TOPIC A9

COLOR TELEVISION

by

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I. INTRODUCTION

Color television is a subject of more than casual interest to engineering personnel throughout RCA for several reasons. The development of this mass communications medium represents an important chapter in our company's history, the medium now accounts for a significant fraction of the Corporation's gross business and profits, and many of the technical concepts developed within the context of the color television system have been carried over into other company projects. Thus, it appears appropriate to include a brief summary of the technical principles of color television in the CCSE Program, even though most of the basic research and development work was done more than 13 years ago (in the period prior to the formal adoption of color television broadcast standards by the Federal Communications Commission in December, 1953).

II. COLOR VISION AND PRIMARY COLORS

In scientific work, color is generally assumed to be an attribute of light, not of physical objects, and the investigation of color properly belongs in the realm of psycho-physics. That is, color can be understood only by considering the physics involved in the radiation of light energy in association with the physiological and psychological factors involved in the interpretation of this light energy by the human eye and nervous system.

The technical foundation of the television industry is the creation of illusions, which may be defined as "perceptions that are not in accord with reality". What a television system actually creates on the kinescope in a televiewer's home is a constantly changing pattern of light generated by a tiny flying spot, but we can make this pattern of light stimulate the eye and nervous system of the televiewer in such a way that he gets the illusion of actually witnessing a scene taking place before the television camera. Color television is more appealing than black-and-white television mainly because it is capable of producing more convincing illusions. Normal vision for the vast majority of human beings is color vision, so any picture-producing process that does not include color puts more of a strain on the observer's imagination than does one that includes color.

Color perception results from the combination of three psychological sensations, each of which is a nonlinear and frequency-dependent function of the light energy falling on the retina. These sensations are commonly known as brightness, hue and saturation. Brightness is that characteristic by means of which colors may be located in a scale ranging from black (darkness) to maximum white. (Brightness is, of course, the only attribute of a color which can be reproduced in a black-and-white photograph or transmitted via monochrome television.) Hueis that characteristic by means of which colors may be placed in categories such as red, green, yellow, blue, etc. Saturation refers to the degree by which a color departs from a gray or neutral of the same brightness; pale or pastel colors are much less saturated than those that are "deep" or vivid.

Let us consider briefly the relationships between color sensations and the light energy that constitutes the physical stimulus. The human eye is sensitive to electromagnetic energy extending over a wavelength range of roughly 400 to 700 millimicrons. The response of the eye is not uniform over this region, but follows a response curve shaped very much like a probability function and peaked at 555 millimicrons, as shown in Fig. 1. This curve describes the spectral characteristics of the brightness sensation only, and indicates that a given amount of energy may appear much brighter at some wavelengths than at others. Response curves vary somewhat from person to person, but Fig. 1 shows the specific curve representing the average response of a great many observers and adopted by the International Commission on Illumination in 1931 as the standard luminosity function or visibility curve.

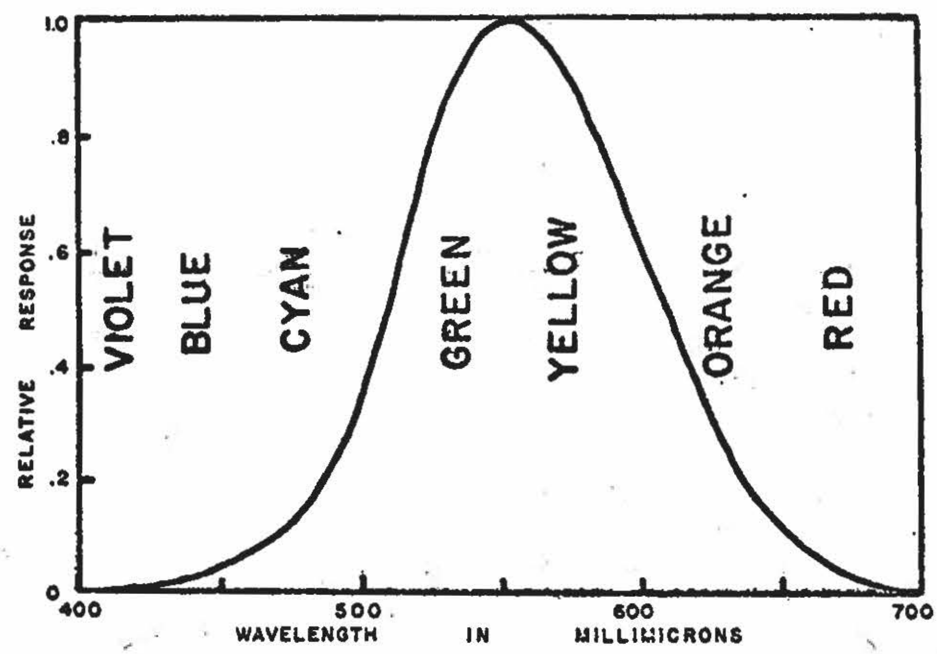


Fig. 1. Chart of the visible spectrum, showing the major hue regions.

The other two variables of color -- hue and saturation -- are controlled by the relative spectral distribution of light energy. To a first degree of approximation, hue is determined by dominant wavelength. In fact, the various wavelength regions of the visible spectrum are commonly designated by specific hue names, ranging from violet and blue for the very shortest wavelengths through cyan (or blue-green), green, yellow, and orange to red for the longest wavelengths. These major hue regions are designated roughly on Fig. 1. Saturation is determined by radiant purity, or the extent to which the light energy is confined to a single wavelenght or a very narrow band of wavelengths.

Fig. 2 should serve to illustrate how hue and saturation are controlled by the spectral distribution of light energy. If the radiant energy from a color is spread out more or less uniformly over the visible spectrum, as shown at A, it is generally perceived as white (or gray, depending upon the relative brightness). If the distribution curve has a slight hump or peak, the color is perceived as a pale or pastel shade of the hue corresponding approximately to the dominant wavelength. For example, a color with a distribution curve corresponding to curve B would be perceived as a pale yellow. If the distribution curve consists of a fairly sharp peak around the same dominant wavelength, as shown in curve C, the color generally has the same hue but is more highly saturated. Maximum saturation occurs when the spectral distribution curve is a single line, corresponding to single-wavelength radiation.

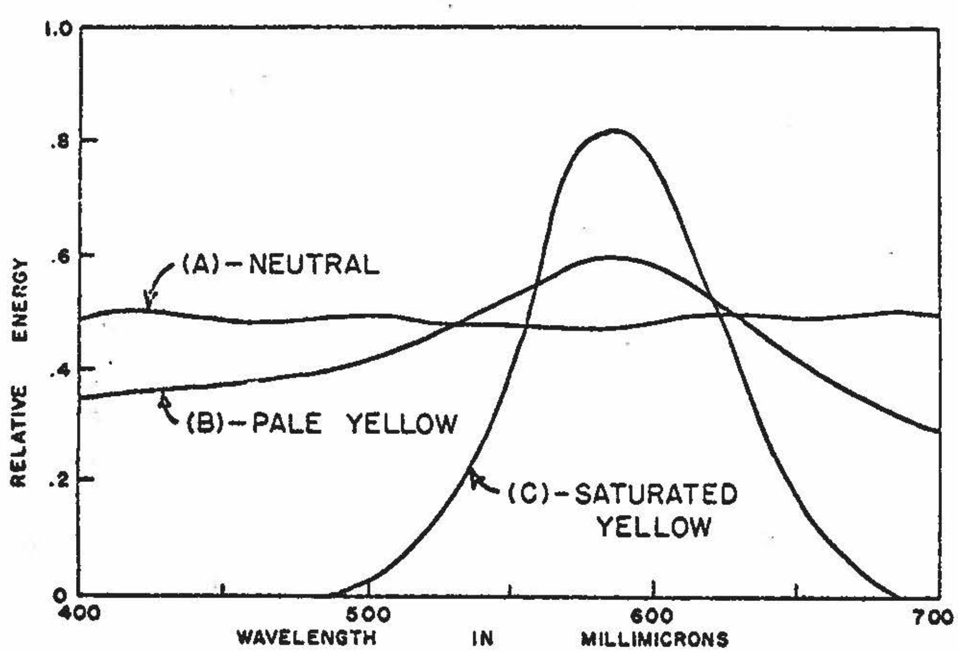


Fig. 2. Chart of the visible spectrum, showing how hue and saturation are controlled by spectral distribution.

Psychologists and physiologists are still searching for a completely satisfactory explanation as to how human beings are able to perceive colors. The most promising theory of color vision is based on the assumption that there must be three kinds of cone cells in the human retina with overlapping spectral sensitivity curves but with peaks occurring in roughly the red, green, and blue portions of the spectrum. According to this theory, the brightness sensation is controlled by the sum of the responses of the three types of cells, while hue and saturation are determined by the ratios of stimulation. If each of the receptor systems is assumed to have an independent and nonlinear automatic-gain-control system, this three-receptor model can account for most of the known phenomena of color vision.

Fortunately, we do not need a complete understanding of all the intricate processes involved in human vision in order to develop a color-reproducing process, because we may employ the primary color concept, which has been verified (though not completely explained) by a great body of experimental data.

It is an experimentally proved characteristic of human vision that nearly all of the colors encountered in everyday life can be matched by mixtures of no more than three primary colors. Consequently, it is possible to produce full-color images of complete scenes by superimposing three primary color images; this basic process is used by nearly all modern color-reproducing systems, including color photography and color television. The practical success of 3-color reproduction processes is, in itself, convincing evidence supporting the tri-stimulus theory of color vision.

Contrary to popular belief, there is no one set of colors with unique properties that make them the primary colors--any set of three will do, provided only that no combination of any two is capable of matching the third. It so happens that the most useful set for color television purposes (i.e., the set with which it is possible to match the greatest range of everyday colors) consists of highly-saturated red, green, and blue. The FCC signal specifications use standard colorimetric designations to describe a specific set of red, green and blue primaries recommended for color television.

III. THE APPLICATION OF COLORIMETRY TO COLOR TELEVISION

The colorimetric principles used in color television are illustrated by Fig. 3. At the receiving end of the system, a full-color image is produced by adding the light output of three registered images in red, green and blue. There are three basic methods for combining the primary images: (a) Superposition by means of dichroic mirrors or by projection to a common viewing screen, (b) rapid sequential presentation at a rate fast enough to cause addition by the "persistence of vision" effect, or (c) presentation of the images in the form of intermingled primary color dots or other elements too small to be resolved separately. Method (c) is the one used in the shadow-mask color kinescopes utilized in the great majority of color receivers.

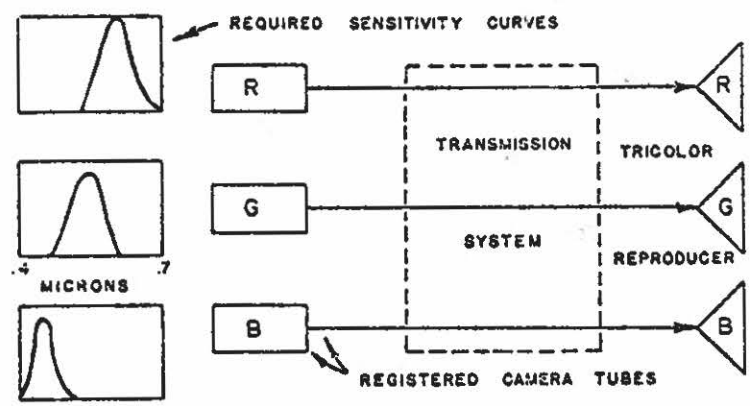


Fig. 3. Block diagram showing the basic colorimetric features of a color television system.

Since the final color picture involves three variables, the color camera must provide three independent video signals. To accomplish this, the camera must have, in effect, three independent pick-up or transducing elements. In some color cameras, three entirely separate pick-up tubes are used in conjunction with an image-dividing optical system, but it is also possible to combine the three sets of transducing elements in a single tube envelope or to use a single tube in three different modes of operation (by means of rotating optical filters). The simplest type of color camera from an analytical point of view is one in which three pick-up tubes are used to provide red, green, and blue signals directly, as indicated in Fig. 3. (Some cameras of recent design actually employ four pick-up tubes, for reasons that should become apparent later in this Study Guide).

By proper manipulation of standardized colorimetric data representing the average response characteristics of a large number of observers, it is possible to compute precisely the optimum shapes for the spectral sensitivity curves of the three pick-up tubes to yield the best color fidelity for the average observer. The sketches in Fig. 3 give a rough indication of the optimum spectral response curves (but readers familiar with colorimetry will note that the secondary response lobes have been eliminated). Note that the peaks of the curves occur in roughly the red, green, and blue portions of the spectrum, but that they overlap appreciably. The relative sensitivities of the three camera tubes are usually adjusted so that the output voltages are equal when a white or neutral is being scanned. In analyzing and discussing television systems, it is customary to express signal voltages in relative or percentage units, such that 100% voltage in all three channels corresponds to the brightest white the system can reproduce.

All systems of color television are based on the same colorimetric principles, regardless of the physical construction of the cameras and receivers or the methods used to transmit the signals. It should be appreciated that the signals which enter the transmission system may be operated upon in a great variety of ways; the only requirement is that they must remain sufficiently independent that red, green and blue signals suitable for the control of a tricolor reproducer can be recovered at the receiving end.

IV. REQUIREMENTS FOR COLOR TELEVISION TRANSMISSION

The most difficult problems to be worked out during the evolution of a color television system suitable for broadcast use lay in the area of transmission techniques. These problems arose through the necessity of handling three independent signals as opposed to the single signal required for monochrome television. Factors which had to be considered in connection with the transmission problem in color television were:

(a) Spectrum Conservation. The radio frequency spectrum is one of the scarcest of our natural resources, and there are many broadcast and communications services clamoring for frequency allotments. Even monochrome television requires great bandwidth, as indicated by the spectrum sketch of the standard television broadcast channel in Fig. 4. (Note that the amplitude-modulated picture signal is transmitted in vestigial-sideband fashion to conserve bandwidth).

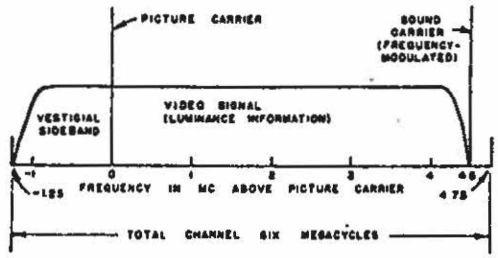


Fig. 4. Sketch of a standard television broadcast channel.

The FCC announced in 1949 that it considered the ability to operate within the same six-megacycle channel used for monochrome one of the basic criteria for color television systems. This presented a real challenge to the industry's engineers, and emphasized the need for techniques permitting maximum effectiveness in the use of the limited spectrum available.

(b) The Multiplexing Problem. The necessity for handling three independent signal components in a color television system results in a need for multiplexing techniques for transmitting these independent signals through a single channel. For many years, various sequential or time-division multiplex systems were explored as possible answers to this problem, but the signal specifications finally adopted are based on techniques known as frequency interlace and two-phase modulation, which will be discussed below.

(c) The Compatibility Issue. Since monochrome television was already well established as a broadcast service before color television was developed to a point where commercialization was possible, it was necessary to consider the economic conditions under which a color telecasting service would have to be introduced. The compatible color television system pioneered by RCA is one in which the transmitted signals are capable of rendering service to monochrome receivers, and which permits receiver designs suitable for the reception of either monochrome or color programs without readjustment. The feature of compatibility enables broadcasters to initiate color broadcasting service without loss of audience, and makes it possible for the owners of color receivers to continue to receive monochrome programs as well as those broadcast in color.

The remainder of this paper will be devoted to a discussion of four basic techniques used to achieve spectrum efficiency and to solve the multiplexing problem in compatible color television. These are: (1) matrixing, (2) band-shaping, (3) two-phase modulation, and (4) frequency interlace.

V. MATRIXING AND BAND-SHAPING

Color picture information as it leaves a simultaneous color camera is "packaged" in the form of three video signals controlled by the red, green, and blue components of the image. By re-packaging this information in the form of a different set of three independent signals, it is possible both to satisfy the compatibility requirement and also to adjust the bandwidths of the three signal components so as to achieve greater efficiency in the use of the radio frequency spectrum.

The repackaging is accomplished by so-called matrix circuits, which cross-mix the three primary-color signals in accordance with the following equations:

$$\begin{aligned} M &= .30\,R + .59\,G + .11\,B \\ I &= .60\,R - .28\,G - .32\,B \\ Q &= .21\,R - .52\,G + .31\,B \end{aligned}$$

One of many possible circuit arrangements for performing the matrix operation is shown in Fig. 5.

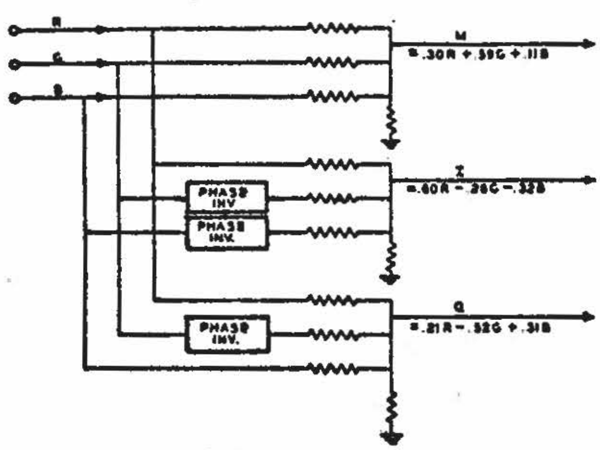


Fig. 5. A typical matrix circuit for re-packaging the primary video signals in a compatible color television system.

The signal component designated by M is very nearly identical to the output of a monochrome television camera, and consequently is capable of rendering good service to monochrome receivers. This signal component is handled in all respects like an ordinary monochrome signal; that is, it is generated in accordance with the conventional scanning standards, it is combined with the standard synchronizing waveform, and it is modulated on a carrier in a conventional television transmitter. (In some modern cameras, the M signal is derived from a fourth pick-up tube in the camera; the R, G, B tubes in such cameras are used only to provide the I and Q signals.)

The I and Q signal components are known as <u>color-difference</u> or <u>chrominance</u> signals; they indicate how the color being transmitted differs from a white or neutral in two independent directions on a color diagram in which white is plotted at the center. The I signal conveys information pertaining to color differences in the orange to cyan (blue-green) direction, while the Q signal conveys information pertaining to color differences in the green to purple direction. Note that both I and Q go to zero when R = G = B, designating a white or neutral condition. To recover red, green, and blue signals suitable for the control of a tricolor reproducer, the M, I, and Q signals are passed through a second matrix circuit in the color television receiver which performs a cross-mixing operation that is the inverse of the original cross-mixing operation at the transmitting end of the system.

Use of the matrixing or cross-mixing technique not only satisfies the compatibility requirement by providing a signal component comparable to an ordinary monochrome signal, but also results in two signal components whose bandwidths can be greatly restricted without significant loss of useful information. Studies of the acuity or resolving power of the human eye have disclosed that the normal acuity for hue and saturation differences is much less than for brightness differences, and that acuity for color differences in the green to purple direction is considerably less than for color differences in the orange to cyan direction. This knowledge has been exploited by adjusting the bandwidths of the M, I, and Q signals used in compatible color television so as to transmit no more than the required amount of information in each case, as indicated by Fig. 6.

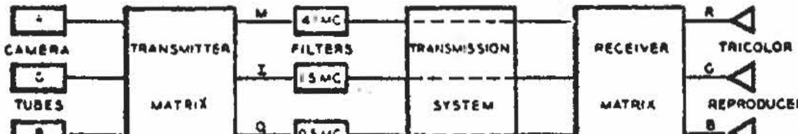


Fig. 6. Simplified block diagram illustrating the application of matrixing and band-shaping techniques to compatible color television.

The M signal component, being comparable to an ordinary monochrome signal, is transmitted with a bandwidth of approximately 4.1 megahertz, so that the brightness resolution in color images is nominally the same as for monochrome images. The bandwidth of the I component is limited to approximately 1.5 megahertz, while that of the Q component is further restricted to only about 0.5 megahertz. Although the resolution of the final color images is not great with respect to color differences, enough information is transmitted to produce perfectly satisfactory images at the normal viewing distance. The eye cannot perceive color differences in very fine detail, so it is pointless to use spectrum space to transmit high-resolution color difference information.

It was once thought that the reproduction of high-quality color television images would require three times as much spectrum space as for a comparable monochrome image (i.e., space for three primary signals, each 4.1 megahertz wide). Thanks to the matrixing and band shaping techniques, it is now possible to transmit high-quality color images with a maximum bandwidth of only 4.1 + 1.5 + 0.5 = 6.1 megahertz, an increase of only 50% above the requirement for monochrome alone. Through techniques which are discussed below, it is possible to achieve even greater savings in spectrum space.

VI. FREQUENCY INTERLACE

Since we have already noted that the M component of a color signal is treated in all respects like an ordinary monochrome signal, it seems, at first glance, that this one component alone must completely fill the available channel, leaving no spectrum space for the additional chrominance signals. It has been found, however, that an additional carrier may be transmitted within the same spectrum space occupied by the luminance signal without causing objectionable interference, provided the added carrier is separated from the main picture carried by some odd multiple of one-half the line frequency. This added carrier may be modulated by a video signal, and thus made to convey additional information. This multiplexing technique is commonly known as frequency interlace.

In practice, the use of an additional transmitter for a color television system is avoided by using the subcarrier principle. That is, the extra information to be transmitted on the added carrier is first modulated upon a subcarrier of less than 4 MC somewhere within the studio, and this modulated subcarrier is then added directly to the monochrome signal. Thus all the color signals are combined into one signal before leaving the color studio, so only one transmission line and one transmitter are required. The subcarrier frequency spacing between the subcarrier and the main picture carrier is preserved when the combined signals are modulated upon the picture carrier within the transmitter.

The desired frequency relationship between the subcarrier and the scanning signals is maintained by means of electronic pulse counters (or equivalent counting stages based on locked-oscillator principles) arranged as shown in Fig. 7. The master timing reference for a color television system is a crystal oscillator set at 3.579545 MH_z ($\pm$ $10H_z$), and the scanning frequencies are derived from this oscillator's output. (The scanning frequencies for color systems are lowered by 0.1% relative to the nominal values used for monochrome to minimize a problem of interference between the subcarrier and the sound carrier in the same channel).

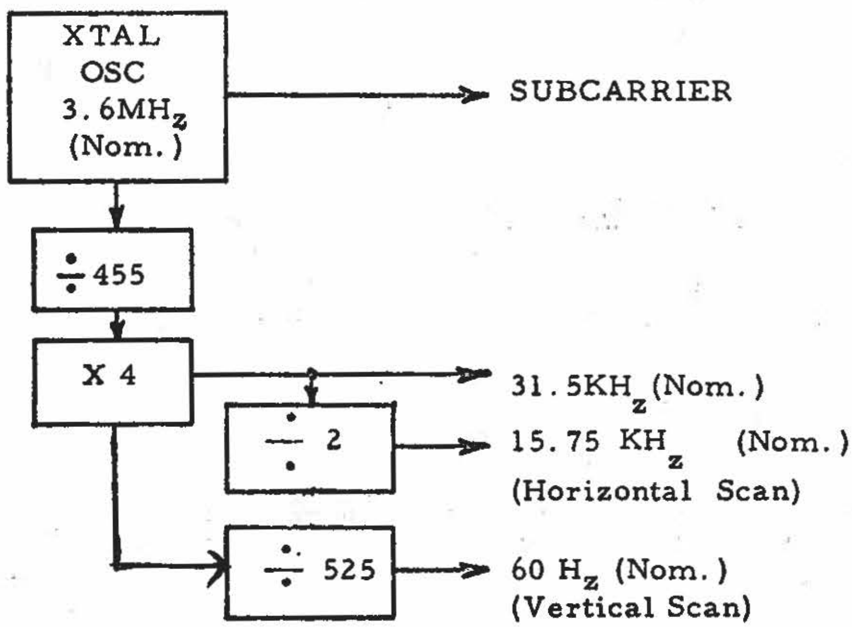


Fig. 7. Arrangement of Counting and Frequency Multiplying Stages in a Color Sync Generator.

Basically, the frequency-interlace technique is a means for exploiting the "persistence of vision" effect to permit the transmission of additional information. Persistence of vision, or the time-integrating property of the human eye, is relied upon even in monochrome television systems; it provides the illusions of smooth motion and continuous illumination from the rapid succession of still images that is actually transmitted. Fortunately for the color television system designer, visual stimuli are integrated or averaged by the eye over considerably longer periods of time for small picture areas than for larger picture areas. Consequently, interfering signals which appear only as small-area dots in the picture may be cancelled out by the eye if provision is made for reversing the polarity of the "dots" between successive scans of each area in the picture.

The clearest way to explain how frequency interlace works is by means of waveform sketches, such as those in Fig. 8. Sketch (A) shows a typical luminance signal for a very small section of one scanning line. Sketch (B) shows the modulated subcarrier signal to be transmitted during the same interval. If the subcarrier is an odd harmonic of one-half the line frequency, it reverses in polarity between successive scans (as indicated by the dotted line) because it passes through some whole number of cycles plus one-half during each frame period. The composite signal to be transmitted — the sum of (A) and (B) — is shown at (C).

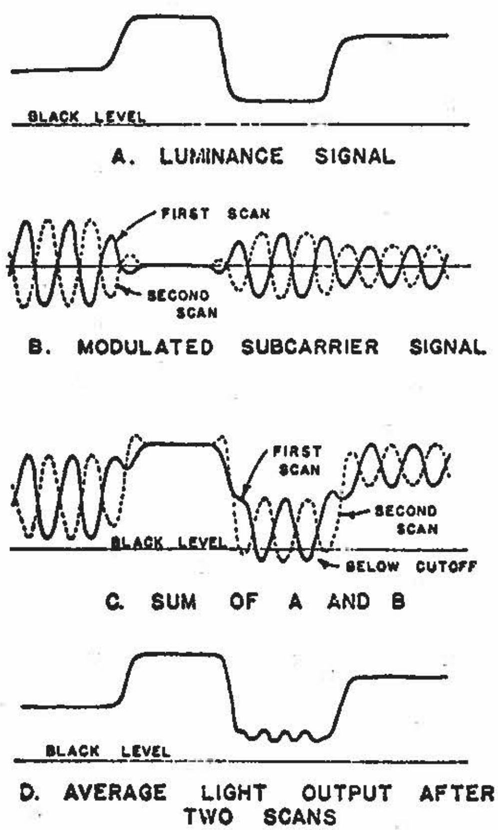


Fig. 8. Waveform sketches illustrating the frequency-interlace principle.

We shall discuss in a later section how chrominance information may be modulated on the subcarrier and later removed from it by demodulation, but at this point we should note that the signal shown at (C) is the one that would be applied to black-and-white kinescopes when ordinary monochrome receivers are tuned to a compatible color transmission. The signal that should ideally be applied to the kinescopes is the luminance signal shown at (A); the subcarrier component is spurious whenever it reaches a kinescope instead of a demodulator. Nevertheless, the interference caused by the subcarrier is not objectionable because it is effectively cancelled out by the persistence of vision. The effective response of the eye is controlled not so much by the instantaneous stimulation provided by any one scan as by the average stimulation after two or more scans. The average signal after two scans is shown at (D). Note that this is identical to the original luminance signal except in cases where the composite signal overshoots below black level; the kinescope is incapable of producing negative light to cancel the positive peaks.

In the interests of accuracy, it should be noted that cancellation of spurious signals by the frequency interlace technique is seldom 100% complete, for the following reasons: (1) For perfect cancellation, the sinusoidal electrical signals shown in Fig. 8 should be transformed to sinusoidal light patterns before reaching the eye; in practice, the electrical signals are applied to non-linear kinescopes which effectively alter the waveforms to make perfect cancellation impossible (the overshoots below black level are an exaggerated case of this general effect). (2) The persistence of vision effect is not perfect over an interval of 1/15th of a second (two frame periods). (3) When there is motion in the image, the waveforms change slightly from frame to frame. On the other hand, the lack of perfect cancellation is not objectionable in practice because: (1) Many mass-produced receivers have relatively low response at the subcarrier frequency specified by FCC Standards (roughly 3.6 MC), so the subcarrier component is pretty well attenuated before it reaches the kinescope. (2) The signals modulated on the subcarrier have the same image geometry as the luminance signal, so any crosstalk resulting from imperfect cancellation does not confuse the picture but simply adds dots or alters gray-scale values in certain areas. (3) The dot pattern resulting from imperfect cancellation corresponds to the second harmonic of the subcarrier, and is therefore even finer in texture than the line structure and cannot be resolved at normal viewing distances.

VII. TWO-PHASE MODULATION

The reader may wonder at this point how we may transmit not one but two chrominance signals (both I and Q) by means of the frequency-interlace technique. It is not desirable to use two separate frequency-interlaced carriers, because the difference frequency between them would be an even multiple of one-half the frame frequency, and hence would have no tendency to be self-cancelling. The difference frequency would be produced as a "beat" between the two carriers whenever the signal is passed through any non-linear device, such as a kinescope. The need for two carrier frequencies can be eliminated by the use of the two-phase modulation technique, which is equivalent to the use of two carriers of the same frequency but with a phase separation of 90 degrees.

The basic equipment needed for a two-phase modulation system is shown in Fig. 9. In the arrangement shown, two independent signals are modulated upon two carriers of the same frequency but 90 degrees apart in phase. The outputs of the two transmitter modulators are added together to feed a common transmission channel. The two independent components are separated at the receiving end by means of two additional modulators (operated as synchronous detectors) which multiply the incoming signal by two carriers having the same relative phases as the original carriers at the transmitter. The carriers at the receiver must be supplied by an oscillator which is maintained in frequency and phase synchronism with the master oscillator at the transmitter; some form of special synchronizing information must be transmitted for this purpose.

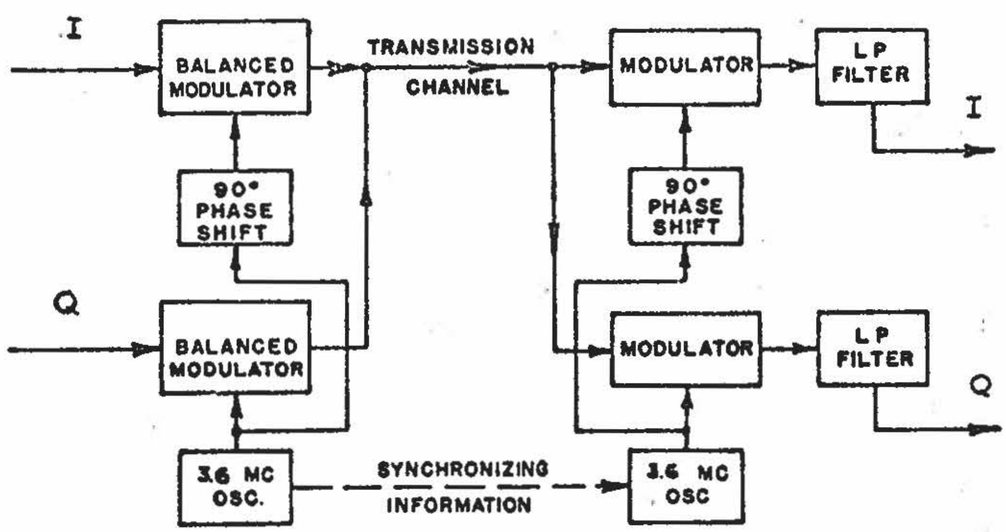


Fig. 9. Simplified block diagram for a two phase modulation system.

The two-phase modulation technique is basically a means for using the two sidebands surrounding a single carrier frequency for the transmission of two variables. It is common knowledge among radio engineers that double-sideband transmission is ordinarily wasteful of spectrum space, since the information contained in the two sidebands is identical. Whereas an ordinary AM wave varies in one respect only (i.e., in amplitude), the signal transmitted by a two-phase modulation system varies in both amplitude and phase.

The most serious disadvantage of the two-phase modulation technique is the need for carrier reinsertion at the receiver. This characteristic makes the technique economically undesirable in many applications, but its use in compatible color television systems is entirely feasible because of the happy fact that time is available for the transmission of subcarrier synchronizing information during the retrace or blanking intervals. As indicated by Fig. 10, only about 86% of each line period in a television signal is available for the transmission of useful picture information; the remaining time is required for a "blanking interval" (transmitted at or beyond the black level) to allow time for the retrace of scanning beams.

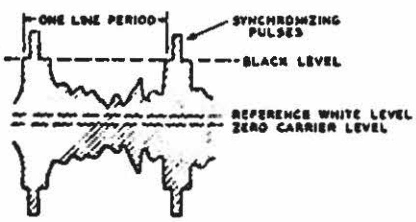


Fig. 10. Waveform sketch of a television picture signal after modulation on an RF carrier for transmission.

A portion of each blanking interval is used for the transmission of a sync pulse, but additional time is available for the transmission of subcarrier synchronizing information. Under the FCC Color Signal Specifications, the subcarrier-synchronizing information consists of "bursts" of at least 8 cycles of the subcarrier frequency at a predetermined phase transmitted during the "back porch" interval following each horizontal synchronizing pulse, as shown in Fig. 11. The "bursts" are separated from the rest of the signal at the receiver by appropriate time-gating circuits, and are used to control the receiver oscillator through a phase detector and reactance tube.

The need for carrier reinsertion in a compatible color television receiver need not be regarded as a serious disadvantage when account

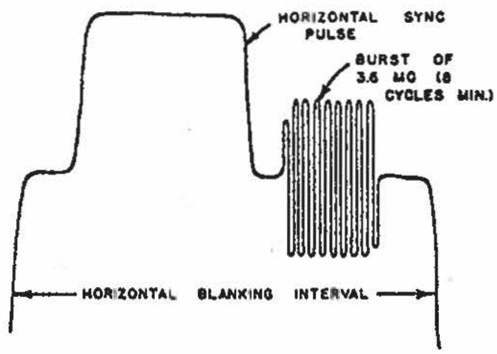


Fig. 11. Waveform sketch for the horizontal blanking interval, showing the color synchronizing burst.

is taken of the fact that an important advantage—suppressed carrier transmission—may be gained without further complexity. In ordinary AM broadcasting, fully half of the radiated energy is in the carrier component, which transmits no information by itself but simply provides the frequency reference against which the sidebands may be heterodyned in simple diode detectors to recover the intelligence in the sidebands. If a locally-generated carrier is available in the receiver, then there is no need to transmit a carrier along with the sidebands. In a compatible color television system, suppression of the subcarrier not only saves signal energy but also reduces the possibility of spurious effects in images, since the complete subcarrier component goes to zero (and hence cannot cause interference) whenever the camera scans a white or neutral surface such that both I and Q equal zero.

Figure 17 is a sketch of the video spectrum available for a compatible color television system employing a subcarrier frequency of

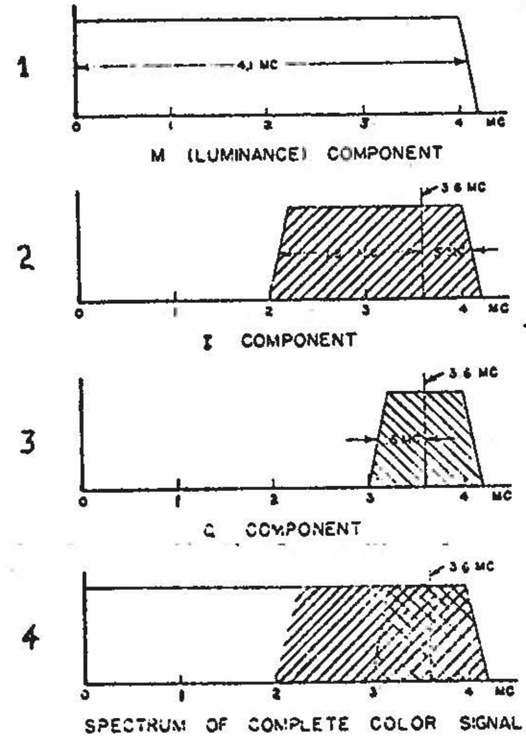


Fig. 17. Chart of the video spectrum for a compatible color television system, showing the bandwidths available for each signal component.

approximately 3.6 MH_z. Note that double sidebands can be obtained for components within about .5 MH_z of the subcarrier. A considerably wider lower sideband is available, however, and it is quite feasible to transmit one subcarrier component in this single-sideband region. As shown by the lower sketches in Fig. 17, the use of two-phase modulation and frequency interlace, provides spectrum space for three independent signals within a standard television channel. As noted previously, the M or luminance signal, has a bandwidth of approximately 4.1 MH_z. One subcarrier component, which we designate the I (or in-phase) component, may have a bandwidth of 1.5 MH_z if transmitted in semi-single sideband fashion (practical filter limitations make it difficult to achieve effective bandwidths much greater than half the subcarrier frequency). The other subcarrier component, the Q (or quadrature-phase) component, may have a bandwidth of .5 MH_z with double sidebands.

VIII. COLOR SIGNAL CHARACTERISTICS

Waveforms resulting from the generation of a color-bar pattern consisting of vertical stripes in the primary colors and their complements (a pattern widely used for test purposes in color systems) are shown in Fig. 18.

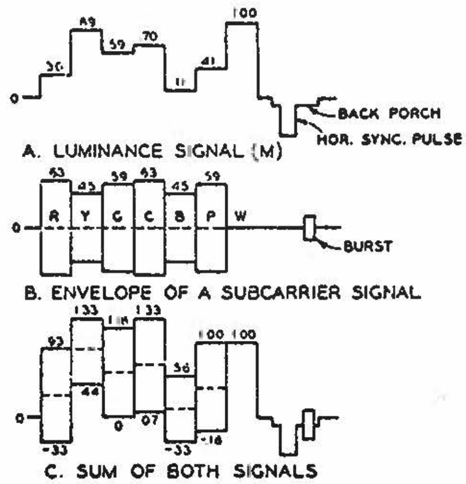


Fig. 18. Bar-pattern waveforms showing the derivation of the composite signal for a compatible system.

The subcarrier signal actually varies, of course, in both amplitude and phase, although only the amplitude variations can be shown in a simplified waveform sketch. Note that the sum of the monochrome (or luminance) signal and the modulated subcarrier occupies an appreciably greater amplitude range than the M signal alone--the subcarrier "overswings" into both the whiter-than-white and blacker-than-black amplitude regions. The signal resulting from the scanning of a normal scene is more nearly confined to the same amplitude range as a monochrome signal, since maximum-saturation colors are quite rare in ordinary scenes. Nevertheless, it is important that color television signals be handled in equipment with exceptionally good amplitude linearity and well-behaved phase characteristics to avoid intermodulation distortion of the important chrominance information.

The significance of the phase variations in the subcarrier signal can be appreciated by studying Fig. 19, which is a composite vector diagram showing the relative phases and amplitudes associated with the primary colors and their complements. (The complement of a primary color is formed by adding equal amounts of the other two primaries.)

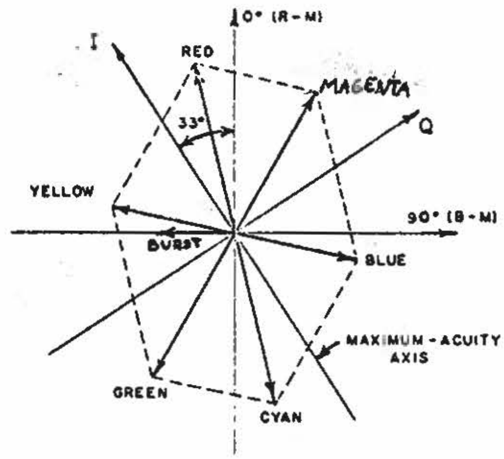


Fig. 19. Composite vector diagram showing the subcarrier amplitudes and phases corresponding to six basic colors.

The axes corresponding to the I, Q, and burst signals are also shown on this diagram. From inspection of this diagram, it should be apparent that the instantaneous phase of the subcarrier signal controls the hue of the color being reproduced. The ratio of the amplitude of the resultant subcarrier to the simultaneous amplitude of the M signal controls the saturation of the reproduced color.

IX. REVIEW OF SIGNAL GENERATION PROCESS

In the preceding pages, we have discussed most of the major principles and techniques employed in compatible color television. It would be well at this point to look at the system as a whole to see how the various principles are inter-related. This review will also give us an opportunity to examine briefly some details of the system not covered in earlier discussions.

All major operations performed at the transmitting end of the system are shown in Fig. 20. The camera contains three pickup tubes or transducing elements which provide electrical signals corresponding to the red, green, and blue components of the scene to be televised. These signals are passed through non-linear amplifier stages (the gamma correctors) which provide compensation for the non-linearity of the kinescope elements at the receiving end of the system. The gamma-corrected signals are then matrixed or cross-mixed to produce a luminance signal (M) and two color-difference or chrominance signals (I and Q). Fig. 20 shows a simple matrix circuit for producing M, I, and Q signals directly from the R, G, B signals in accordance with the equations previously given.

In the "filter section" shown in Fig. 20, the bandwidths of the M, I, and Q signals are established. The 4.1 MH_z filter for the luminance

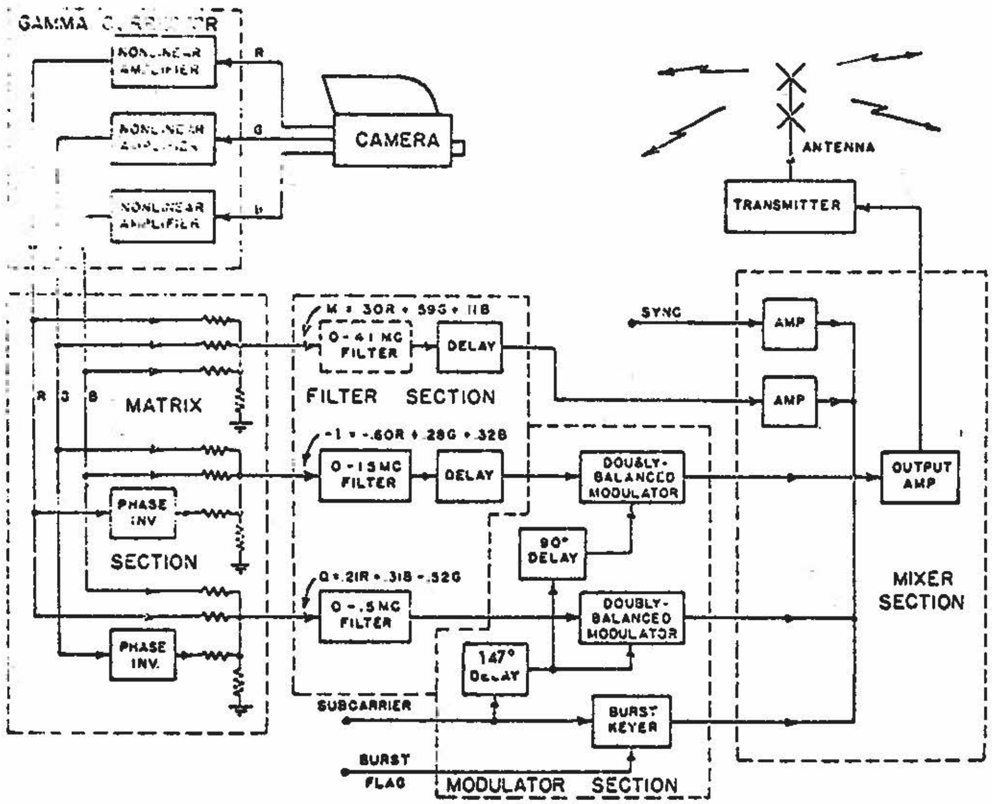


Fig. 20. Block diagram showing major operations at the transmitting end of the RCA color television system.

channels is shown in dotted lines because in practice it is not necessary to insert a special filter to achieve this band-shaping—the bandwidth of the luminance signal is usually determined by the attenuation characteristics of the transmitter, which must, of course, confine its radiation to the assigned broadcast channel. The bandwidths of 1.5 MH_z and .5 MH_z 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, which places the burst exactly 180° out of phase with the B-M component of the signal, was chosen mainly because it permits certain simplifications in receiver designs. Timing information for "keying in" the burst may 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 the mixer section is a complete color television signal containing both picture and synchronizing information. This signal may then be put "on the air" by means of a standard television transmitter, although elaborate signal-handling systems are usually needed between the point of signal generation and the final transmitter.

X. SPECIAL PROBLEMS IN THE HANDLING OF COLOR TELEVISION SIGNALS

The amount of handling to which a color television signal is subjected after leaving the colorplexer depends upon the complexity of the broadcast plant. In small stations, the signal may be sent almost directly (usually through some sort of simple switching system) to the transmitter. In more elaborate plants and in major networks, the signal must pass through a number of distribution amplifiers, switchers, stabilizing amplifiers, microwave relay links and television tape recorders before it reaches the transmitter. All of the equipment handling the color signal (including the transmitter) must be designed to operate within relatively narrow tolerance limits with respect to the following parameters:

(a) Amplitude versus frequency. A change in response at the color subcarrier frequency relative to the lower frequencies causes an undesirable increase or decrease in the saturation of colors.

(b) Envelope delay versus frequency. All signal components must arrive in time coincidence at the second detector of the receiver if certain edge effects or transients are to be avoided. The FCC standards provide for envelope delay compensation at the transmitter for normal receiver errors in this respect.

(c) Differential gain. (Subcarrier amplitude as a function of monochrome level.) If an amplifier or other device compresses the signal in either the black or white region, there is a corresponding loss of color saturation in either the highlights or the shadows.

(d) Differential phase. (Subcarrier phase as a function of monochrome level.) If subcarrier components transmitted near white level (corresponding to bright colors) are distorted in phase relative to those transmitted near black level (dark colors), there will be objectionable hue shifts as illumination conditions are varied in the televised scene.

The FCC standards do not specify performance requirements for each individual piece of studio equipment, but overall tolerance limits are placed on the signal as radiated. It is considered the manufacturer's responsibility to design equipment using no more than a fair share of the available tolerances.

Much of the recent effort by overseas laboratories to develop alternative techniques for encoding and decoding color television signals has been motivated by a desire to reduce the requirements for extremely high fidelity in transmission and recording equipment. American experience has shown, however, that the problems of transmitting and recording color signals are not so serious as to be insoluble. The American system of color television (as pioneered by RCA) has turned in a good account for itself in comparative tests of more-recently-developed alternative systems.

XI. DECODING OPERATIONS IN COLOR RECEIVERS

While many variations in receiver design are possible, the basic functions which must be performed are shown in Fig. 21. The signal brought in from a television receiving antenna is heterodyned down to an intermediate frequency range (in the vicinity of 40 megahertz) and amplified in a multi-stage IF amplifier. The bandwidth of the RF and IF portions of a color receiver must be somewhat wider than that normally provided in a monochrome receiver so as to pass the color subcarrier at full amplitude. A rectifier-type second detector is used

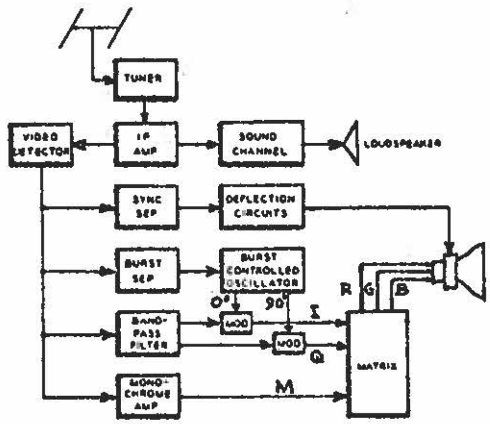


Fig. 21. Simplified block diagram of a compatible color television receiver.

to demodulate the composite video signal from its carrier. A sound channel consisting of a 4.5 MC intermediate frequency amplifier, an FM detector, an audio amplifier, and a loudspeaker, is usually fed from the output of the video IF amplifier. The video signal from the second detector is utilized in four circuit branches as follows:

(1) The sync separator, which provides pulses for control of the deflection and convergence operations associated with the color kinescope.

(2) The burst separator, which is turned "on" by pulses derived from the horizontal deflection circuit. The separated bursts are used to control a local 3.6 MH_z subcarrier oscillator.

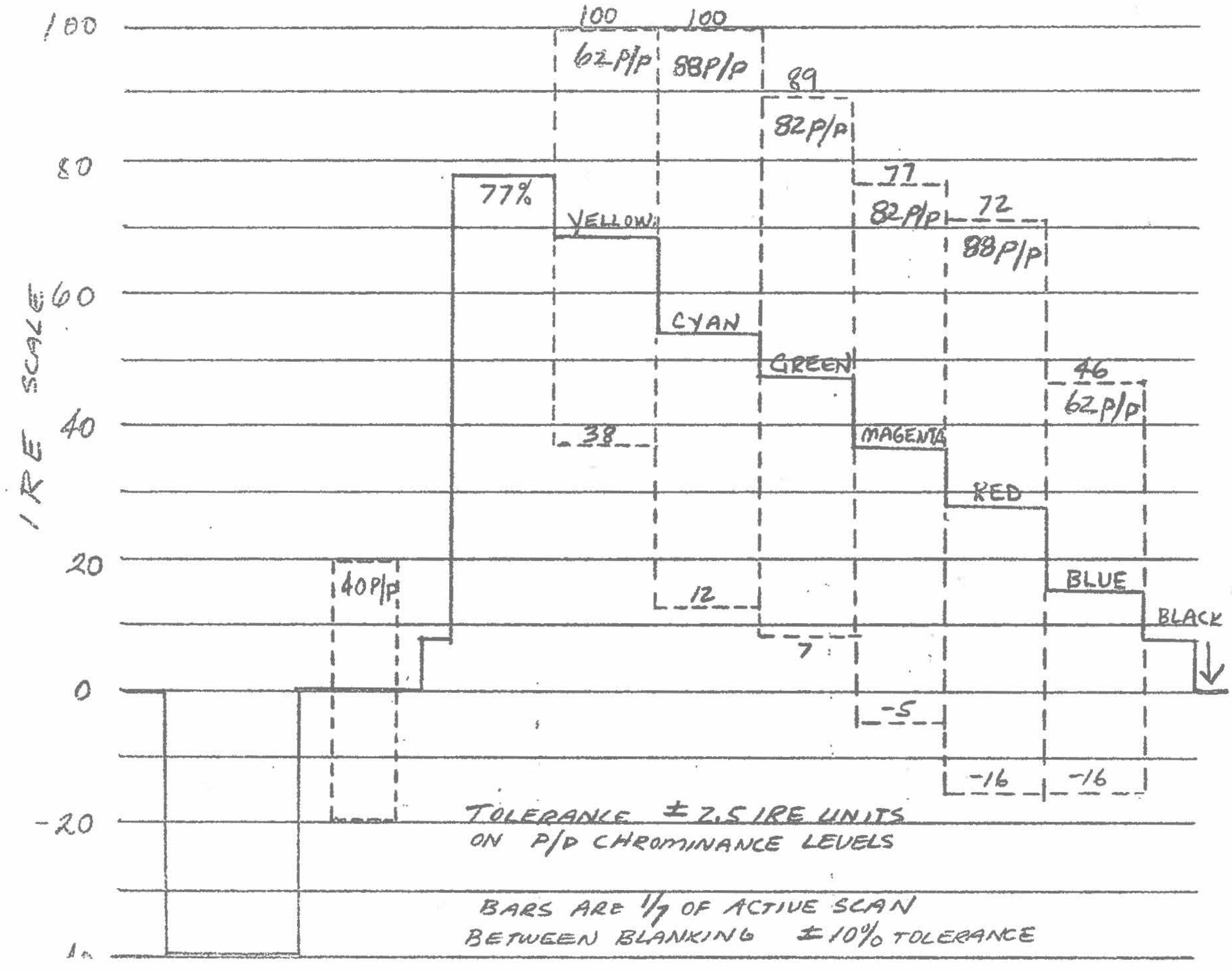
(3) The monochrome channel, which passes the monochrome signal component and rejects or attenuates the color subcarrier frequency.

(4) The chrominance channel, which consists of a band-pass filter centered around 3.6 MH_z, plus a pair of synchronous detectors adjusted to recover the two independent components of the modulated subcarrier.

The monochrome signal and the demodulated chrominance signals are cross-mixed in a matrix network to produce red, green, and blue signals suitable for driving the corresponding guns of a color kinescope. The complete color image is then produced on the kinescope's phosphor screen.

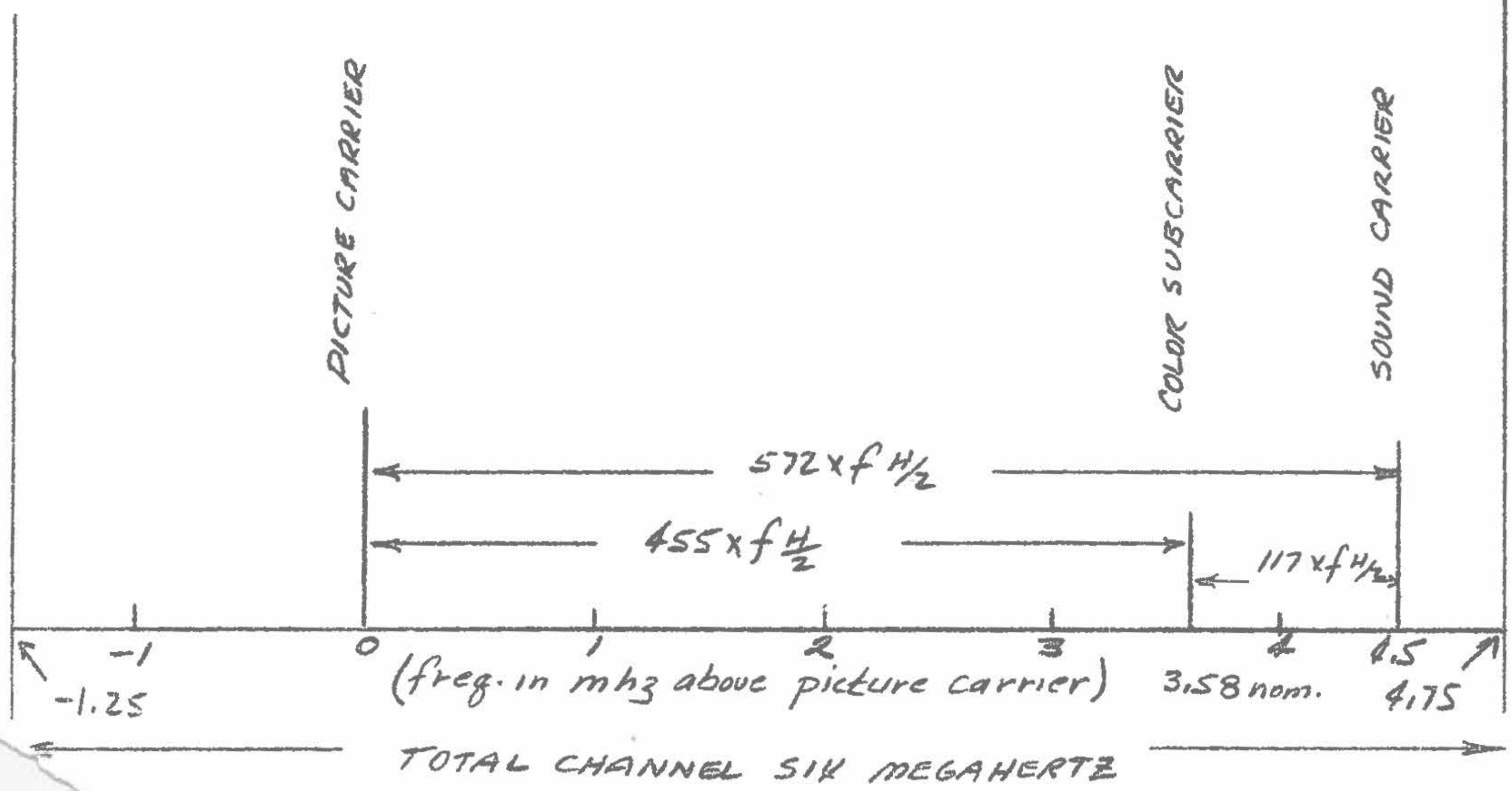
XII. CONCLUSION

In this brief Study Guide, it has not been possible to give more than superficial treatment of many of the engineering developments which both preceded and followed the formal adoption of signal specifications for color television broadcasting. Color kinescope and color receiver designs have been greatly refined in recent years, and a new generation of color television studio equipment (based on solid-state designs) is now beginning to appear on the market. The technology involved in recording color television signals on magnetic tape that has evolved during the past few years is a major subject in itself, and laboratories outside the U. S. A. are beginning to make major contributions to color television. Although the total engineering effort within RCA is no longer concentrated on broadcast communications to the degree that it was during the Company's formative years, the engineering personnel concerned with this aspect of RCA's business continue to find challenging problems and opportunities for creative work.


100
80
60
40
20
0
-20
IRE SCALE
100
100
62 P/P
88 P/P
89
82 P/P
77
82 P/P
72
88 P/P
77%
YELLOW
CYAN
GREEN
46
62 P/P
MAGENTA
38
RED
40 P/P
12
BLUE
BLACK
7
-5
-16
-16
TOLERANCE ± 2.5 IRE UNITS
ON P/P CHROMINANCE LEVELS
BARS ARE 1/7 OF ACTIVE SCAN
BETWEEN BLANKING ± 10% TOLERANCE

$f_{H/2}$ = ½ line frequency

82
5.75
87.75
88.10
87.75
.35



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