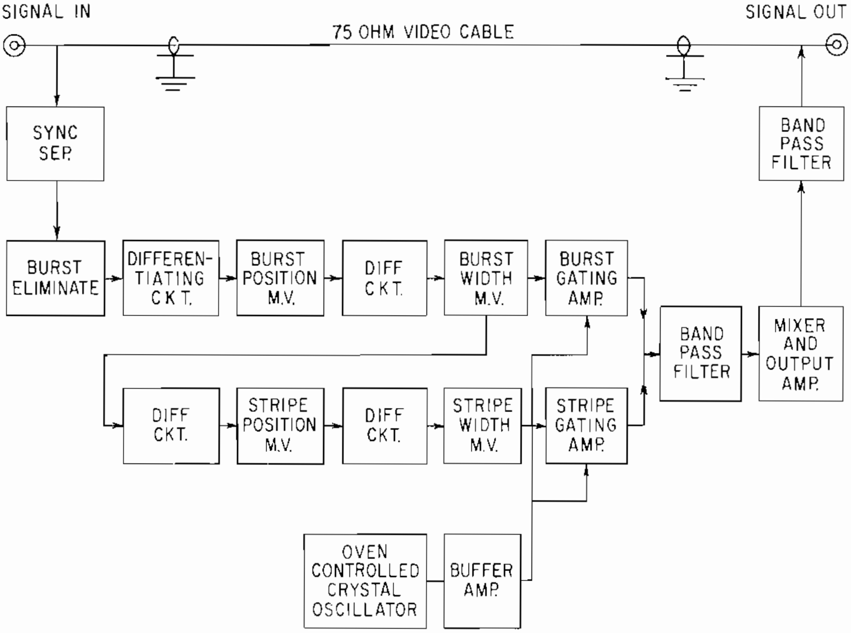

Fig. 6-4. Block diagram of color-stripe generator.

Circuitry of the color-stripe generator is shown in the block diagram of Fig. 6-4. The purpose of the sync separator is to strip sync from the composite monochrome signal. The "burst-eliminate" circuit prevents the separation of pulses during the vertical sync and equalizing pulse intervals. No bursts or stripes should appear for nine lines during the vertical blanking interval. The output of this stage, therefore, is a series of pulses at horizontal rate with a nine-line gap during the vertical interval. This information is differentiated and applied to the burst-position multivibrator, which, in turn, drives the burst-width multivibrator. Its output is the positive pulse necessary to trigger the burst gating amplifier. A second output drives the stripe-position multivibrator, which, in turn, drives the stripe-width multivibrator. Its output is also a positive pulse necessary to trigger the stripe gating amplifier. The subcarrier signal at 3.579545 Mc is produced by a stable oven-controlled crystal oscillator. Its output is supplied to the gating amplifiers. The gating amplifiers feed the mixer and output stage, which, in turn, feeds back to the video line. Thus, the video line is never broken. If failure of the stripe generator should occur, the monochrome signal would not be affected. Coupling of the output signal to the video line is so loose that the monochrome signal is essentially unaffected, but the color bursts or envelopes are added or superimposed on it.

All controls for the generator are accessible from the front. Front-panel controls consist of the REMOTE-OFF-LOCAL switch which applies +B to the subcarrier oscillator and mixer output tubes in the remote and local positions and removes it from the tubes in the off position; pulse discriminator bias pot for adjusting the clipping level so that under all values of picture information nine lines of bursts are eliminated during the vertical blanking interval; subcarrier frequency control—a trimmer to adjust the oscillating frequency of the oven-controlled crystal to exactly 3.579545 Mc; subcarrier output control—a level-setting control common to both burst and stripe for adjusting their amplitudes with respect to the monochrome signal; three separate controls associated with the color burst for adjusting its width, its amplitude, and its position with respect to sync; envelope-shaper control—essentially a control to adjust a bandpass filter (a low-Q resonant circuit) for best shape of the burst and stripe envelopes; oscillator plate tuning—an inductance control for adjustment of the crystal oscillator plate circuit for maximum stability; and the on-off power switch.

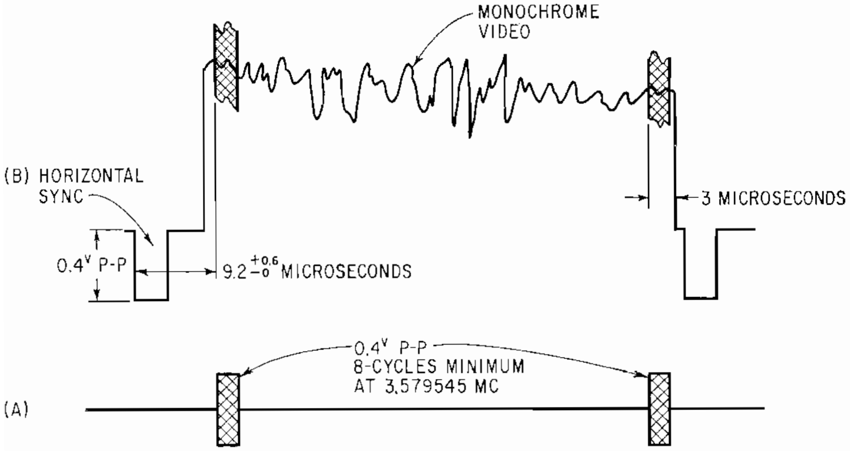

FIG. 6-5. Diagram showing signal produced by the color-burst generator. Line (*A*) represents color bursts of subcarrier frequency, and line (*B*) is the composite signal from the color-stripe generator.

WA-7 Linearity Checker

The WA-7 linearity checker generates a test waveform consisting of a staircase signal with provisions for superimposing a 3.58-Mc sine wave on the steps and for varying the average picture level of the signal. Differential gain measurements can be made in video amplifiers, transmitter circuits, and transmission systems by use of the linearity checker alone. Differential-phase measurements can be made by employing the linearity checker together with the color-signal analyzer to serve as a phase detector to analyze the signal after it passes through the device under test. Another important use of the linearity checker is in the adjustment of white stretch to compensate for the nonlinear transfer chraacteristics of grid modulation in the transmitter.

The linearity checker includes a Hi-Lo filter which is used at the input to the oscilloscope. When the filter is switched between high, low, and normal positions, the subcarrier, step wave, or composite signal can be viewed separately and the waveforms interpreted accordingly. The instrument incorporates a subcarrier-freqnency generator.

Burst-controlled Oscillator

The burst-controlled oscillator is an accessory for the color-signal analyzer for use in special cases where differential-phase measurements are to be made over a studio-to-transmitter link or in any other circumstances where the test-signal source is at a distance from the point of measurement. The oscillator provides a continuous subcarrier frequency of 3.579545 Mc. Output is locked in frequency and phase to the color-synchronizing bursts which are part of the incoming signal being measured.

This item is not necessary if the studio and transmitter are at the same location or if test procedures are not carried out at a point remote from subcarrier signal sources.

Signals for Grating and Dot Patterns

Signals to produce grating and dot patterns useful in the adjustment of scanning linearity and beam convergence can be obtained from the TG-2 sync generator. Circuits built into the TG-2 provide a stable pattern of 13 by 17 bars, white on black background with blanking added. A selector switch in the grating circuits allows choice of horizontal bars, vertical bars, both horizontal and vertical bars, dots at the intersections of the bars, or a test position where sync and blanking are mixed for observation of the front porch.

TRANSMITTER TEST EQUIPMENT

Equipment required for test and monitoring of the color transmitter is listed in Table 6-2, which appears at the beginning of this part. The burst-controlled oscillator, although not listed, may be required if the studio and transmitter are not at the same location, as previously stated.

In addition to the linearity checker and color-signal analyzer, transmitter tests require use of the BW-5 sideband-response analyzer, BW-4 visual sideband demodulator, and a suitable RF load and wattmeter.

The sideband-response analyzer provides for the display on an oscilloscope of the entire frequency and sideband-response capability of the transmitter and sideband filter without laborious point-to-point curve plotting. The unit is used in the adjustment of video amplifiers and modulators as well. The analyzer includes a video sweep oscillator, making it unnecessary to provide separate video sweep generators for measurement purposes.

The visual sideband demodulator produces a signal for monitoring and checking transmitter output. It provides information on waveform characteristics such as wave shape, sync percentage, depth of modulation, resolution, and transient response, as well as a composite picture of the signal for checking compliance with FCC standards.