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SIMULTANEOUS SIGNAL SEPARATION IN THE TRICOLOR VIDICON

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Approved

Stuart Wm. Seeley

The operation of the tricolor Vidicon, a single pickup tube now under development for color television, presents a novel circuit problem. The target structure contains a considerable capacitance which couples the three output electrodes. Extraction of separate color signals in the presence of this cross-coupling impedance must be performed while maintaining a satisfactory signal-to-noise ratio. This bulletin presents a general analysis of the problem and suggests several practical solutions. The system described involves low input impedance, feedback preamplifiers and mixed-high circuitry.

Introduction

A novel circuit problem is encountered in the design of camera equipment associated with the tricolor Vidicon[1], a developmental pickup tube for color television. The tricolor tube has three output electrodes for delivering three electrical signals corresponding to the red, green and blue information contained in the scene. However, the three output signals may be coupled together by the large inherent capacitance of the tube structure. The problem is to extract separate color signals in the presence of the cross-coupling impedance while maintaining a satisfactory signal-to-noise ratio.

The target of the tricolor Vidicon contains color filters in a repetitive sequence of red, green, and blue strips. Superposed in registry with each filter is a narrower transparent conducting signal strip. All signal strips behind filters of the same primary color are connected to a common output terminal. The capacitance from one set of signal strips to the other two is of the order of *1200 μμf* in the developmental targets. A single electron beam scanning the photoconductor which has been deposited on the target induces video signal currents in each set of strips in proportion to the primary color component.

Introductory Calculations

In use, three preamplifiers are connected to the three output leads of the target. The video signal current produces voltage fluctuations in the input load resistor of each preamplifier. Ideally, each separate color signal should be amplified only by its corresponding preamplifier. Actually, because of the interstrip capacitance, it is possible for the signals of higher frequency to cross-couple. An equivalent circuit of the target is shown in Fig. 1 as a delta, whose sides are the cross-coupling capacitances, C_t, and whose vertices are the signal strips connected to three amplifiers with input impedances represented by Z_{in}. Complete symmetry is assumed throughout. Since the beam acts as a high source impedance, a primary color signal is represented as a single current source driving the corresponding set of strips. In general the signals from the three sets of signal strips are present concurrently.

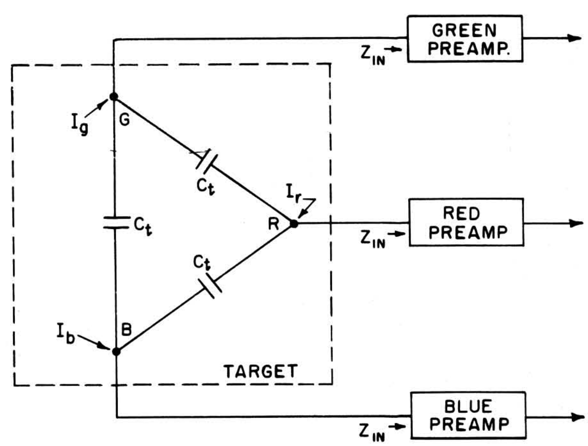

Fig. 1 – Equivalent circuit of the target.

To appreciate the signal separation problem consider some simple calculations. In Fig. 1, C_t, 600 *μμf*, has a reactance, X_c, of 204 ohms at 1.3 mc, the upper limit of desired signal separation defined by the U.S. compatible color television system. Suppose conventional black-and-white preamplifiers, with Z_{in} consisting of a resistor of 50,000 ohms shunted by *30 μμf*, are used.

1. *LB–1043 The Tricolor Vidicon*, by P.K. Weimer et. al.

Imagine a scene of a green picket fence on a dark background with optical image size such that the pickets correspond to one megacycle information. For this case there is but one signal current, I_g, which divides and flows through the three preamplifiers according to the impedances presented; 34.4 percent into the green and 32.8 percent into each of the red and blue. The green picket fence would appear white on a color monitor because it would be made up of almost equal parts of green, red and blue video signals.

The three alternative paths for I_g have impedance Z_{in} through the green amplifier, $Z_{in} - jX_c$ through the red, and $Z_{in} - jX_c$ through the blue. If Z_{in} were much smaller than X_c, there would be one low impedance path through the green amplifier and two relatively high impedance paths through the other two amplifiers; most of the signal current would flow through the desired channel. Suppose amplifiers of low input impedance are provided by placing a 75 ohm resistor to ground at the head of each amplifier. The signal separation would be excellent at the lower frequencies and become worse at the higher frequencies. This method of reducing amplifier input impedance reduces cross-talk, but as shown below, the signal-to-noise ratio is quite poor.

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The equivalent root-mean-square noise current in amperes flowing into a camera preamplifier due to the input circuit and first amplifier stage may be expressed as:[2]

$$I_n = \sqrt{4kTf_o}\sqrt{\frac{1}{R} + \frac{R_{eq}}{R^2} + \frac{R_{eq}}{3X_c^2}}, \qquad (1)$$

where:

k = Boltzman constant (1.38×10^{-23} Joules/^oK),

T = absolute temperature taken as 300°K,

f_o = upper limit of frequency band,

X_c = capacitive reactance to ground at f_o,

R = resistance to ground, and

R_{eq} = equivalent noise resistance of the amplifier input tube.

For a 1.3 mc chroma bandwidth, $X_c = \dfrac{1}{4\pi f_o C_t} = 102$ ohms

(assuming Z_{in} small compared to the target reactance, and direct capacitance to ground small compared with $2C_t$). R is 75 ohms and R_{eq} is 45 ohms (for two Western Electric type 417-A triodes in parallel). Since the target presents a very large capacitance, a reduction in noise is obtained through the paralleling of input tubes to reduce the equivalent noise resistance.

Substituting in the above expression:

$$I_n = 1.47 \times 10^{-7}\sqrt{0.0133 + 0.0080 + 0.0014},$$

or $I_n = 0.0221$ microamperes.

Since a typical total signal is 0.6 microamperes peak-to-peak or 0.2 microampere in each channel, the signal-to-noise ratio is approximately 9 for each color. This poor performance is due largely to the first two terms under the radical which reflect the small value of R. Noise of any one amplifier has been assumed not to cross-talk to the other two amplifiers.

Mathematical Analysis

The problem of signal separation may be analyzed from the equivalent circuit shown in Fig. 2. The analysis is simplified by making the assumption of complete symmetry. The cross-coupling capacitances, C_t, between the sets of signal strips are equal and have impedances Z_t. Likewise, the impedance Z at the input of the three identical amplifiers are all the same, each comprising a resistor R and capacitor C in parallel. The fictitious

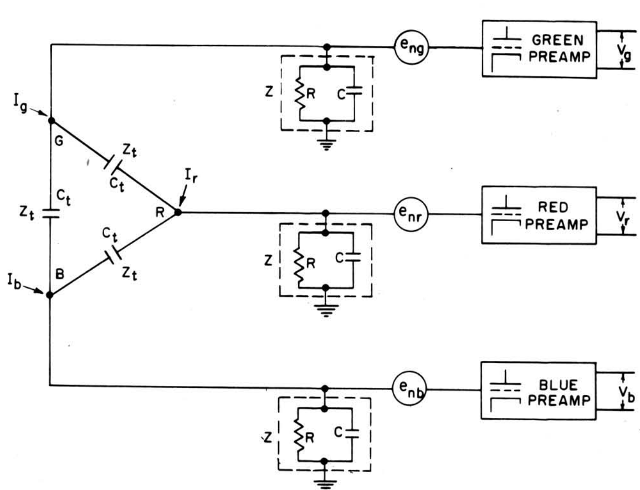

Fig. 2 – Equivalent circuit for analysis.

2. H.B. DeVore and H. Iams, "Some factors affecting the choice of lenses for television cameras", Proc. I.R.E., vol. 28, pp. 369-374; August, 1940.

noise voltage generators, e_{ng}, e_{nr} and e_{nb}, represent the noise developed in each head amplifier stage, but exclude the thermal agitation noise due to R. Certainly for best design R should be chosen very large so that its noise will be dominated by amplifier noise. The unity gain amplifiers have voltage outputs, V, which include signals plus noise.

Each amplifier noise source is effectively in series with the input control grid. The Superposition Theorem is employed to sum up the effects of the three current generators in the form of voltages at R, G and B. For example, the total input voltage to the green amplifier is the sum of the separate voltages produced by I_g, I_r, and I_b at G plus the noise voltage e_{ng}. Therefore, an expression for V_g in terms of the I's and e_{ng} is;

$$V_g = I_g \frac{Z(Z+Z_t)}{3Z+Z_t} + I_r \frac{Z^2}{3Z+Z_t} + I_b \frac{Z^2}{3Z+Z_t} + e_{ng}\,. \qquad (2a)$$

The other two expressions are derived in similar fashion:

$$V_r = I_g \frac{Z^2}{3Z+Z_t} + I_r \frac{Z(Z+Z_t)}{3Z+Z_t} + I_b \frac{Z^2}{3Z+Z_t} + e_{nr}, \qquad (2b)$$

and

$$V_b = I_g \frac{Z^2}{3Z+Z_t} + I_r \frac{Z^2}{3Z+Z_t} + I_b \frac{Z(Z+Z_t)}{3Z+Z_t} + e_{nb}\,. \qquad (2c)$$

The solutions for the three unknown signals, I_g, I_r and I_b plus noise, in terms of the V's are given below.

(3a)

$$I_g + \left(\frac{2}{Z_t} + \frac{1}{Z}\right) e_{ng} - \frac{1}{Z_t} e_{nr} - \frac{1}{Z_t} e_{nb} =$$

$$\left(\frac{2}{Z_t} + \frac{1}{Z}\right) V_g - \frac{1}{Z_t} V_r - \frac{1}{Z_t} V_b$$

(3b)

$$I_r - \frac{1}{Z_t} e_{ng} + \left(\frac{2}{Z_t} + \frac{1}{Z}\right) e_{nr} - \frac{1}{Z_t} e_{nb} =$$

$$-\frac{1}{Z_t} V_g + \left(\frac{2}{Z_t} + \frac{1}{Z}\right) V_r - \frac{1}{Z_t} V_b$$

(3c)

$$I_b - \frac{1}{Z_t} e_{ng} - \frac{1}{Z_t} e_{nr} + \left(\frac{2}{Z_t} + \frac{1}{Z}\right) e_{nb} =$$

$$-\frac{1}{Z_t} V_g - \frac{1}{Z_t} V_r + \left(\frac{2}{Z_t} + \frac{1}{Z}\right) V_b$$

Since all noise sources other than the first stage shot noise have been excluded in this analysis, the above solutions are optimum. In addition they are perfectly general, for regardless of the method chosen for separating signals, once pure signals have been secured, the indicated noise will also be present.

Possible Electronic Solutions

The mathematical solutions to the simultaneous equations indicate a direct method for solving the signal separation problem. With the noise terms omitted, Eqs. (3) may be expressed as follows:

$$Z_t\, I_g = \left(2 + \frac{C}{C_t}\right) V_g - V_r - V_b\,, \qquad (4a)$$

$$Z_t\, I_r = -V_g + \left(2 + \frac{C}{C_t}\right) V_r - V_b\,, \qquad (4b)$$

$$Z_t\, I_b = -V_g - V_r + \left(2 + \frac{C}{C_t}\right) V_b\,. \qquad (4c)$$

It has been assumed that $R \gg \frac{1}{\omega C}$ and therefore $\frac{1}{Z} = j\omega C$.

Fig. 3 is a block diagram showing how the above operations may be done electronically. One channel is represented and only a green signal has been derived. Since the input impedance is capacitive, the subsequent stages of amplification contain correcting networks to insure that the signal is amplified uniformly irrespective of frequency. An "electronic matrix" could be built to operate on the three observables, the V's, and yield the three desirables, the I's.

Some disadvantages of the electronic matrix are: (1) it is critical of adjustment since each pure color signal is obtained from the difference of two nearly identical signals. (2) The system is somewhat complex. (3) The compensation for the capacitive input impedance over the required number of frequency decades is rather awkward.

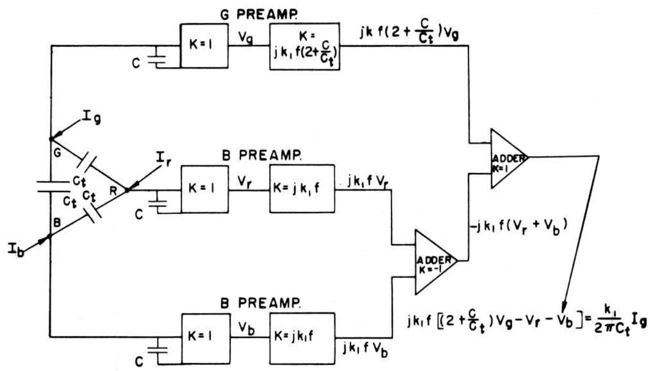

Fig. 3 – One channel of the 'electronic matrix'.

A simpler method for the solution of the signal separation problem involves low input impedance preamplifiers. The previous analysis is applicable if R, the actual impedance to ground at the amplifier input, is maintained large. If the low impedance is obtained dynamically, signal separation may be achieved while the optimum signal-to-noise ratios are approached. A dynamic impedance does not exhibit thermal agitation noise as does a physical resistance. Two methods of dynamically obtaining a low value input impedance are: (1) by using negative feedback from the output of each amplifier to its own input and (2) by the use of a grounded-grid amplifier. These low input impedance preamplifiers do accomplish signal separation within the target. The cross-feeding of signals is accomplished by the delta of Z_t's itself. This method, though not identical with the mathematical solutions given previously, approaches this solution as the input impedance is made to approach zero.

Expressions for the input impedance, Z_{in}, and the output voltage, V_{out} of a single-stage feedback amplifier are readily derived as:

$$Z_{in} = \left(\frac{Z_f}{R_{BP}} + 1\right) \frac{1}{g_m} \tag{5a}$$

and
$$V_{out} = IZ_f , \tag{5b}$$

where $R_{BP} = \dfrac{r_p R_B}{r_p + R_B}$

R_B is the plate load resistor,

r_p and g_m are the plate resistance and transconductance of the amplifier tube, respectively,

Z_f is the impedance in the feedback path, and I is the signal current.

The above expressions are valid if the physical impedance to ground at the preamplifier input,

$$Z \gg Z_f$$

and
$$g_m \gg \frac{1}{Z_f} + \frac{1}{R_{BP}} .$$

If two parallel-connected type 417-A triodes are used, $g_m = 0.060$ mhos and $r_p = 750$ ohms. A practical value for the plate load resistor, R_B, is 3000 ohms. If it is desired to have $Z_{in} = 75$ ohms, then $Z_f = 2200$ ohms. $V_{out} = 440$ microvolts for a signal current of 0.2 microamperes peak-to-peak in each color channel. Assuming a large R, say 200,000 ohms, and all the above values, the imposed conditions are sufficiently satisfied.

Expressions for the input impedance and output voltage for a grounded-grid amplifier may be found in the literature[3] and are given below:

$$Z_{in} = \frac{R_B + r_p}{\mu + 1} , \tag{6a}$$

and
$$V_{out} = IR_B , \tag{6b}$$

where the amplification factor, $\mu = g_m r_p$, and all other terms are the same as previously defined. The above expressions are valid if the resistor in the cathode circuit, is much greater than Z_{in}. Assuming the same plate load resistor, the input impedance for the grounded-grid arrangement is about 81 ohms.

3. REFERENCE DATA FOR RADIO ENGINEERS, Third Edition, Federal Radio and Television Corporation, 1949, p. 253.

Neither the feedback nor the grounded-grid method requires unusual circuits subsequent to the preamplifiers and neither should be critical in operation. The feedback amplifier is more flexible because a wide range of input impedances may be obtained by inserting the proper feedback impedance. In the cathode-driven arrangement the input characteristic is primarily determined by the input tube which has been selected for noise considerations. It appears that a practical method of achieving signal separation is to use special low input impedance preamplifiers of the feedback variety.

Feedback Preamplifier Design

The first stage in each of the feedback preamplifiers, shown in Fig. 4, was chosen by signal separation and noise considerations to consist of two parallel-connected type 417-A triodes with a feedback path of 2200 ohms between the plates and grids. The amplifier second stage is determined only after an examination of the noise that it introduces, since signal degradation at this point should be made as insignificant as possible. A cascode-connected 417-A is used as the second stage because it produces 9 db less noise voltage than a 6AH6 pentode. With this arrangement the second stage noise has not been made negligible, but has been reduced to a reasonable value. The considerable gain obtainable from the cascode amplifier insures that the signal level at the input to the third stage will be sufficiently high that further degradation of the signal by noise may be ignored. The subsequent stages in the preamplifier are conventional.

The Mixed-High System

The present standards for color television require only 1.3 mc of chroma information. Since all signals, separated as well as cross-coupled, pass through the preamplifiers, a total signal above this frequency may be obtained by adding the three preamplifier outputs through a high-pass filter. It is apparent that a signal obtained by summing the three equations (3a, 3b, and 3c) results in a cancellation of the larger noise terms, since noise originating in one channel appears reversed in phase in the other channels. This feature may be referred to as "correlated noise".

A method of utilizing the correlated noise to improve the signal-to-noise ratio from the tricolor Vidicon[4] is shown in block diagram form in Fig. 5. The signals are fed directly into three feedback preamplifiers, each presenting a low input impedance, where they are amplified to about 0.5 volt peak-to-peak. The signals then pass into a level setter which establishes a reference voltage related to black-level during horizontal retrace

4. H. Borkan and P.K. Weimer, U.S. Patent No. 2,698,874.

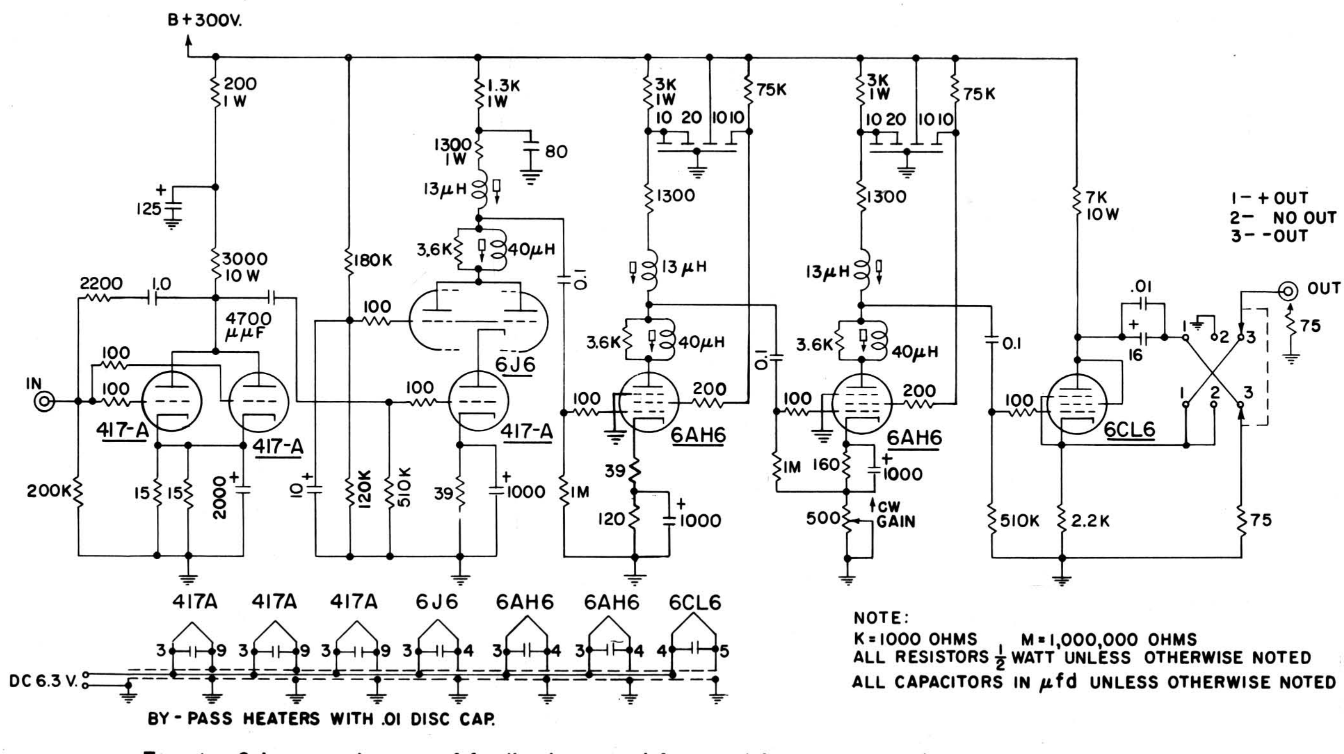

Fig. 4 — Schematic diagram of feedback preamplifier used for experimental tests of Tricolor Vidicon

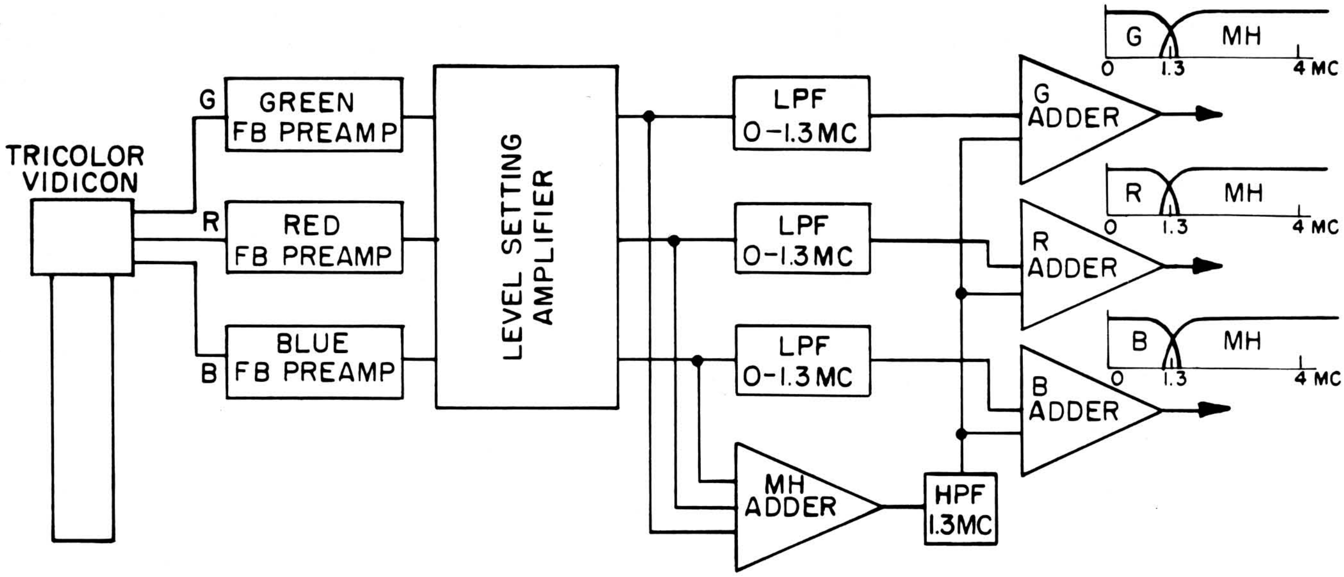

Fig. 5 – Mixed-high system providing noise reduction in Tricolor Vidicon signals.

time. The signals then split up into two paths. One path is through the mixed-high adder which combines the three signals and passes them through a high-pass filter. This is the mixed-high channel which carries information made up of equal parts of the original red, green, and blue signals above 1.3 mc. The other path for each signal is through a low-pass 1.3 mc filter. Since the preamplifiers have separated the color information out to beyond this frequency, each of these three signals contain essentially information of one primary color. The mixed highs are added to each of the color signals in the final adders. The resultant signals may be fed to a simultaneous monitor or used to produce the standard color signal.

Evaluation of the Feedback Method

The feedback preamplifier method of signal separation is evaluated by an analysis of two factors: signal separation ability and signal-to-noise ratio. Fig. 6 is a phasor diagram illustrating the magnitude and phase of the three output signals produced by a pure primary color as a function of signal frequency. All sources of cross-talk other than capacitive coupling through the target have been neglected. The diagram is applicable for $Z_{in} = 75$ ohms and $C_t = 600\ \mu\mu f$. While the graph shows color mixing at the higher frequencies, subjectively it has been found that the residual color cross-talk is accept-

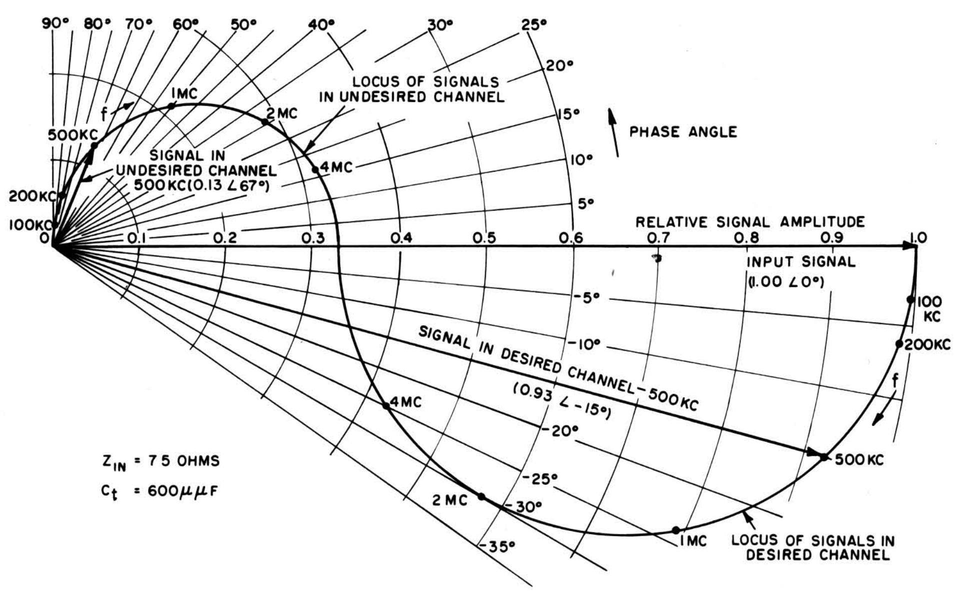

Fig. 6 – Phasor diagram showing signals in desired and undesired channels for primary color signals of various frequencies. (500 kc signal illustrated).

able, since the eye is not sensitive to chromatic differences in small areas. However, should a lower value of input impedance be desirable, it is attainable with slight additional noise degradation in the mixed highs due to the second amplifier stage.

In the appendix, optimum values for signal-to-noise ratios have been calculated to be 29.4 for each color channel and 330 for the mixed highs. These values are for a 0.6 microamperes peak-to-peak white signal. The calculated value for each color channel is determined only by first-stage amplifier noise. Since thermal agitation noise, beam noise and second-stage noise are found to be negligible when compared with first-stage amplifier noise, the feedback amplifier signal-to-noise ratio for color information is substantially the same as the optimum value. In practice the system appears better than the value of 29.4 calculated for each color channel because of noise cancellation at the kinescope. The mathematical analysis has demonstrated that when all three signals are added together, a reduction in total noise results. In the white areas of the picture, the eye tends to add the three noise components and a reduction in its visibility results.

Thermal agitation and beam noise may also be neglected for the mixed high channel, but second stage noise is appreciable. Its effect is to reduce the attainable signal-to-noise ratio from the optimum value of 330 to about 240.

The optimum signal-to-noise ratios assume realistic amplifying tubes and load resistors. If lower-noise amplifier tubes become available, performance will naturally improve. However, one can parallel more tubes at the input and improve the signal-to-noise ratio in color while not appreciably damaging the signal-to-noise ratio in the mixed highs. The prime obstacle to both perfect signal separation and high signal-to-noise is the inherent inter-strip capacitance. The color channel signal-to-noise ratio varies inversely as this capacitance and the chromatic cross-talk varies approximately as the capacitance.

The Tricolor Vidicon in the Compatible Color Television System

The simultaneous signals from the tricolor Vidicon processed by the mixed-high circuits may be used to form the standard signal in the usual manner. The standard signal could likewise be produced without the mixed-high circuits, but would benefit less from the correlated nature of the noise. While the specific signal-to-noise ratios have been computed for the output signals of the system shown in Fig. 5, the same technique may be used in calculating signal-to-noise ratios for the E_Y, E_I and E_Q signals.

The analysis has shown that minimum noise occurs when the simultaneous signals are combined equally. A tricolor Vidicon made with relative sensitivities in each color channel corresponding to the luminance coefficients would offer reduced noise compared with a tube made with equal sensitivities. The additional noise arising from the inter-strip capacitance could then be confined to the chrominance channels and excluded from the luminance. This feature would contribute to reduced noise visibility on both color and black-and-white receivers.

Harold Borkan

Harold Borkan

The optimum values for signal-to-noise ratios in each color channel and in mixed highs may be calculated from Eqs. (3). While the assumed noise sources in the expressions are voltage generators, in combination with the modifying impedance terms they represent noise currents.

The equivalent noise current in each color channel, calculated from Eq. (1) with R assumed large, is represented as

$$\sqrt{4kTf_o} \quad \sqrt{\frac{R_{eq}\,\omega_o^2\, C_o^2}{3}} \qquad (7)$$

where $f_o = \dfrac{\omega_o}{2\pi}$ is the upper frequency limit of desired color information, taken as 1.3×10^6 *cps; k, T* and R_{eq} are the same quantities previously defined and C_o is the total effective input capacitance. C_o is determined by the coefficients of the noise terms in Eq. (3a) where the noise currents add as the square root of the sum of the squares of the individual noise currents. Thus

$$C_o = \sqrt{(2C_t + C)^2 + (C_t)^2 + (C_t)^2} \qquad (8)$$

or $C_o = \sqrt{6}\; C_t$ for C much smaller than C_t. With $R_{eq} = 45$ ohms and $C_t = 600\ \mu\mu f$ the equivalent noise current for each color channel is 0.00682 microamperes. The signal-to-noise ratio is then 29.4 for a signal current of 0.2 microamperes peak-to-peak in that channel. It has been assumed that beam noise from the pickup tube is negligible.

The optimum signal-to-noise ratio for the high frequencies is evaluated by the sum of Eqs. (3),

$$I_g + I_r + I_b + \frac{1}{Z}(e_{ng} + e_{nr} + e_{nb}) = \frac{1}{Z}\,(V_g + V_r + V_b)\,. \qquad (9)$$

Eq. (1) is for a pass-band 0 to f_o. The corresponding expression for a pass-band f_1 to f_2 is easily derived and may be expressed as follows:

$$I_n = \sqrt{4kT\,(f_2 - f_1)}\,\sqrt{\frac{1}{R} + \frac{R_{eq}}{R^2} + \frac{R_{eq}}{3X_{\bar{c}}^2}} \qquad (10)$$

where $X_{\bar{c}} = \dfrac{1}{2\pi\bar{f}C}$, with $\bar{f} = \sqrt{f_1^2 + f_1 f_2 + f_2^2}$. From Eqs. (9) and (10), with R assumed large, the equivalent noise current in the mixed-high channel is given by

$$2\pi\bar{f}\,C\,\sqrt{4kT\,(f_2 - f_1)\,R_{eq}}\;, \qquad (11)$$

where $f_2 = 4.2$ *mc*,
$f_1 = 1.3$ *mc*,
and $\bar{f} = 4.94$ *mc*.

Since C may be assumed to be $40\ \mu\mu f$, the equivalent noise current is 0.00182 microamperes. The corresponding signal-to-noise ratio is then about 330 for a total signal of 0.6 microamperes peak-to-peak.