THE RMS PHASE ERROR OF A PHASE-LOCKED LOOP FM DEMODULATOR FOR STANDARD NTSC VIDEO

by

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I. Introduction

The RMS phase error of a phase-locked loop (PLL) is a major consideration when designing a PLL FM demodulator. The general rule is to keep the phase error small thus allowing the PLL to maintain a linear phase error transfer relationship. This both simplifies the theoretical analysis of the PLL and prevents distortion due to phase detector nonlinearity and loss of lock.

The loop bandwidth must be selected to keep the phase error small (wide loop bandwidth) and at the same time keeping the noise bandwidth narrow enough to result in an acceptable output signal to noise ratio (narrow loop bandwidth). In the context of this report, the undamped natural frequency f_n of the PLL linear model is considered as the independent parameter and the major factor in determining the demodulator loop bandwidth. Both computer analysis and experimental work are employed to study the optimum range of f_n when designing a PLL FM demodulator. Since, in this report, quantitative signal-to-noise-ratio and threshold measurements are not evaluated, the optimum value of f_n is considered to be the minimum frequency for which the phase error remains relatively small. Below this value, the RMS phase error E_{RMS} increases drastically for decreasing f_n.

As mentioned, both software and hardware measurements were made and compared thus verifying the accuracy of each. The test signal in each case was chosen to be a standard NTSC (National Television Systems Committee) 100% saturated color bar test pattern. The software simulation employs linear, frequency domain filtering techniques and equivalent low pass modeling to process the chrominance (color) information. The luminance (monochrome) information is processed at baseband. Separation of the chrominance and luminance signals allows a more efficient means of processing the data and allows the programmer, if so desired, to study the RMS phase error effects of the chrominance and luminance signals separately. The hardware implements the software simulation by employing a PLL designed and built for use in a satellite FM receiver. The NTSC color bar generator, FM preemphasis filter and the 70 MHz FM modulator were designed and built solely for the purpose of phase error testing.

II. System Overview

The phase-locked loop RMS phase error was determined by experimental testing and computer analysis using the system illustrated in Figure 2.1. Both hardware tests and software simulations were employed to test the PLL phase error for a fixed NTSC test pattern. In both cases, noise, 70 MHz IF prefiltering and audio subcarriers are not considered as part of the system. The addition of audio subcarrier(s) would present additional system parameters such as the audio subcarrier frequency, the message content and, most importantly, the relative amplitude of the subcarrier.

The major objective was to acquire RMS phase error data for the PLL demodulator as a function of the undamped natural frequency f_n of the PLL linear model. The natural frequency was chosen as the independent parameter due to its large effect on the loop phase error. The remaining system parameter values are based either on fixed hardware parameters (PLL open loop gain, FM transmitter conversion gain, etc.) or standards set by the NTSC or the CCIR (International Radio Consultative Committee).

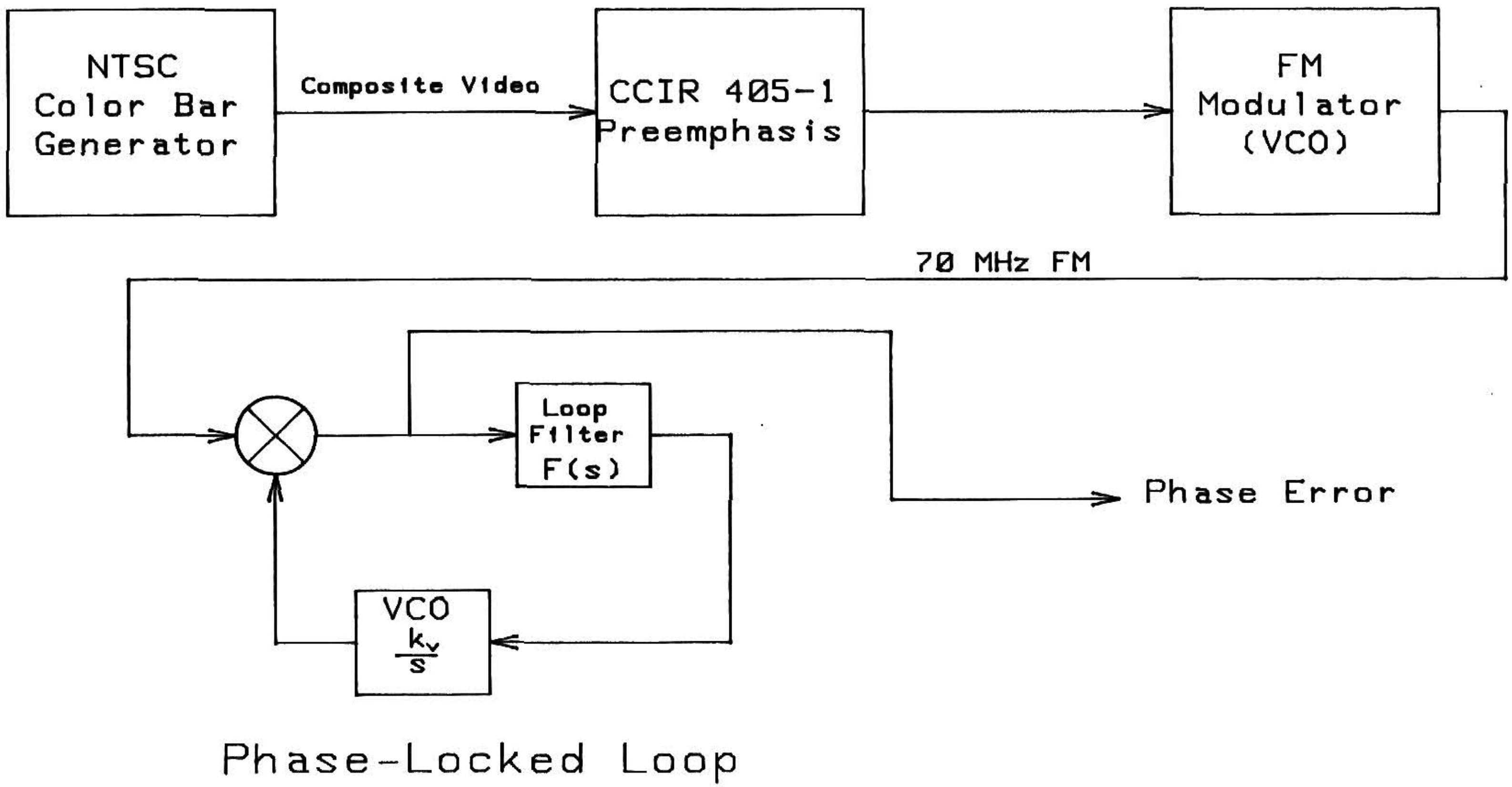

Figure 2.1. Block diagram of the phase error measurement system.

III. Computer Simulation of RMS Phase Error

Referring again to Figure 2.1, the computer model consist of four major components: 1) the NTSC color bar generator, 2) FM preemphasis, 3) the FM modulator (VCO), and 4) the PLL video demodulator. A simulation of the model was written in FORTRAN and run on a VAX 11/750. The simulation employs primarily frequency domain linear filtering techniques as well as equivalent low pass modeling.

NTSC Color Bar Generator

The block diagram of the NTSC standard for encoding color television signals is shown in Figure 3.1. For the case of an NTSC standard 100% saturated color bar pattern, the red, green and blue camera inputs (r(t),g(t) and b(t) respectively) consist of 1 volt peak-to-peak square wave pulses as shown in Figure 3.2. The horizontal syncronization signal p(t) consists of a horizontal sync pulse plus the horizontal blanking pedestal. The color burst signal is formed by modulating the color burst pulse u(t) on the color subcarrier frequency f_c. The NTSC specification for f_c is

$$f_c = 3.579545 \text{ MHz.}$$

The color subcarrier frequency is exactly 227.5 times the horizontal line frequency f_h which is

$$f_h = 15.73426 \text{ kHz.}$$

Referring again to Figure 3.1, the linear transformation matrix $\underline{A}$ is used to form the I and Q chrominance signals (i(t) and q(t) respectively) and the Y luminance signal y(t). The linear transformation is

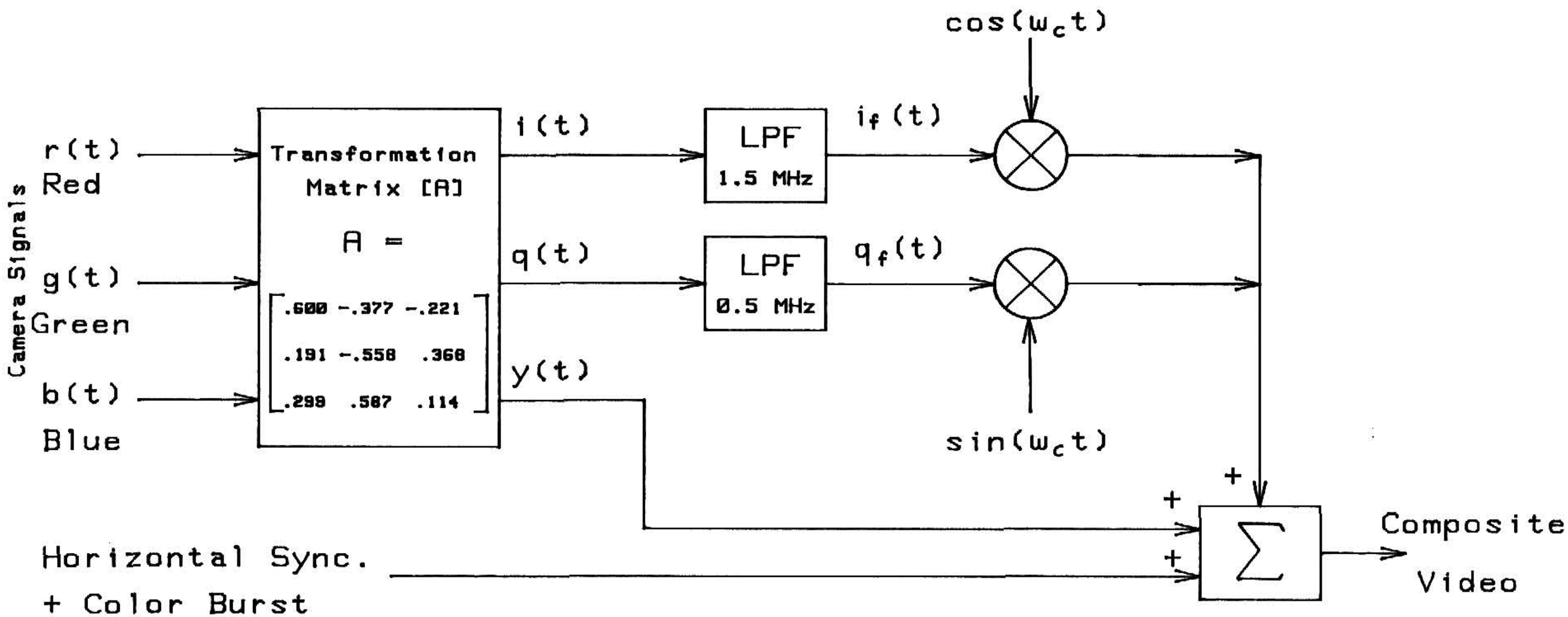

Figure 3.1 NTSC encoder.

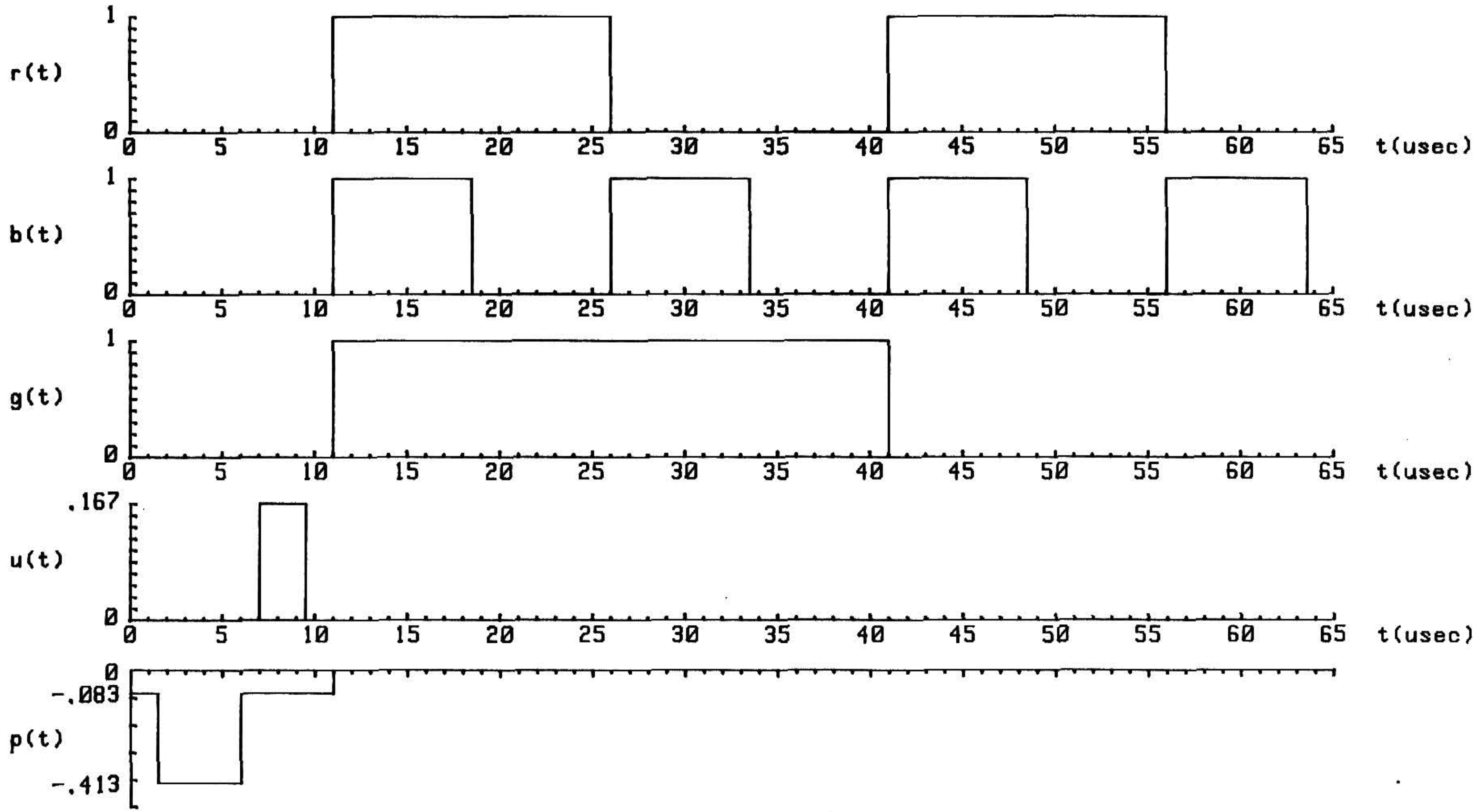

Figure 3.2 NTSC encoder inputs for NTSC standard 100% saturated color bars (single horizontal scan).

expressed as

$$\begin{bmatrix} i(t) \\ q(t) \\ y(t) \end{bmatrix} = \begin{bmatrix} 0.600 & -0.377 & -0.221 \\ 0.191 & -0.558 & 0.368 \\ 0.299 & 0.587 & 0.114 \end{bmatrix} \begin{bmatrix} r(t) \\ g(t) \\ b(t) \end{bmatrix} . \tag{3.1}$$

The chrominance signals i(t) and q(t) are then low pass filtered and modulated in phase quadrature. The color burst signal is then added to form the bandpass chrominance signal c(t).

The luminance signal consists of the sum of the Y signal y(t) and the horizontal synchronization signal p(t), i.e.,

$$\ell(t) = y(t) + p(t). \tag{3.2}$$

Both y(t) and p(t) are low pass filtered prior to forming the luminance signal $\ell(t)$.

To facilitate a more efficient means of processing the chrominance signal c(t), it was decided to express the signal in terms of its low pass equivalent $\tilde{c}(t)$ given as

$$\tilde{c}(t) = \left[2c(t)\, e^{-j\omega_c t}\right]_{LPT} , \tag{3.3}$$

where $\omega_c = 2\pi f_c$

LPT indicates retention of only the low pass term.

From inspection of Figure 3.1, we can write

$$c(t) = \frac{1}{2}\left\{i_f(t)\cos\omega_c t + q_f(t)\sin\omega_c t\right\} , \tag{3.4}$$

where $i_f(t)$ and $q_f(t)$ denote the low pass filtered versions of i(t) and q(t) respectively.

As previously mentioned, the color burst pulse u(t) is also modulated on the color subcarrier for use as a color phase reference. The phase of the color burst signal is 180° with respect to $\sin\omega_c t$. By combining the color burst with the existing chrominance signal, equation 3.4 can be rewritten as

$$c(t) = \frac{1}{2}\left\{i_f(t)\cos\omega_c t + [q_f(t) - u(t)]\sin\omega_c t\right\} . \qquad (3.5)$$

The equivalent low pass version of equation 3.5 is obtained by applying equation 3.3 and simplifying:

$$\tilde{c}(t) = \frac{1}{2}\left\{i_f(t) - j[q_f(t) - u(t)]\right\} . \qquad (3.6)$$

Figure 3.3 illustrates the equivalent low pass model of the NTSC encoder. Both u(t) and $\ell(t)$ are filtered by a 3-pole Butterworth low pass video filter denoted by $H_v(\omega)$. The equivalent low pass chrominance signal $\tilde{c}(t)$ is filtered by the frequency shifted version of the video filter denoted by $H_v(\omega+\omega_c)$. Specifications for the chrominance and luminance filters are summarized in Table 3.1.

Table 3.1 Specifications for the NTSC encoder low pass filters.

Filter	Filter Type	Number of Poles	3 dB Cutoff Frequency
$H_v(\omega)$	Butterworth low pass	3	4.2 MHz
$H_i(\omega)$	Butterworth low pass	3	1.5 MHz
$H_q(\omega)$	Butterworth low pass	3	0.5 MHz

The outputs of the NTSC encoder are the baseband luminance signal $\ell(t)$ defined by equation 3.2 and the equivalent low pass chrominance signal $\tilde{c}(t)$ defined by equation 3.6. The composite video signal v(t) can be calculated from $\ell(t)$ and $\tilde{c}(t)$ by the following equation:

$$v(t) = \ell(t) + |\tilde{c}(t)|\cos[\omega_c t + \angle\tilde{c}(t)], \qquad (3.7)$$

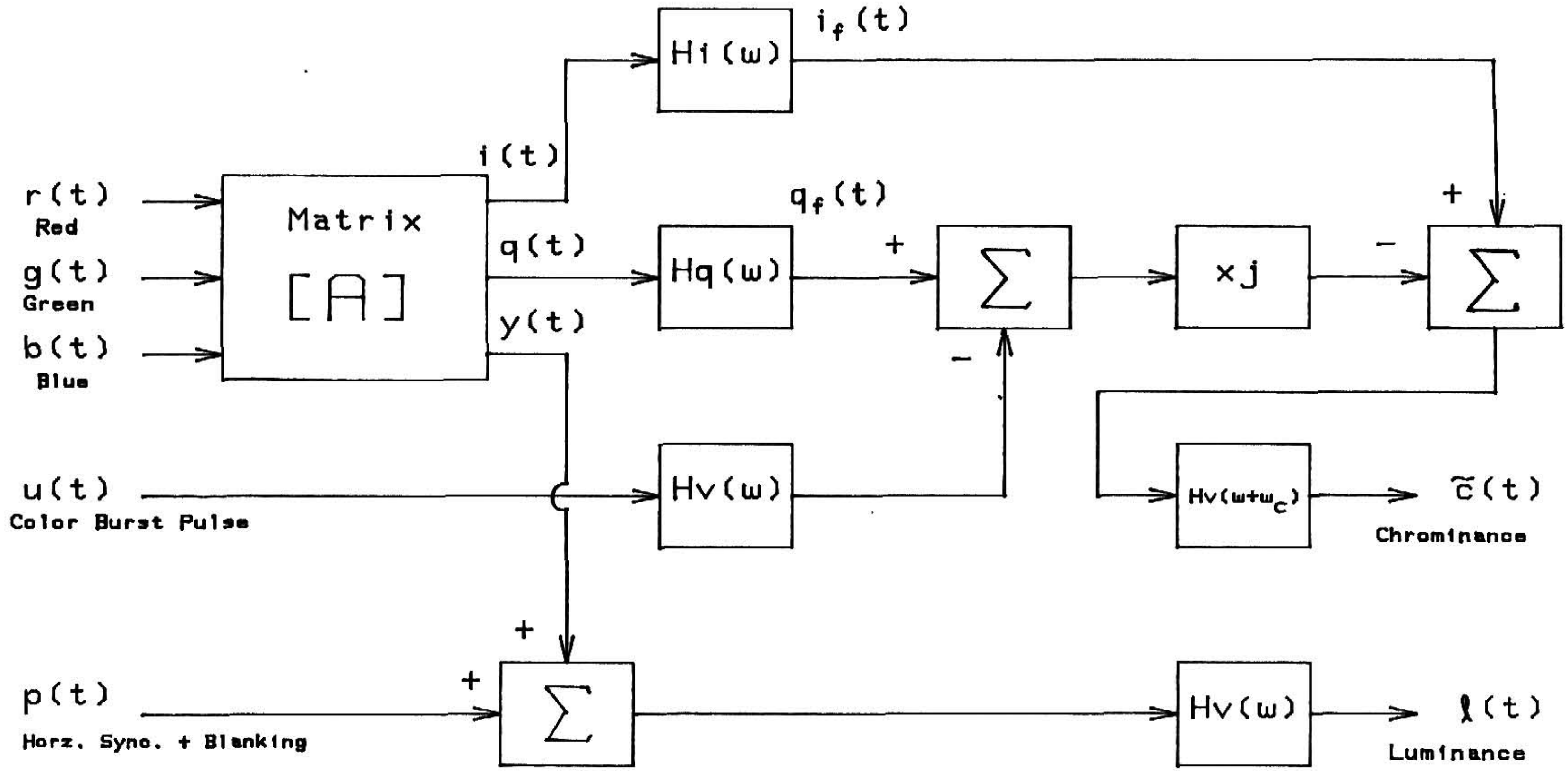

Figure 3.3. Equivalent low pass model of the NTSC encoder.

where $\angle$ denotes phase angle in radians.

Figure 3.4 illustrates the composite signal v(t) for the case where both the luminance and the chrominance filters are inactive. The figure illustrates a single horizontal scan (63.56 μsec) which is periodic with a fundamental frequency of f_h.

FM Preemphasis

To comply with current standards for satellite FM transmission, the chrominance and luminance outputs of the NTSC encoder must be preemphasized to improve the noise performance of the FM system. The preemphasis circuit shown in Appendix 3 is as specified by the International Radio Consultative Committee (CCIR) recommendation 405-1 for a 525 line TVRO (television receive only) system. Appendix 3 also gives the component values for the FM deemphasis network employed in the TVRO demodulator.

By applying nodal analysis to the preemphasis $(H_p(\omega))$ or deemphasis $(H_d(\omega))$ network, a general transfer function H(ω) can be written as

$$H(\omega) = \frac{1}{4} \frac{(2 + \frac{R}{Z2})(\frac{R}{Z1}) + 1}{(1 + \frac{R}{Z1})(1 + \frac{R}{Z2})} \tag{3.8}$$

where R is the 75 Ω termination impedance.

For the preemphasis filter $H_p(\omega)$, we have

$$Z1 = \frac{R1}{1 + j\omega C_p R1} \tag{3.9}$$

and

$$Z2 = R3 + j\omega L_p . \tag{3.10}$$

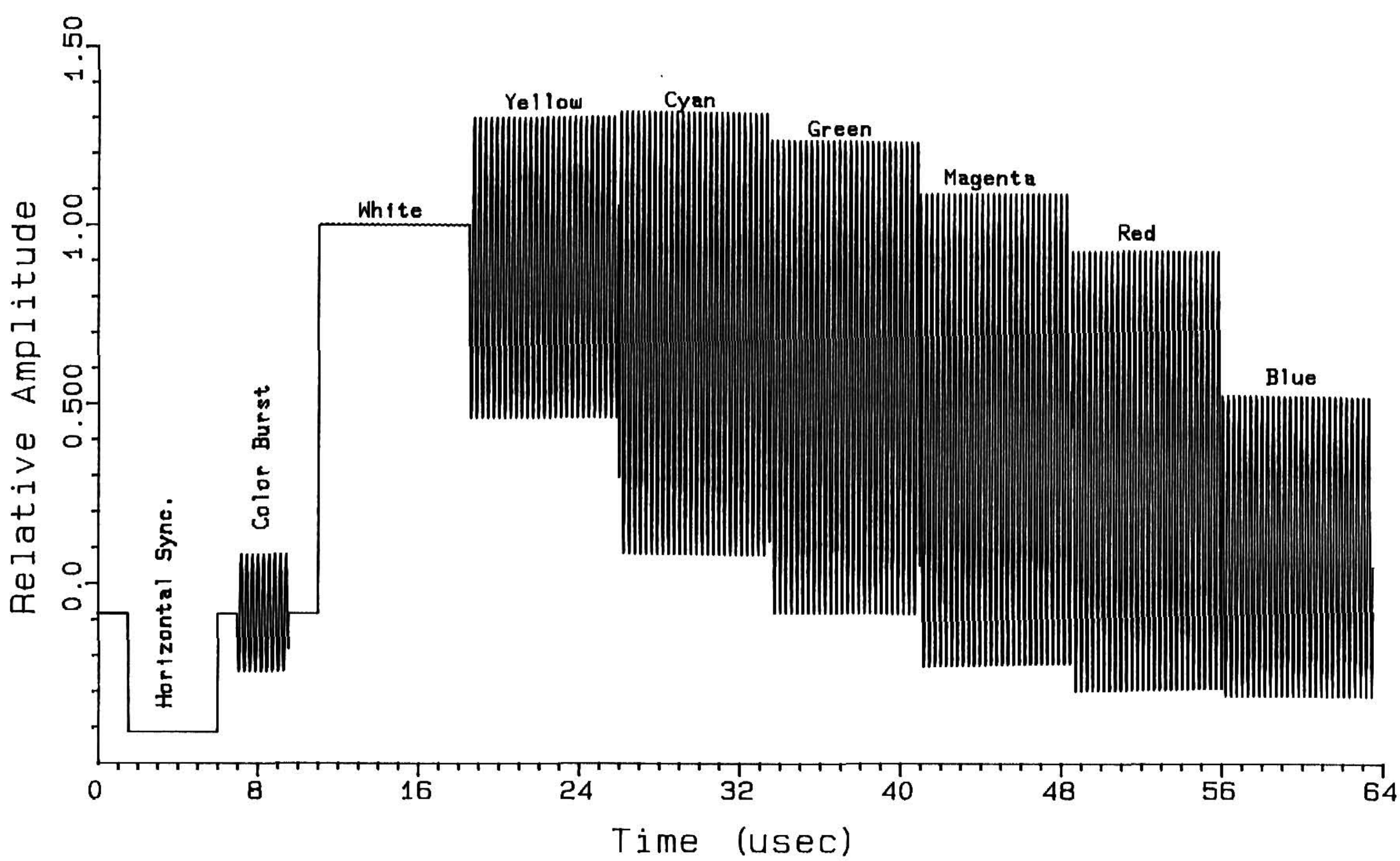

Figure 3.4. Single horizontal scan of the unfiltered composite NTSC color bar pattern.

For the deemphasis filter $H_d(\omega)$, Z1 and Z2 are given by

$$Z1 = \frac{R1}{1 - j\,\frac{R1}{\omega L_d}} \tag{3.11}$$

and

$$Z2 = R3 - \frac{j}{\omega C_d}\,. \tag{3.12}$$

The component values for R1, R3, L_p, C_p, L_d and C_d are given in Appendix 3. Figures 3.5 and 3.6 illustrate the gain and phase characteristics for the specified preemphasis and deemphasis networks. Figure 3.7 shows the placement of the preemphasis filter in the equivalent low pass phase error simulation. The baseband luminance signal $\ell(t)$ is filtered by the preemphasis network $H_p(\omega)$ whereas the equivalent low pass chrominance signal $\tilde{c}(t)$ is filtered by the frequency shifted preemphasis filter $H_p(\omega+\omega_c)$.

Integration

The phase transfer function of a direct FM modulator (VCO) with a linear voltage to frequency transfer function is given as

$$I(\omega) = \frac{k_m}{j\omega}\,, \tag{3.13}$$

where k_m is the VCO conversion gain in radians/second/volt.

Equation 3.13 represents simple integration in the time domain. The preemphasized luminance signal $\ell_p(t)$ is filtered by $I(\omega)$ to yield the luminance phase input $\alpha(t)$ into the PLL error model. The equivalent low pass chrominance phase signal $\tilde{\beta}(t)$ is obtained by filtering the preemphasized chrominance signal $\tilde{c}_p(t)$ by the frequency shifted integration function denoted by $I(\omega+\omega_c)$. The result is the phase input for the PLL error model operating in a linear mode.

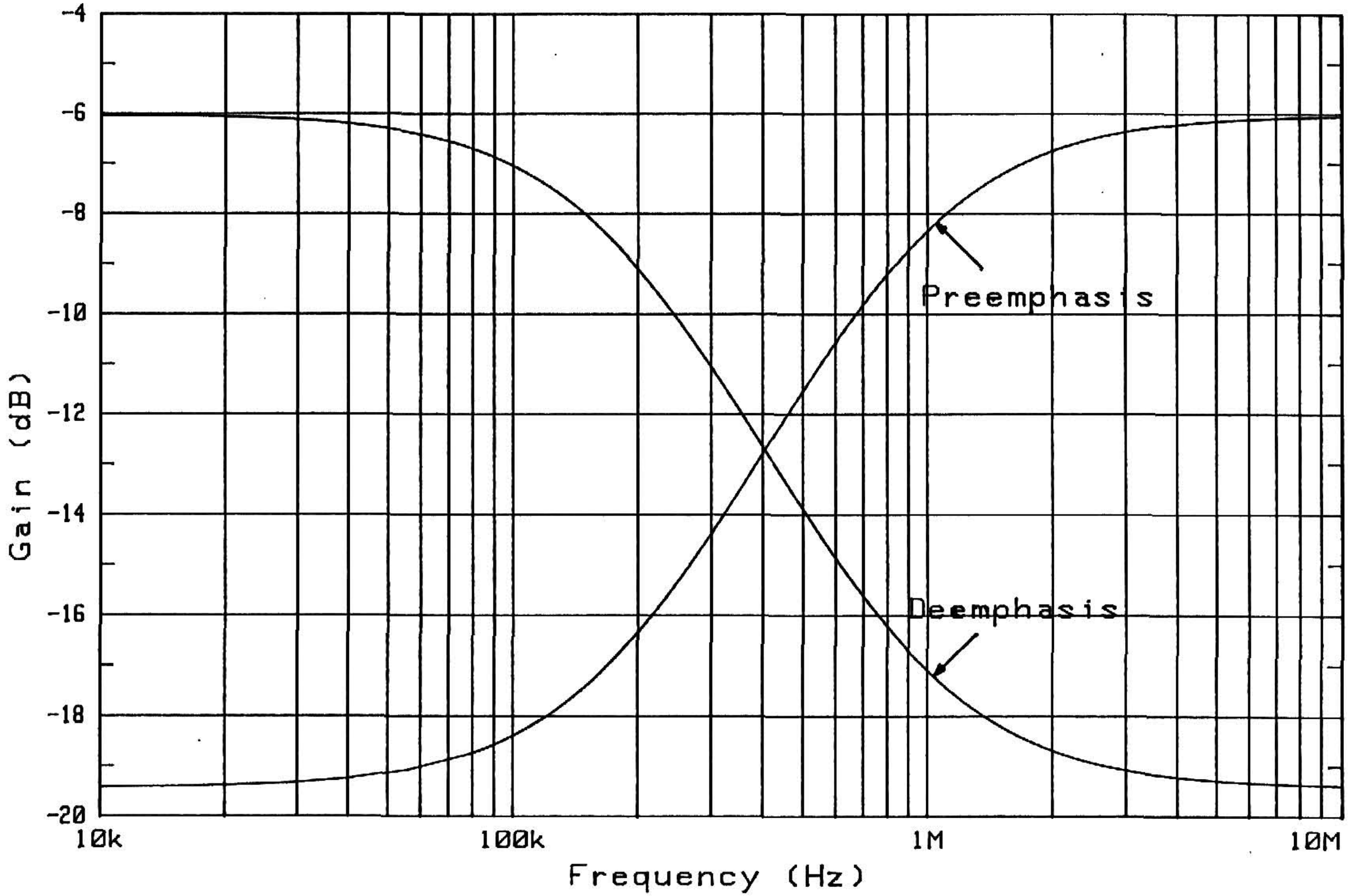

Figure 3.5. Gain characteristics for the CCIR 405-1 FM preemphasis and deemphasis filters for a 525 line TVRO system.

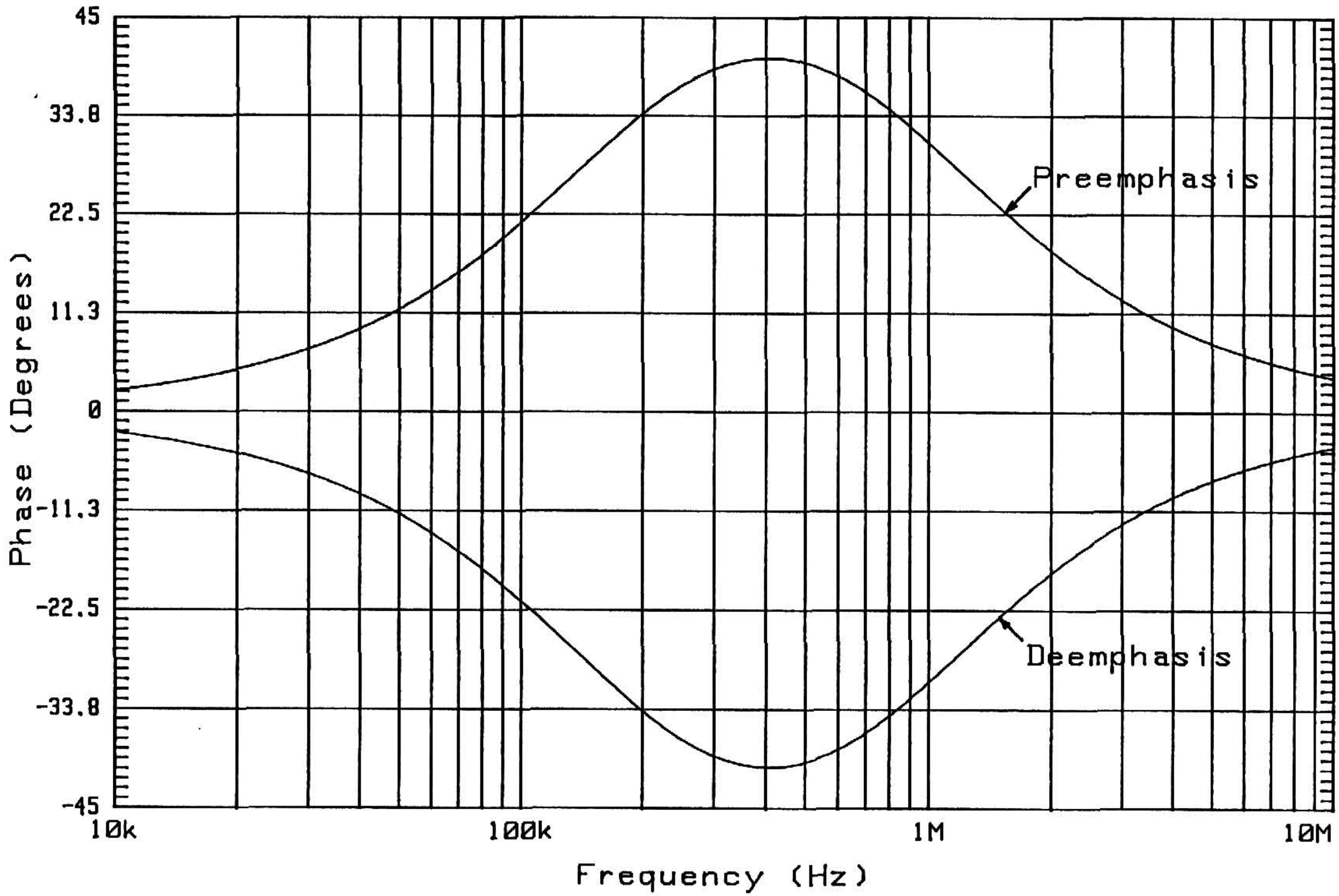

Figure 3.6. Phase characteristics for the CCIR 405-1 FM preemphasis and deemphasis filters for a 525 line TVRO system.

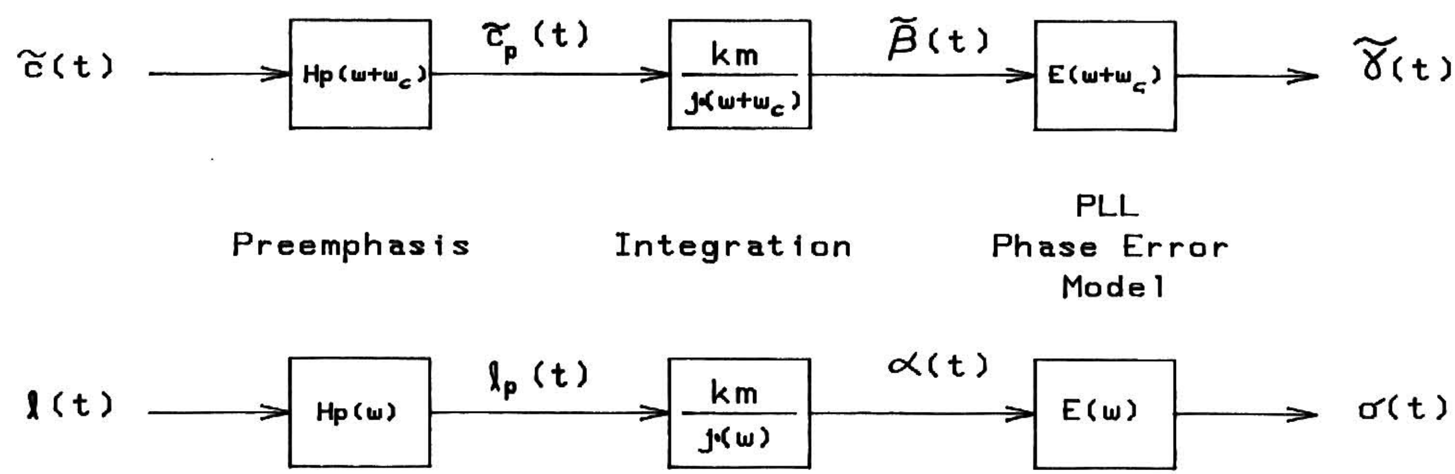

Figure 3.7. Equivalent low pass, linear model of the FM transmitter (preemphasis plus direct FM modulation) and the phase-locked loop error model.

Figure 3.7 illustrates the placement of the integrator in the phase error simulation.

The value of k_m was chosen to maintain the peak FM frequency deviation Δf at 10.7 MHz which is standard for most satellite video transponders. By first computing the peak-to-peak value of the preemphasized composite video signal, k_m can then be found by the following equation

$$k_m = \frac{4\pi\ \Delta f}{V_{p-p}}, \tag{3.14}$$

where V_{p-p} is the peak to peak amplitude of the video input to the FM modulator,

Δf is the peak FM frequency deviation in Hz,

and k_m is the VCO conversion gain in radians/second/volt.

The phase error can then be computed by applying the PLL error transfer function to the chrominance and luminance phase signals.

Phase-Locked Loop Error Function

For the error simulation, a second order PLL employing a lag-lead loop filter was simulated in the linear mode. Figure 3.8 illustrates the linear PLL model. The error transfer function $E(\omega)$ can be written as

$$E(\omega) = \frac{\phi_e(\omega)}{\theta(\omega)} = \frac{1}{1 + \frac{k_d k_v}{j\omega} F(\omega)}, \tag{3.15}$$

where $k_d k_v$ is the open loop gain in seconds^{-1}.

For the lag-lead loop filter, $F(\omega)$ is defined as

$$F(\omega) = \frac{1 + j\ \tau_2\ \omega}{1 + j\ \tau_1\ \omega}, \tag{3.16}$$

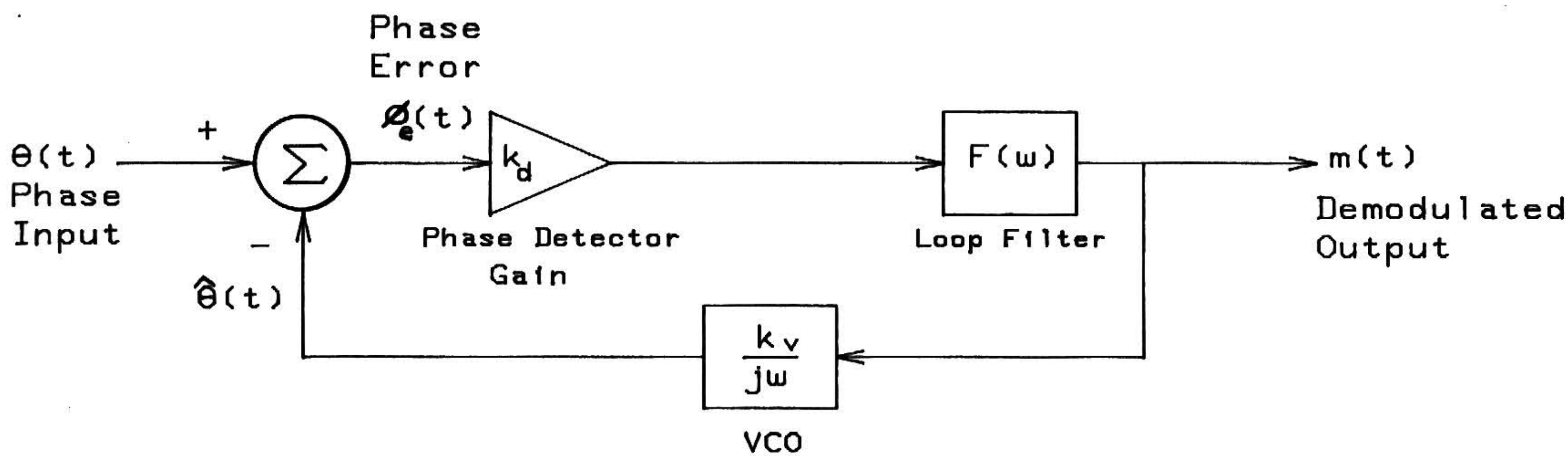

Figure 3.8. Phase-locked loop linear model for small phase error.

where τ_1 and τ_2 are the pole and zero time constants for $F(\omega)$ in seconds.

Substitution of equation 3.16 into equation 3.15 yields

$$E(\omega) = \frac{-\omega^2 + j\,\frac{\omega}{\tau_1}}{\frac{k_d k_v}{\tau_1} - \omega^2 + j\omega\left(\frac{1 + k_d k_v\,\tau_2}{\tau_1}\right)} \,. \qquad (3.17)$$

For the standard notation as applied to a linear second order response, the following substitutions are made:

$$\omega_n^2 = \frac{k_d k_v}{\tau_1} \,, \qquad (3.18)$$

where ω_n is the undamped natural frequency in radians/second,

and

$$\xi = \frac{1 + k_d k_v\,\tau_2}{2\omega_n} \,, \qquad (3.19)$$

where ξ is the loop damping coefficient.

Substitution of equations 3.18 and 3.19 into equation 3.17 yeilds

$$E(\omega) = \frac{-\omega^2 + j\,\frac{\omega}{\tau_1}}{\omega_n^2 - \omega^2 + 2j\,\xi\omega_n\,\omega} \,. \qquad (3.20)$$

For the simulation, f_n $(\omega_n/2\pi)$ was considered as the independent parameter. The open loop gain $k_d k_v$ was fixed at the value measured for the hardware phase error tests outlined in Section IV. The loop filter time constants τ_1 and τ_2 were adjusted for each value of f_n to keep ξ at 0.707 which provides a good trade off between PLL frequency response and stability. Figure 3.7 illustrates the placement of the PLL error function for the luminance and chrominance signals. The output of the error function $E(\omega)$ is the luminance phase error $\sigma(t)$

and the output of the frequency shifted error function $E(\omega+\omega_c)$ is the equivalent low pass error $\tilde{\gamma}(t)$ due to the chrominance signal.

RMS Phase Error Calculation

As previously pointed out, the luminance signal $\ell(t)$ and chrominance signal $\tilde{c}(t)$ are parallel processed by the system illustrated in Figure 3.7 to produce the luminance and chrominance error signals $\sigma(t)$ and $\tilde{\gamma}(t)$ respectively. The signals $\sigma(t)$ and $\tilde{\gamma}(t)$ can be expressed as the following Fourier series approximations which were used in the computer simulation:

$$\sigma(t) = \sum_{n=0}^{N} \frac{k_m\, H_p(n\omega_h)\, E(n\omega_h)\,\ell_n}{jn\omega_h}\, e^{jn\omega_h t}, \qquad (3.21)$$

where ℓ_n are the Fourier series coefficients for $\ell(t)$,

$\omega_h = 2\pi\, f_h$,

N is the physical size of the complex data file for $\ell(t)$ and $\tilde{c}(t)$ (N = 1024 complex data points);

and

$$\tilde{\gamma}(t) = \sum_{n=0}^{N} \frac{k_m\, H_p(n\omega_h+\omega_c)\, E(n\omega_h+\omega_c)\, \tilde{c}_n}{j(n\omega_h+\omega_c)}\, e^{jn\omega_h t}, \qquad (3.22)$$

where $\tilde{c}_n$ are the Fourier series coefficients for $\tilde{c}(t)$.

The composite error signal $\varepsilon(t)$ can now be expressed in terms of $\sigma(t)$ and $\tilde{\gamma}(t)$ by

$$\varepsilon(t) = \sigma(t) + |\tilde{\gamma}(t)|\, \cos[\omega_c t + \angle\, \tilde{\gamma}(t)]\ . \qquad (3.23)$$

For the purposes of calculating the RMS value of equation 3.23, it was first necessary to compute the time domain coefficients for the chrominance and luminance phase error signals ($\tilde{\gamma}_t$ and σ_t respectively) by application of an inverse discrete Fourier transform. The RMS value of $\varepsilon(t)$ is thus found to be

$$E_{RMS} = \sqrt{\frac{1}{N} \sum_{n=1}^{N} \left[\frac{1}{2} |\tilde{\gamma}_t|^2 + |\sigma_t|^2\right]} \qquad (3.24)$$

where $\tilde{\gamma}_t$ and σ_t are the discrete time coefficients for $\tilde{\gamma}(t)$ and $\sigma(t)$ respectively,

and E_{RMS} is the PLL RMS phase error in radians.

Section IV contains the data obtained for the RMS phase error for selected values of the loop natural frequency f_n. The computer generated data is compared with the experimental results for the same values of f_n. A description of the hardware implementation is also given in Section IV and Appendix 3.

Signal Analysis Routines

To verify the proper operation of the software simulation and to obtain a better understanding for the system behavior, several algorithms were written to allow the creation of data files representative of various time and frequency domain signals. These signals of interest include: the composite video signal, the log magnitude spectrum of the video signal, the PLL input phase signal, the log magnitude FM spectrum and the composite demodulated video signal. Example plots of these signals along with their respective experimental measurements are given in Section V.

The time domain composite video signal v(t) is found by equation 3.7. The preemphasized video signal $v_p(t)$ is found by application of equation 3.7 on the preemphasized chrominance and luminance signals $\tilde{c}_p(t)$ and $\ell_p(t)$ respectively. In both cases, the resulting data file for v(t) or $v_p(t)$ contains 2048 real data points which can be plotted using an external graphics routine (see software listing in Appendix 1).

The single sided, log magnitude frequency spectrum for v(t) or $v_p(t)$ is found by plotting the log magnitude of the positive frequency Fourier coefficients for the luminance signal (ℓ_n) along with the log magnitude of the equivalent low pass chrominance coefficients ($\tilde{c}_n$) centered on the chrominance subcarrier f_c. To better represent the discrete nature of the video frequency spectra, the number of data points needed was doubled for which every other data point was set to a specified noise floor. The result is a very accurate representation of the video spectrum (see Section V, Figure 5.5). To represent the time domain phase input θ(t) (radians) into the PLL, the algorithm shown in Figure 3.9 was employed. The inputs are the frequency domain signals representing the chrominance phase $\tilde{\beta}(\omega)$ and the luminance phase $\alpha(\omega)$. A 5-pole Butterworth lowpass filter is applied to the 4096 point θ(t) file to eliminate unwanted harmonics above the Nyquist frequency of approximately 8 MHz. Figure 3.9 also illustrates the algorithm for obtaining the FM spectra $|\tilde{s}(\omega)|$ from θ(t). The $|\tilde{s}(\omega)|$ data file also contains 4096 real data points.

The demodulated video signal m(t) can be obtained by refering to the PLL linear model of Figure 3.8. The error signal $\phi_e(t)$ is filtered by the loop filter F(ω) to obtain m(t). The phase detector gain factor k_d is disregarded since we are only concerned with the relative content of m(t) as it compares with the original signal v(t). Deemphasis $(H_d(\omega))$ is also included to restore the original video

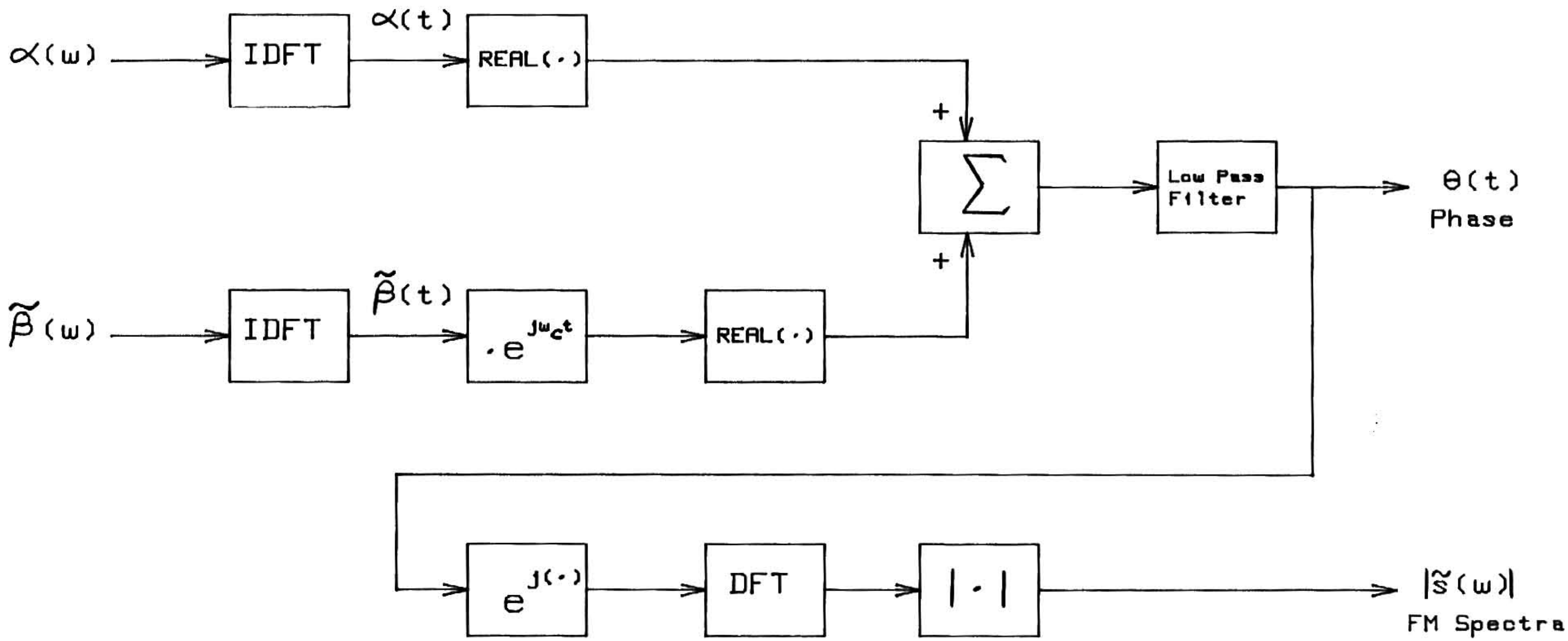

Figure 3.9. Method of obtaining the time domain PLL phase input $\theta(t)$ and the magnitude of the FM spectra $|\tilde{s}(\omega)|$.

signal. The resulting outputs as shown in Figure 3.10 are the demodulated chrominance $\left(\hat{c}(t)\right)$ and luminance $\left(\hat{\ell}(t)\right)$ signals to which equation 3.7 can be applied to obtain the composite signal m(t).

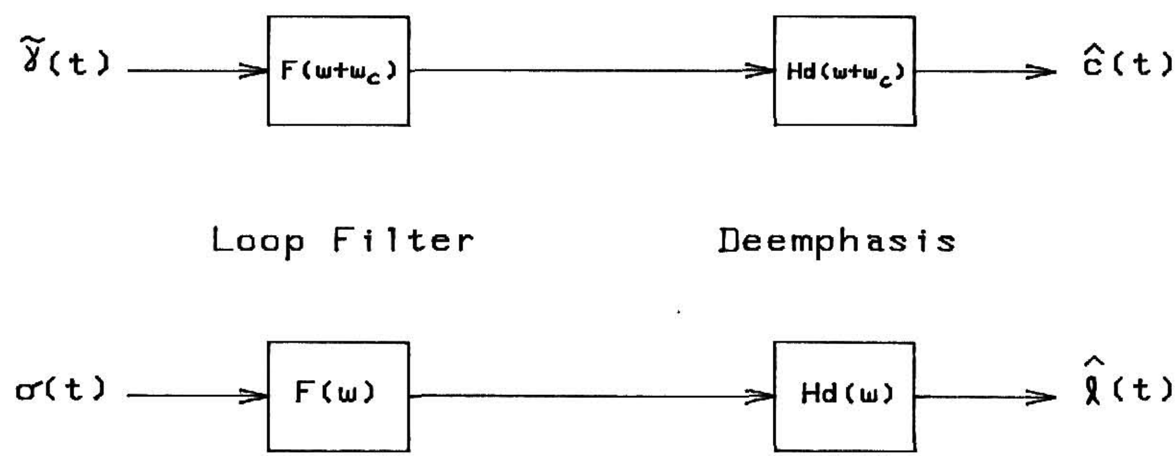

Figure 3.10. Equivalent low pass model for obtaining the PLL demodulated signal.

IV. Experimental Measurement of Phase Error

The major components used in the hardware phase error measurement system are shown in Figure 2.1. Schematics and parts lists for the NTSC color bar generator, the CCIR 405-1 preemphasis filter, the FM modulator and the PLL demodulator are given in Appendix 3.

Before making the phase error measurements, the chrominance levels of the NTSC color bar generator were adjusted for 100% saturated color bars. The peak-to-peak output of the generator was also adjusted to maintain the peak FM frequency deviation Δf of the FM modulator at 10.7 MHz. The measured conversion gain for the modulator was found to be

$$k_m = 79.3 \text{ MHz/volt.}$$

Using equation 3.14 with k_m in units of radians/second/volt, we obtain the peak-to-peak video level V_{p-p} for the FM modulator input which is found to be

$$V_{p-p} = 270 \text{ mV.}$$

To make the signal levels from the FM modulator output to the PLL input compatable, it was necessary to place a 20 dB attenuator between the two system components. The signal level into the PLL was maintained at 30 mV_{RMS} to insure that the PLL phase detector gain k_d was kept at a maximum.

The phase detector gain k_d of the PLL was measured by free running the PLL VCO while applying a 70 MHz CW signal at the phase detector input. Refering to the PLL schematic in Appendix 3, jumper 1 was placed in the 1 to 2 position and R100 (Free Run Adj.) was adjusted to maintain a 2 MHz sinewave at pin 11 of the phase detector

(IC101). The peak value of this sinewave indicates the phase detector gain k_d which was measured as

$$k_d = 0.125 \text{ volts/rad.}$$

The gain k_v for the VCO of the PLL was measured to include the conversion gain of the VCO chip (IC100) and the gain of the loop amplifier which consists of transistors Q100 and Q101. The measured value of k_v was

$$k_v = 294 \text{ MHz/volt}$$

or

$$k_v = 1.848 \times 10^9 \text{ radians/second/volt.}$$

The open loop gain of the PLL is simply

$$k_d k_v = 321 \times 10^6 \text{ seconds}^{-1}.$$

The above value for $k_d k_v$ is fixed for both the hardware tests and software simulations.

To measure the phase error of the PLL, the loop was first closed by placing jumper 2 in the 2 to 3 position. Jumper 2 was placed in the 2 to 3 position to allow the phase error signal to be measured at the composite video output (J102) of the demodulator board. The video filter between Q103 and Q104 is required to eliminate the presence of 70 MHz carrier which would otherwise result in erroneous data. The 3 dB cutoff of the filter is approximately 8 MHz which allows a flat response over the video bandwdith of 0 to 4.2 MHz.

The gain G_p for the signal path from the phase detector output (pin 11 of IC101) to the composite video output (J102) was measured as

$$G_p = 0.893 \frac{\text{volts}}{\text{volt}} .$$

After measuring the true RMS value (V_{RMS}) of the composite video output, the RMS phase error is then found by

$$E_{RMS} = \frac{V_{RMS}}{G_p \; k_d} , \tag{4.1}$$

where k_d is in units of volts/radian.

The true RMS value of the video signal was measured using a Fluke model 910A 10 MHz true RMS meter. The resulting RMS phase error is found from equation 4.1.

The four major components used in the hardware phase error tests are shown in Figure 4.1. Figure 4.2 illustrates the complete lab measurement setup including the true RMS meter and a oscilloscope plus spectrum analyzer for monitoring the signals at various points in the system.

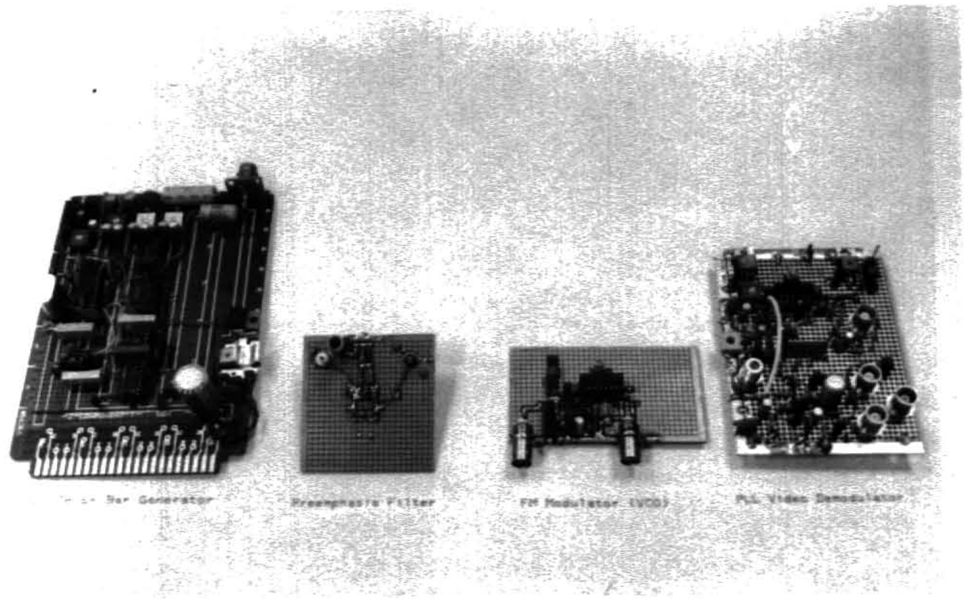

Figure 4.1 The four major components employed in the experimental phase error measurements.

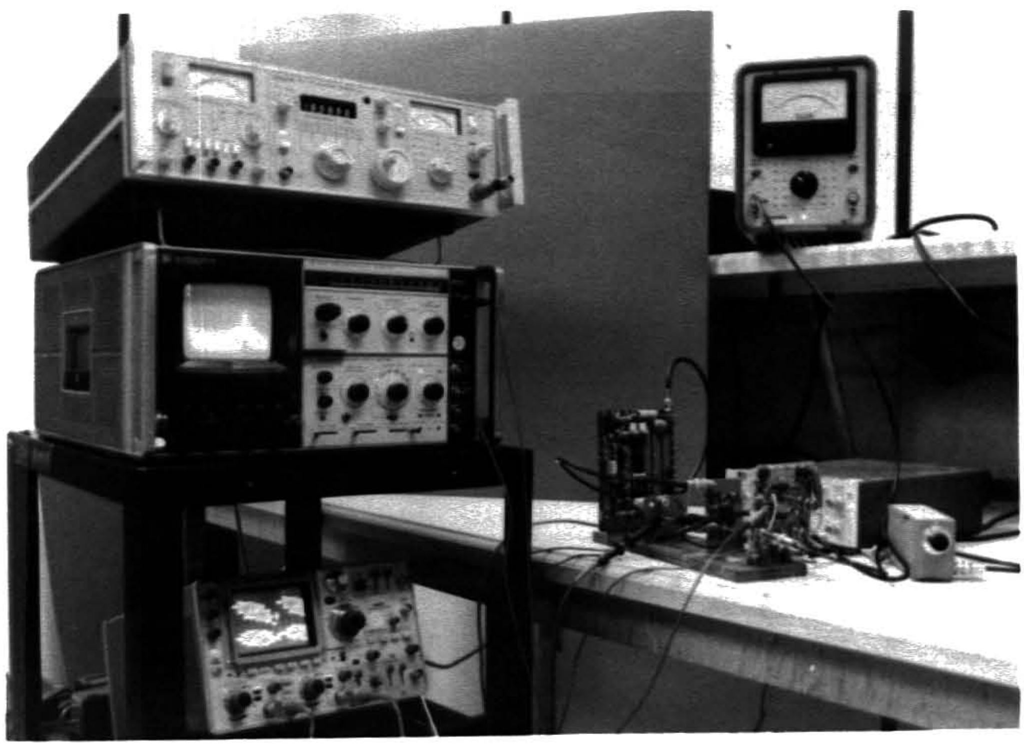

Figure 4.2 Lab setup for the experimental phase error measurements.

V. Comparison of Measured and Simulated System Performance

To verify that a good correlation exists between software generated and hardware implemented signals, the following series of illustrations (Figure 5.1 to 5.7) are included. For each case, f_n is maintained at 15 MHz. The remaining system parameters are summarized in Table 6.1.

In addition, Figure 5.8 illustrates the PLL phase input signal $\theta(t)$ for the parameter values indicated. Figure 5.9 is a sample of the demodulated NTSC test signal $m(t)$. The demodulated signal, for most values of f_n, was found to be almost exactly correlated with the original video signal $v(t)$.

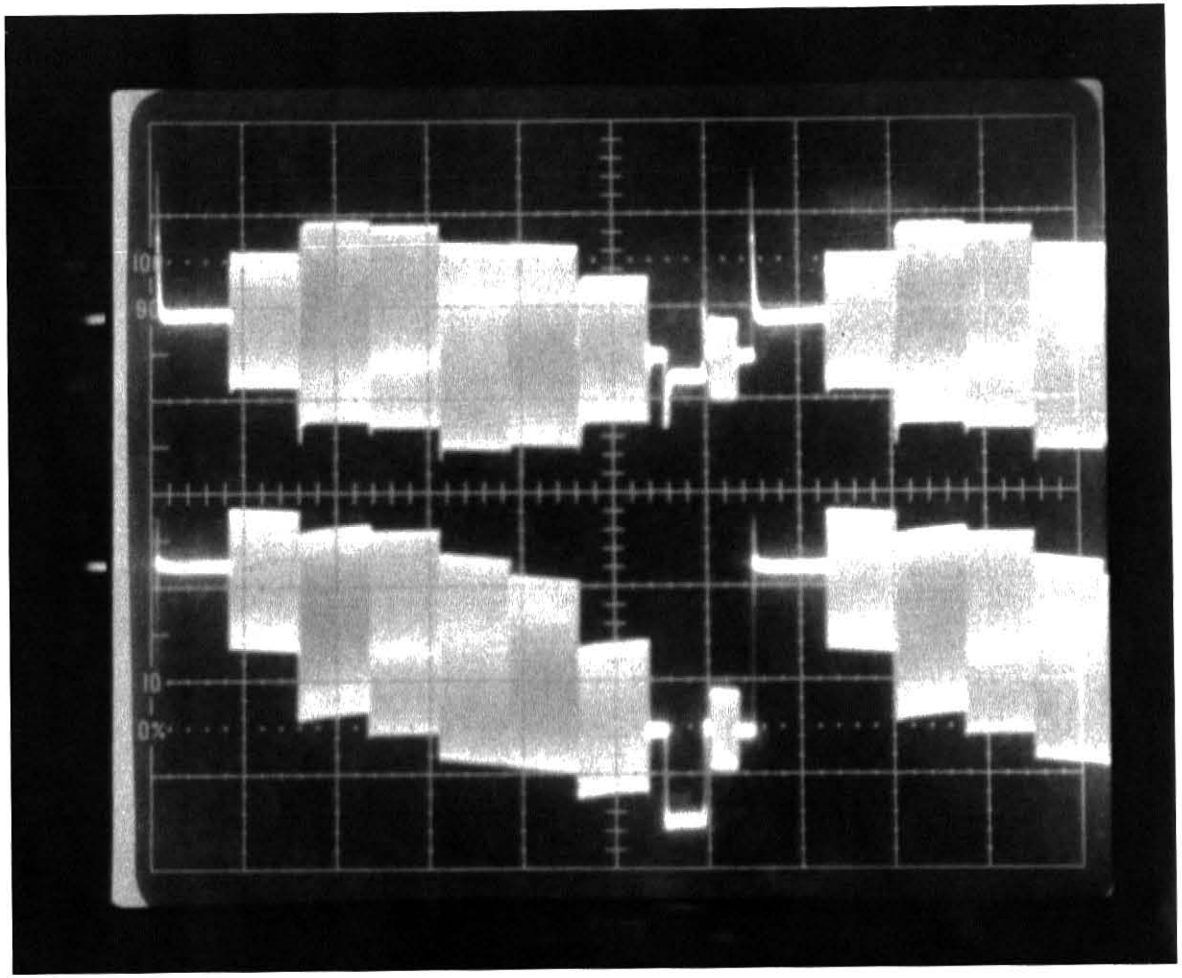

Figure 5.1 Measured time domain video signal with preemphasis (Top) and without preemphasis (Bottom).

Horizontal: 10 μsec./div.
Vertical: 0.1 V/div.

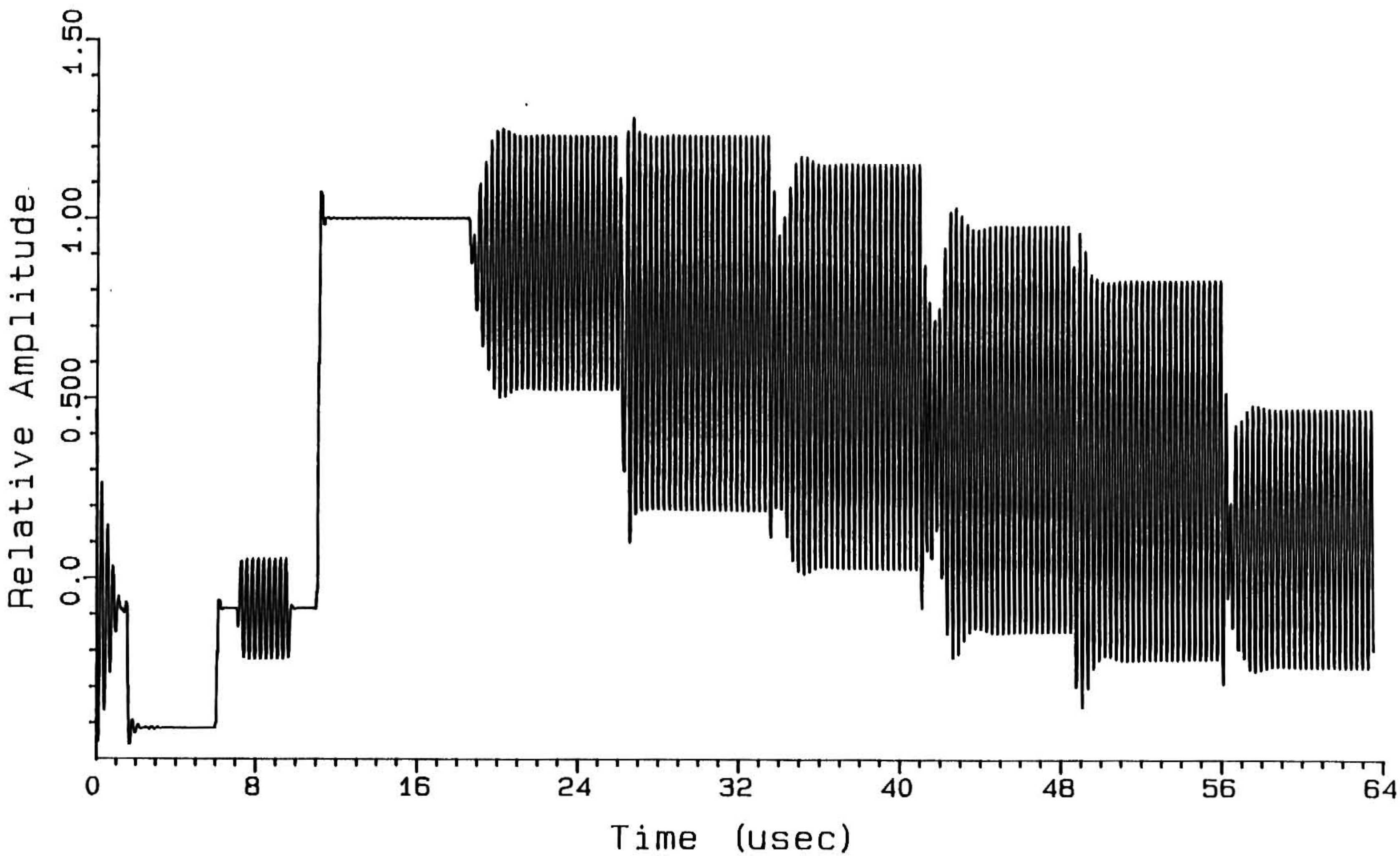

Figure 5.2. Simulated NTSC color bar test signal with chrominance and luminance low pass filters applied.

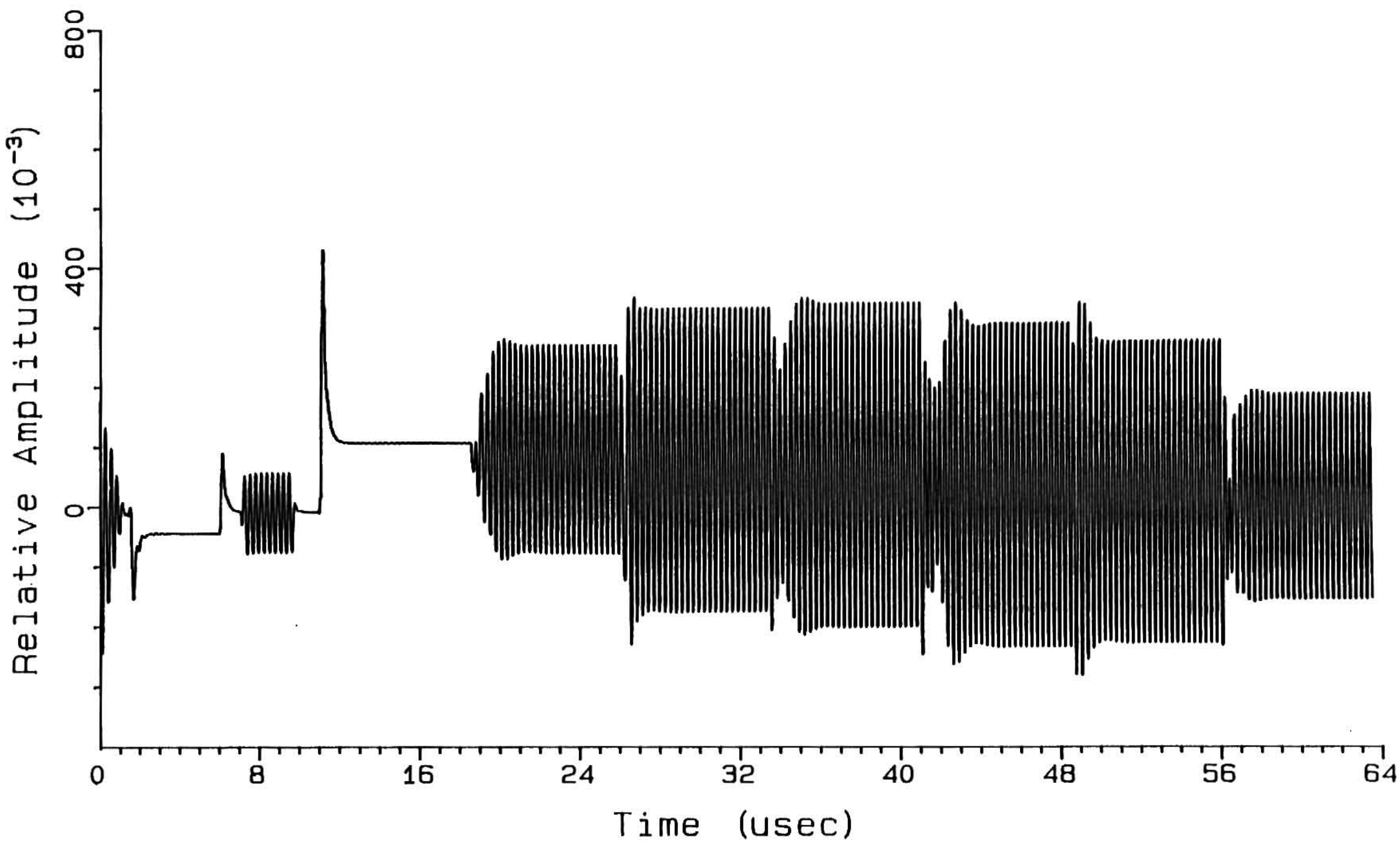

Figure 5.3. Simulated NTSC test signal with FM preemphasis.

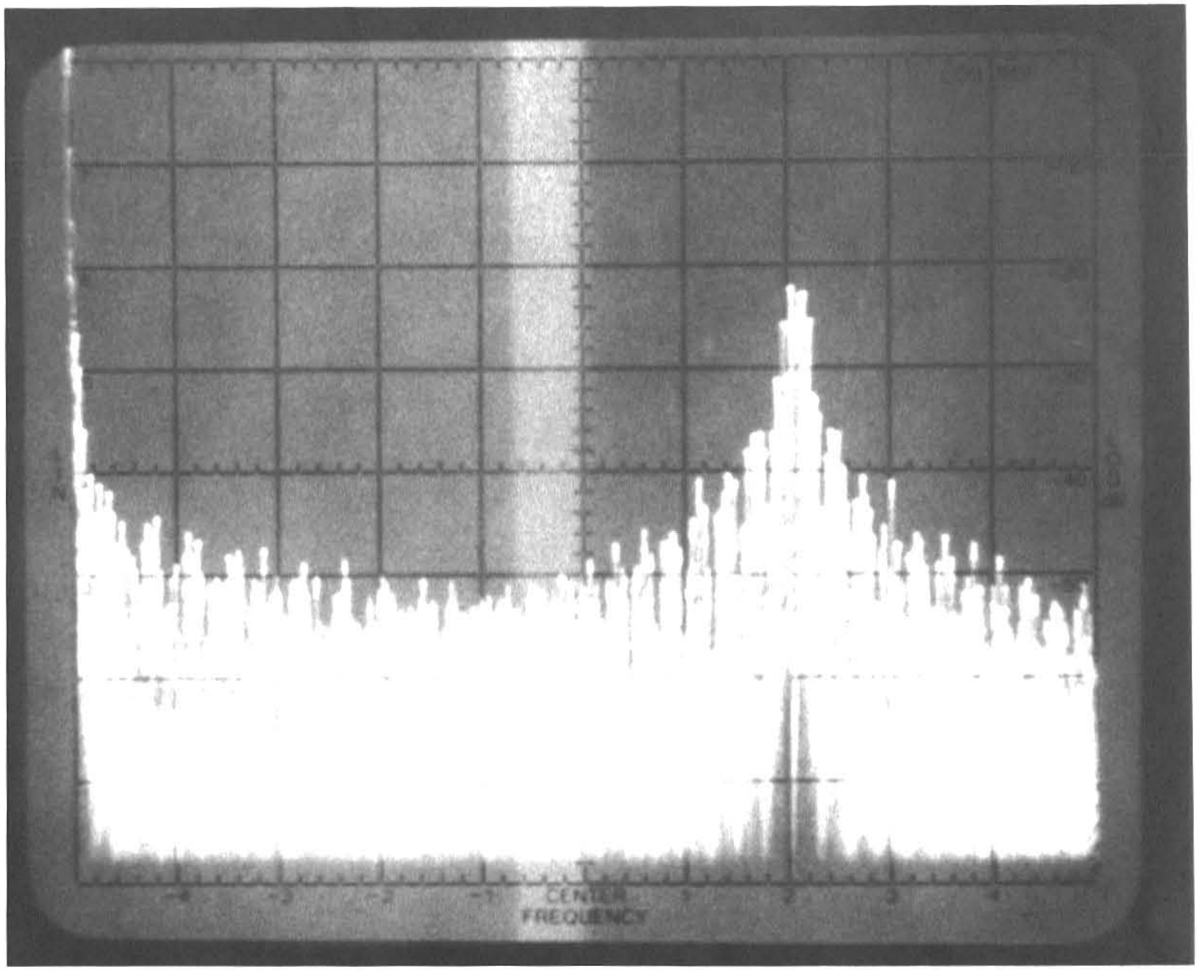

Figure 5.4 Measured video spectrum for the preemphasized NTSC color bar pattern.

Horizontal: 0.5 MHz/div., 2.5 MHz center
Vertical: 10 dB/div.

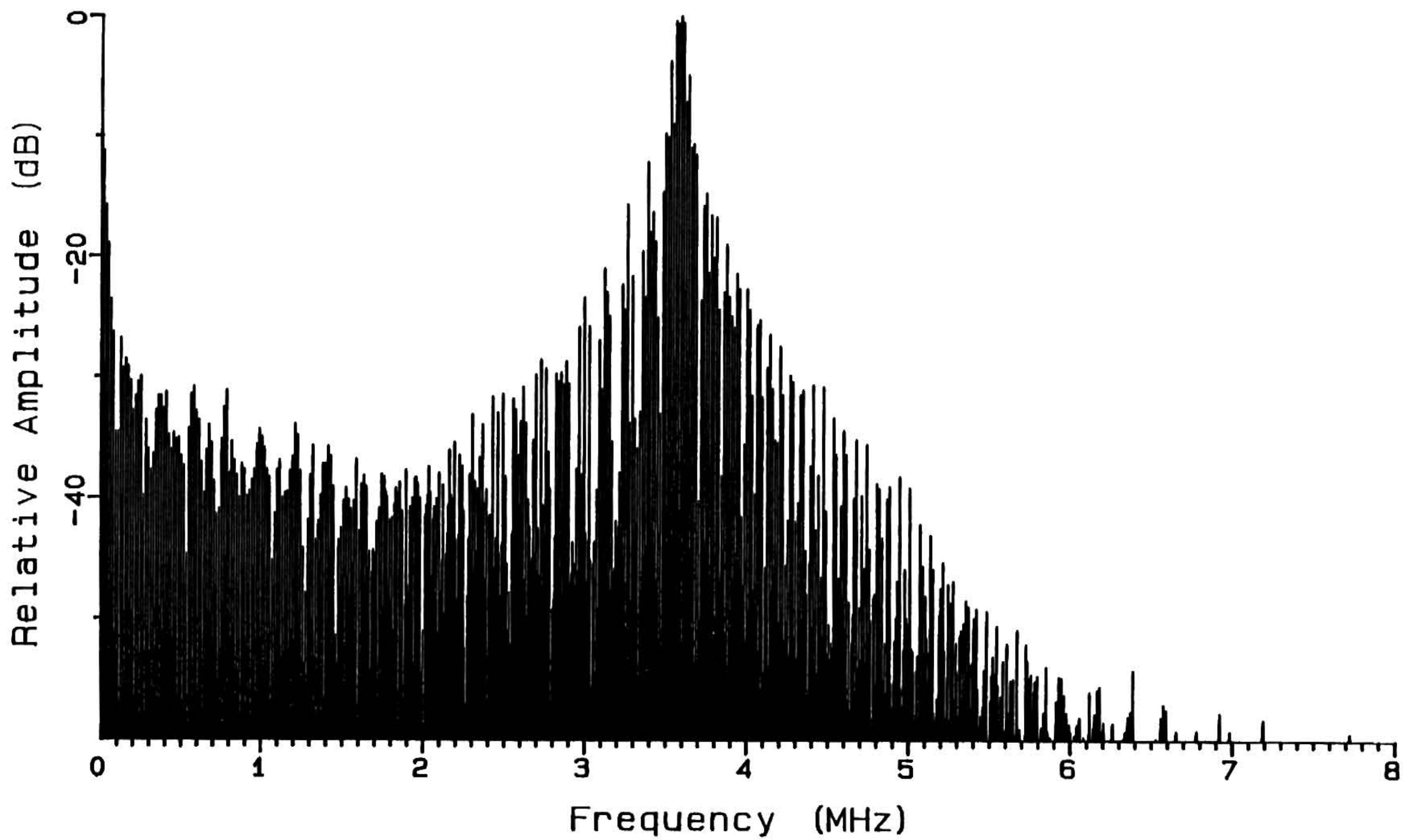

Figure 5.5. Simulated spectrum of the preemphasized NTSC test signal.

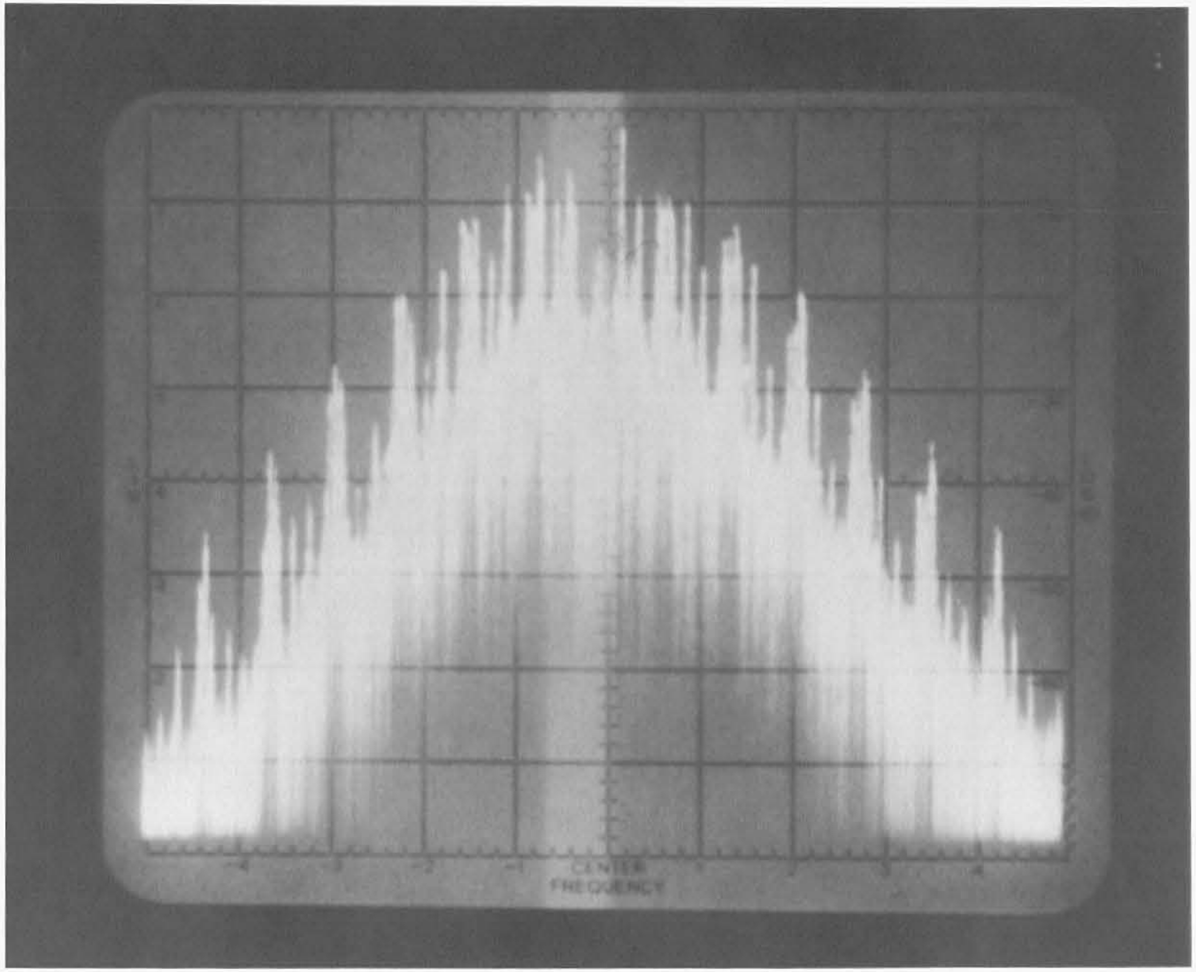

Figure 5.6 Measured FM spectrum for the NTSC test signal with Δf = 10.7 MHz.

Horizontal: 5 MHz/div., 70 MHz center
Vertical: 10 dB/div.

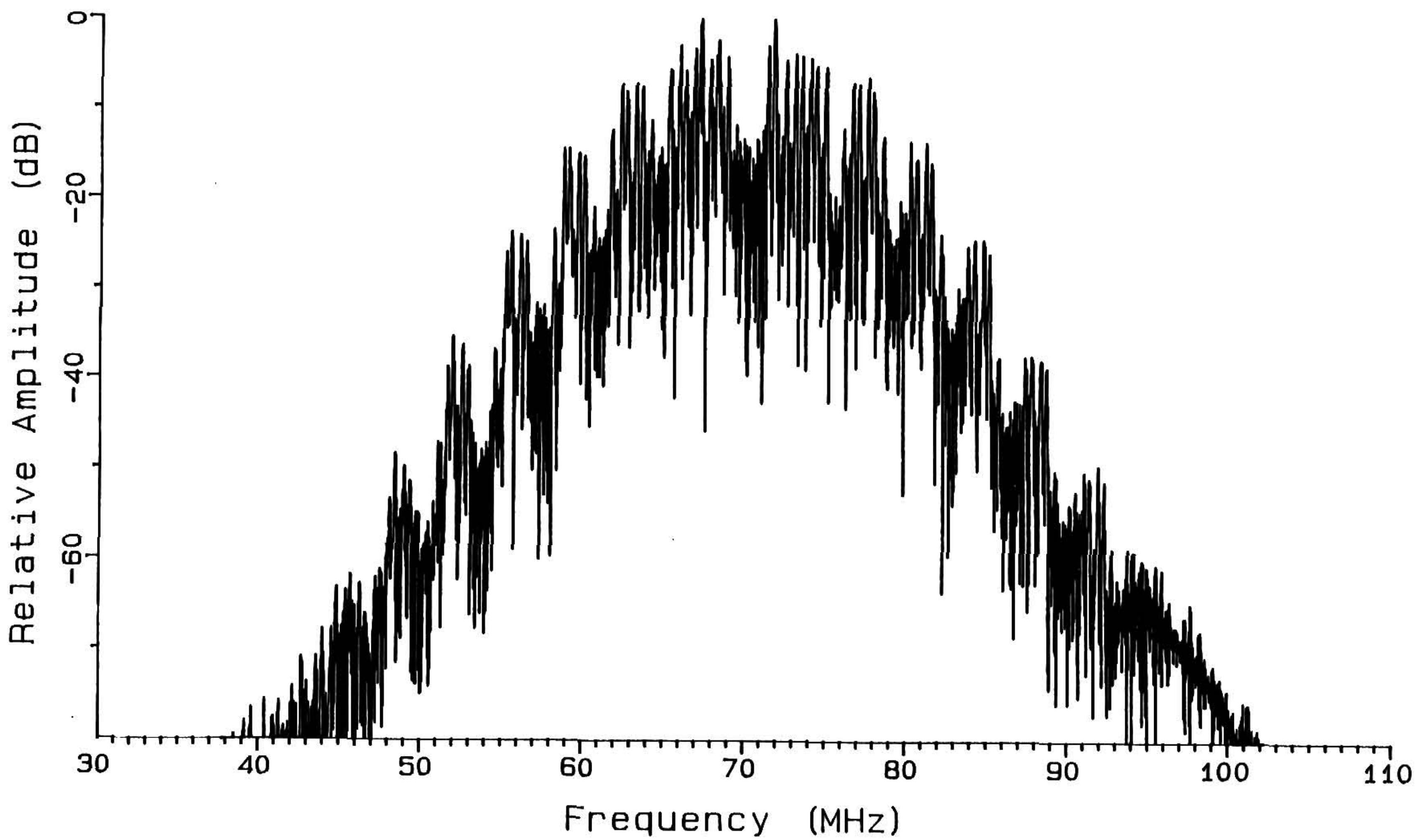

Figure 3.7. Simulated FM spectra for the NTSC test signal with Δf = 10.7 MHz.

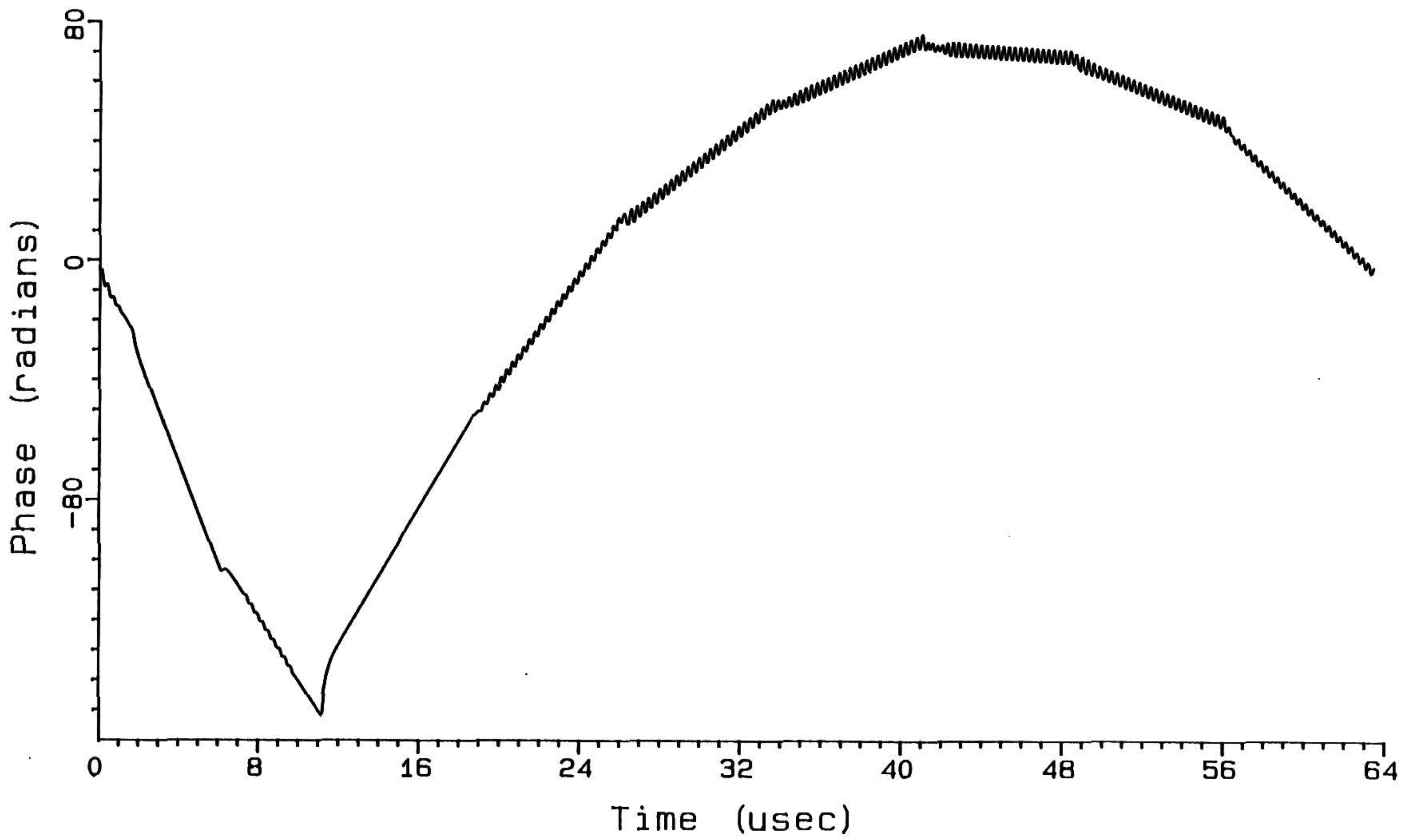

Figure 5.3. Simulated time domain PLL phase input.

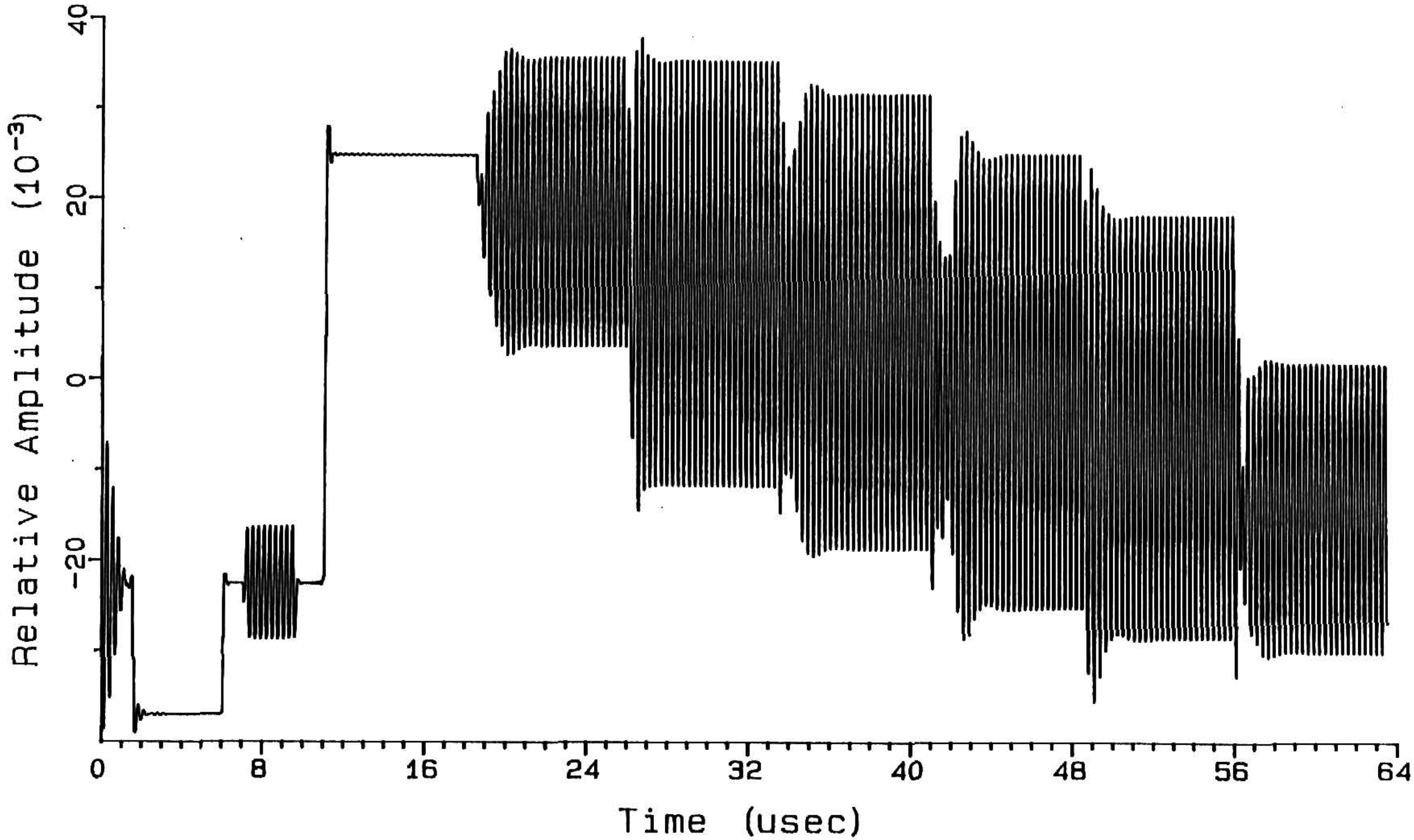

Figure 5.9. Example of a demodulated test signal with deemphasis applied.

VI. Phase Error Results

Table 6.1 summarizes the values of the fixed system parameters based on the hardware described in Section IV or the standards set forth by NTSC and CCIR. The nine values of f_n chosen for phase error testing range from 5 MHz to 25 MHz and are spaced on an interval of 2.5 MHz. To make the hardware PLL parameters compatable with the software parameters, it was necessary to compare the theoretical and measured closed loop demodulator frequency response curves for each value of f_n. Refering to Figure 3.8, the loop frequency response $D(\omega)$ is defined as

$$D(\omega) = \frac{\hat{\theta}(\omega)}{\theta(\omega)} . \tag{6.1}$$

Figure 6.1 illustrates the theoretical frequency response curves for the values of the natural frequency previously mentioned. By adjusting the hardware PLL parameters (namely τ_1 and τ_2), the frequency response of the PLL can be made to match the theoretical response curve for each value of the loop natural frequency. Referring to the PLL demodulator schematic of Appendix 3, the values of τ_1 and τ_2 can be varied by adjusting the loop filter components R103 and C108. It should be noted that for small values of f_n (namely 5 MHz and 7.5 MHz), it was necessary to place additional capacitance in parallel with C108 and additional resistance in series with R103 to obtain the desired loop response. By first matching the theoretical and measured loop responses as closely as possible, a pair of phase error data points could then be taken for a given natural frequency.

Figure 6.2 illustrates the results of the aforementioned phase error tests. It is interesting to note that previous calculations and assumptions made prior to this report assumed a range of 20 MHz to 25

Table 6.1 Summary of the fixed system parameters for the experimental and simulated phase error measurements.

Parameter Name	Description	Value	Units
(PERSAT)	Percentage color saturation for the NTSC color bar pattern	100	%
(YPOL)	The number of poles for the Butterworth video filter $H_v(\omega)$	3	--
(QPOL)	The number of poles for the Q chrominance filter $H_q(\omega)$	3	--
(IPOL)	The number of poles for the I chrominance filter $H_i(\omega)$	3	--
(YCUT)	The 3 dB cutoff frequency of $H_v(\omega)$	4.2	MHz
(QCUT)	The 3 dB cutoff frequency of $H_q(\omega)$	0.5	MHz
(ICUT)	The 3 dB cutoff frequency of $H_i(\omega)$	1.5	MHz
Δf (FMPKDEV)	The peak FM frequency deviation of the FM modulator	10.7	MHz
ξ (DAMP)	The loop damping coefficient for the PLL linear model	0.707	--
$k_d k_v$ (KDKV)	The open loop gain of the PLL	231×10^6	sec^{-1}

Note: The parameter names used in the software simulation are given in ( ).

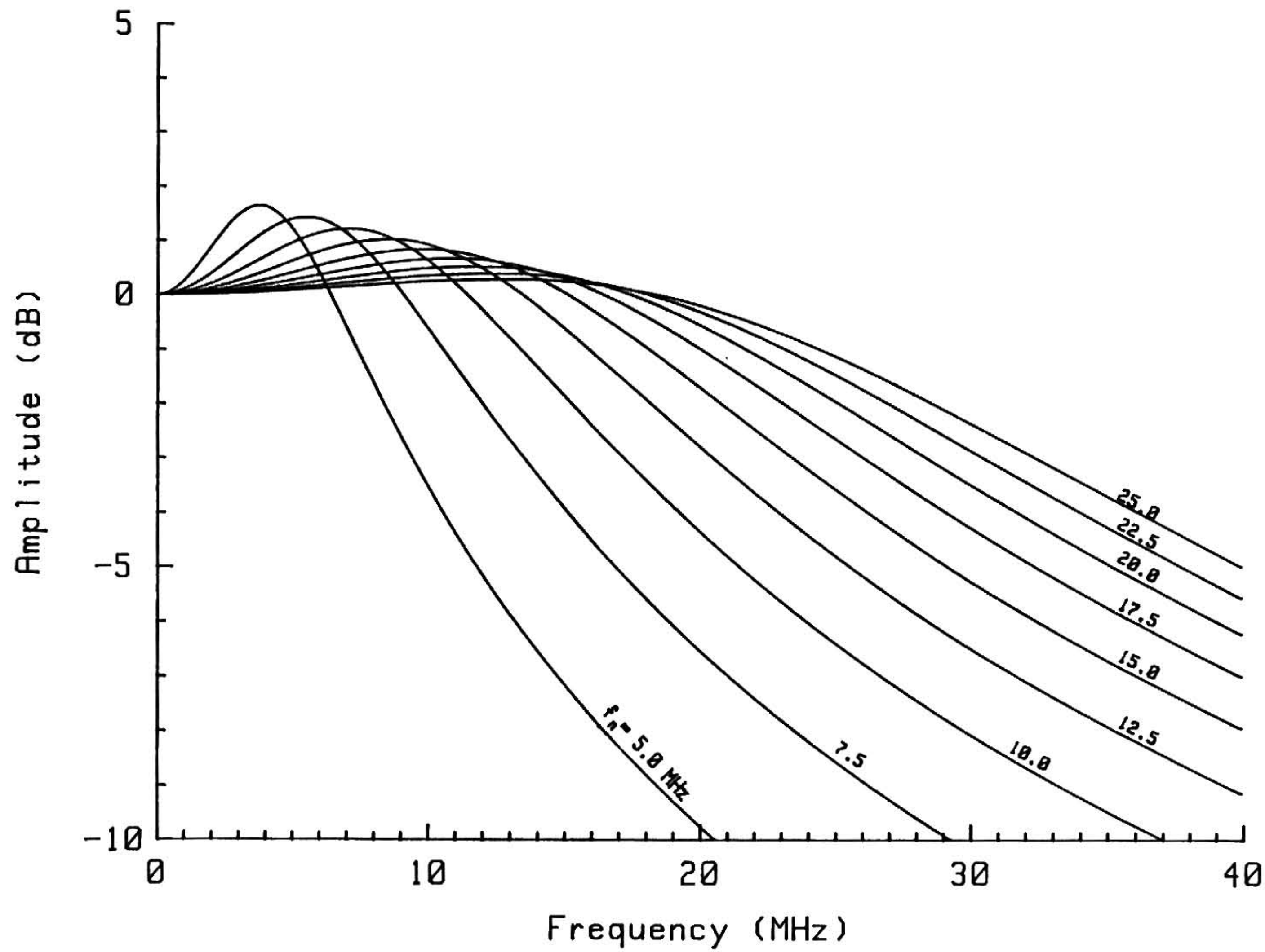

Figure 6.1. Theoretical PLL demodulator frequency response curves for the nine tested values of f_n.

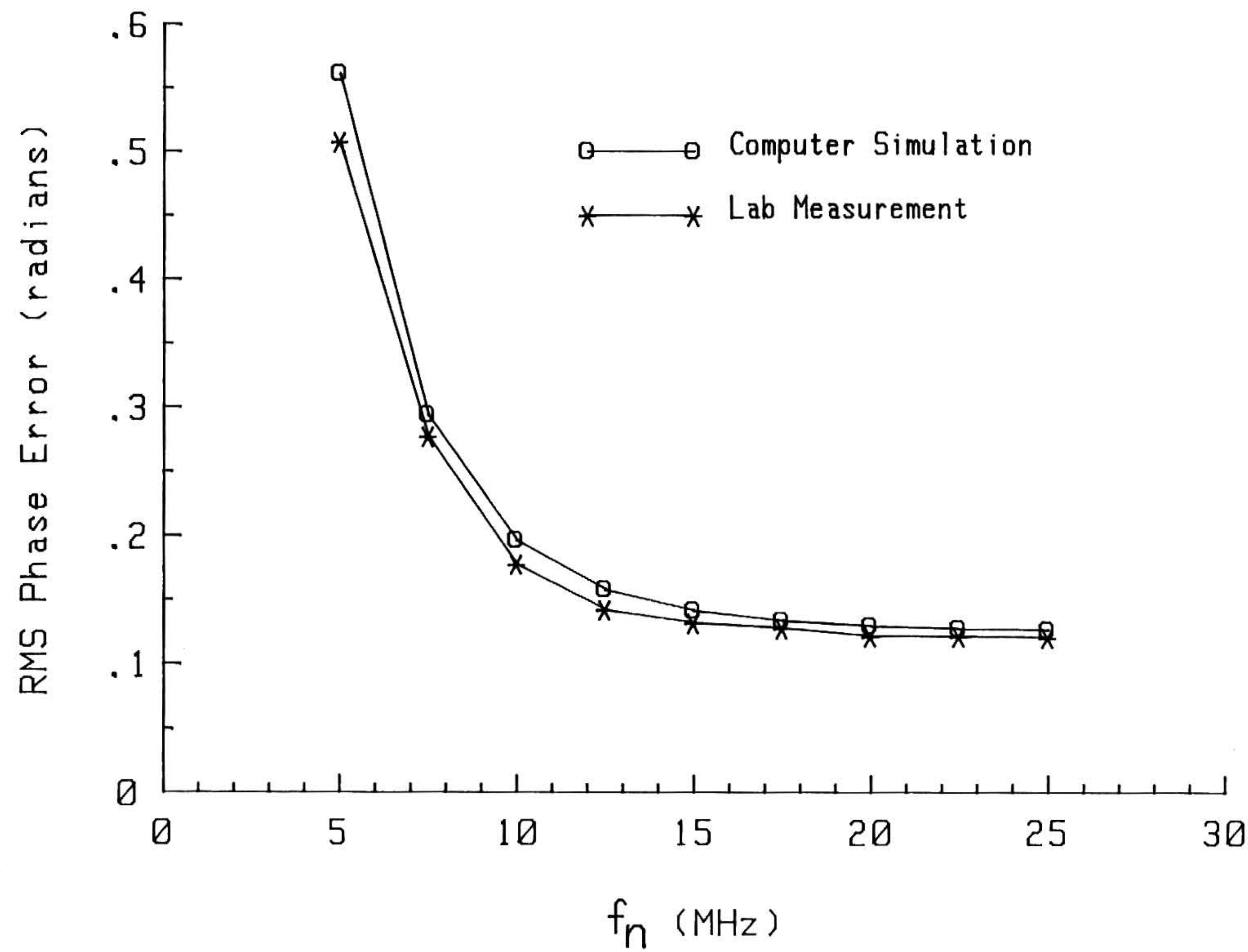

Figure 6.2. RMS phase error data for the software simulation and the hardware tests.

MHz as an ideal range of natural frequency. Figure 6.2, however, indicates that a natural frequency as low as 10 MHz would maintain a small phase error while keeping the noise bandwidth low enough for satellite FM demodulation of a signal with a relatively low signal-to-noise ratio. Additional observations indicate that for low values of f_n ($f_n \leq 7.5$ MHz), the resulting increased phase error caused severe distortion in the demodulated signal. After testing the demodulator in a satellite receiver (see Section VII), it was observed that loop natural frequencies greater than 20 MHz caused a noticeable decrease in the demodulator output signal-to-noise ratio due to high PLL noise bandwidth. In the context of this experiment, the data taken and the qualitative observations made, the author has reached the general conclusion that a loop natural frequency of 10 MHz to 20 MHz is best for a second order PLL FM video demodulator. For the satellite receiver briefly mentioned in the following section, a natural frequency of $f_n = 15$ MHz was chosen and found to perform very well.

VII. Satellite FM Receiver

To supplement the work documented in this paper, it was the author's intent to build a satellite receiver to allow a "real world" application for the PLL constructed for the hardware phase error tests. Such a receiver was designed and constructed in the fall of 1985 and spring of 1986. The block diagram of the receiver is shown in Figure 7.1. As well as the PLL video demodulator, the receiver also includes a 70 MHz IF prefilter, an analog video processor board, a dual PLL stereo demodulator and a DC control and metering card. A more detailed description of the receiver operation and alignment procedures is outlined in a separate manual (PLL Satellite Receiver Technical Manual) which supplements this report. The receiver proved to be an interesting and informative tool for verifying the performance of the PLL in the environment for which it was originally intended to be used.

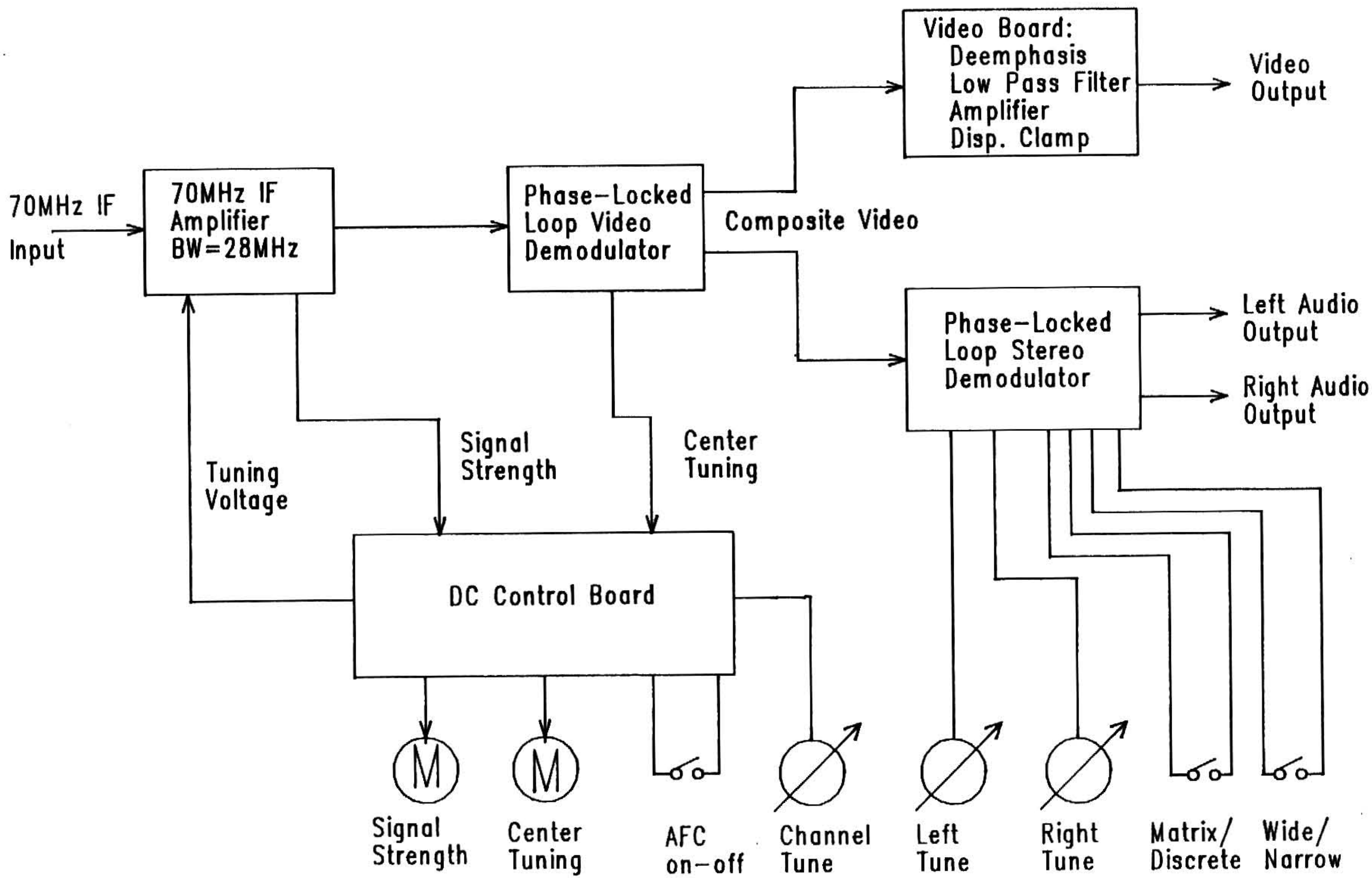

Figure 7.1. Satellite television receiver employing a second order PLL video demodulator.

VIII. Conclusions and Future Suggested Studies

The entire study documented in this report has proved to be an interesting, informative and worthwhile topic of research. The conclusions, though somewhat limited, provide invaluable information for the design of a second order PLL video demodulator. The author suggests future studies in the same area which would include such factors as the audio subcarriers, 70 MHz IF prefiltering, nonlinearities due to satellite FM transmission and the nonlinearity of the PLL phase detector.

An additional proposed study would make use of the satellite receiver to compare the PLL demodulator to an FM quadrature detector which is currently a popular scheme for FM video demodulation. Regardless of the details of any future work, it is hoped that studies in the area of satellite transmission and reception will continue at this institution due to their popularity in the field of electronic communications.

IX. Bibliography

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S. Reed, Satellite Television Handbook, Reed Publications, Maitland, Florida, 1980.

Appendix 1. Software Listing

```
C*****************************************************************************
C
C
C
C       VAX-11 FORTRAN SOURCE FILENAME:          NTSC.FOR
C
C       DEPARTMENT OF ELECTRICAL ENGINEERING     KANSAS STATE UNIVERSITY
C
C       REVISION        DATE                     PROGRAMMER(S)
C       --------        ----                     -------------
C        4.0            5/31/86                  DALE DUBBERT
C
C*****************************************************************************
C
C       INITIATING SEQUENCE:
C
C               RUN NTSC
C
C       PURPOSE:
C
C               This program is intended to study the rms phase error of
C               a second order phase locked loop employed as a satellite
C               FM video demodulator.  the program consists of three major
C               blocks which are:
C
C                       1)  NTSC color bar pattern generator with CCIR 405-1
C                           preemphasis for satellite FM transmission.
C
C                       2)  FM transmitter phase simulation (integration)
C
C                       3)  Linear phase locked loop simulation with rms
C                           phase error computation
C
C               Each program segment contains menu selections for user input
C               of system parameters and desired operations.  The user also
C               has the option of generating data files for the following
C               signals which can be displayed using any graphics package
C               employing the SGOPEN and SGTRAN data transfer routines:
C
C                       1)  Time domain video signal (single horizontal scan)
C
C                       2)  Video spectra (log magnitude data)
C
C                       3)  Time domain pll phase input signal (radians)
C
C                       4)  FM spectra (log magnitude data)
C
C                       5)  Time domain demodulated video signal
C
C               The subroutines for the NTSC program are located in the
C               following files:
C
C                       1)  NTSCAUX.FOR    (Auxiliary subroutine such as
C                                           data storage and retrieval,
C                                           menu generators, parameter storage
C                                           and retrieval, etc.)
C
C                       2)  NTSCFIL.FOR    (DFT and frequency domain filter
C                                           subroutines)
```

```
C
C                 3)  NTSCGEN.FOR    (NTSC signal generating subroutines)
C
C            The common area of variables and data arrays is located in:
C
C                     NTSCCOM.FOR
C
C            The NTSC generator and FM modulator/PLL demodulator default
C            parameters are located in:
C
C                     NTSCPARA.TXT
C
C            After compilation, the .FOR files can be linked by the
C            following VMS command:
C
C                     LINK NTSC,NTSCAUX,NTSCFIL,NTSCGEN
C
C
C        ROUTINE(S) ACCESSED OR CALLED BY THIS ROUTINE:
C
C            NTSCAUX SUBROUTINES:
C
C                 MENGET      (Menu for NTSC signal generator or NTSC data
C                              retrieval)
C
C                 MENGEN      (Menu for editing the NTSC generator
C                              parameters)
C
C                 MENNXT1     (Menu for selecting the next action after
C                              the NTSC generator)
C
C                 MENFMPLL    (Menu for editing the FM modulator and PLL
C                              demodulator parameters)
C
C                 MENNXT2     (Menu for selection of the next action after
C                              the PLL demodulator and phase error
C                              calculation)
C
C                 GETPARA     (System default parameter retrieval routine)
C
C                 SHOWPARA    (System parameter display routine)
C
C                 STOREPARA   (System parameter storage routine)
C
C                 FIGET       (Data retrieval routine)
C
C                 FISTORE     (Data storage routine)
C
C                 WAIT_RET    (Wait for <RETURN> to continue program)
C
C                 DATSTAT     (Returns the maximum, minimum and average
C                              of a real data array)
C
C                 PHAERROR    (Calculates the RMS phase error from the
C                              complex PLL error DFT coefficients)
C
C            NTSCGEN SUBROUTINES:
C
C                 NTSCGEN     (Generates the DFT luminance and chrominance
C                              coefficients for the NTSC color bar signal)
```

```
C
C                       TIMEVIDEO  (Generates the time domain NTSC video
C                                   signal)
C
C                       FREQVIDEO  (Generates the log magnitude spectra of the
C                                   NTSC video signal)
C
C                       TIMEPHASE  (Gentrates the time domain PLL input phase
C                                   signal in radians)
C
C                       FMSPEC     (Generates the log magnitude FM spectra of
C                                   the PLL input)
C
C                       PLLDEMOD   (Generates the time domain demodulated
C                                   video signal)
C
C               NTSCFIL SUBROUTINES:
C
C                       DFT        (Discrete Fourier  and inverse Fourier
C                                   transform for complex data arrays)
C
C                       INTEG      (Frequency domain integration for complex
C                                   data arrays)
C
C                       BWLPF      (Butterworth low pass filter for complex
C                                   data arrays)
C
C                       PREEMPH    (CCIR 405-1 FM preemphasis and deemphasis
C                                   for complex data arrays)
C
C                       ERRFUNC    (Linear PLL error function for complex data
C                                   arrays)
C
C
C******************************************************************************
C
C       BEGIN THE MAIN ROUTINE
C
C******************************************************************************

        INCLUDE 'NTSCCOM.FOR'

        CHARACTER*15 FINAME

        CHARACTER*1 RESPONSE

        INTEGER NUM,CHOICE

        LOGICAL PHAFLG

C*****************************************************************************
C
C       INITIALIZE ALL CONSTANTS FOR THE NTSC ROUTINE
C
C*****************************************************************************

        PI      = 3.141593

C       Set horizontal line frequency FH & WH (Hz & rad/sec)
        FH      = 15734.26
```

```
        WH     = 2.0 * PI * FH

C       Set color subcarrier frequency FC & WC (Hz & rad/sec)
        FC     = 3579545.0
        WC     = 2.0 * PI * FC

C       Set the video max and min variables to 0
        MAX    = 0.0
        MIN    = 0.0

C       Set the default parameter values
        CALL GETPARA

C***********************************************************************
C
C       CALL THE MENU TO SELECT THE SOURCE OF THE NTSC DFT
C       COEFFICIENTS
C
C***********************************************************************
100     CALL MENGET(CHOICE)

C======================================================================
C
C MENU SELECTION #1:  GENERATE THE NTSC SIGNAL
C
C======================================================================
        IF (CHOICE.EQ.1) THEN

C          Display the menu for the ntsc generator routine parameters
C          and let the user select the desired parameters
           CALL MENGEN

C          Generate the ntsc dft coefficients
           STATUS = LIB$ERASE_PAGE(1,1)
           TYPE*,'GENERATING THE NTSC COEFFICIENTS'
           CALL NTSCGEN

C          Prompt the user for storage of the coefficients
           TYPE*,' '
           TYPE111
111        FORMAT (T2,'STORE THE DFT COEFFICIENTS? (Y/N) -----> ',$)
           ACCEPT112, RESPONSE
112        FORMAT (A1)

           IF (RESPONSE.EQ.'Y'.OR.RESPONSE.EQ.'y') THEN
              TYPE*,' '
              TYPE*,'STORE THE LUMINANCE DFT COEFFICIENTS (l(w))'
              CALL FISTORE ('LUM.DAT',N,'COMPLEX',LUM)
              TYPE*,' '
              TYPE*,' '
              TYPE*,'STORE THE CHROMINANCE DFT COEFFICIENTS (c~(w))'
              CALL FISTORE ('CHR.DAT',N,'COMPLEX',CHR)
              CALL WAIT_RET
           END IF
        END IF

C======================================================================
C
C MENU SELECTION #2:  RECALL THE NTSC COEFFICIENTS
C
```

```
C=======================================================================
        IF (CHOICE.EQ.2) THEN

C          Recall a previously stored set of dft coefficients
           TYPE*,' '
           TYPE*,'RECALL THE LUMINANCE DFT COEFFICIENTS:'
           CALL FIGET ('LUM.DAT',NUM,'COMPLEX',LUM)
           TYPE*,' '
           TYPE*,' '
           TYPE*,'RECALL THE CHROMINANCE DFT COEFFICIENTS:'
           CALL FIGET ('CHR.DAT',NUM,'COMPLEX',CHR)
           CALL WAIT_RET
        END IF


C*********************************************************************
C
C CALL THE MENU TO SELECT THE NEXT DESIRED ACTION
C
C*********************************************************************
200     STATUS = LIB$ERASE_PAGE(1,1)
        CALL MENNXT1 (CHOICE)

C=======================================================================
C
C MENU SELECTION #1:  GENERATE THE TIME DOMAIN VIDEO SIGNAL
C
C=======================================================================
        IF (CHOICE .EQ. 1) THEN
           STATUS = LIB$ERASE_PAGE(1,1)
           TYPE*,'GENERATING THE TIME DOMAIN VIDEO SIGNAL'
           CALL TIMEVIDEO

C          Find the max and min of the video signal
           CALL DATSTAT (VIDEOSIGNAL,N2,MAX,MIN,AVE)

C          Store the time domain signal
           TYPE*,' '
           TYPE*,'STORE THE TIME DOMAIN VIDEO SIGNAL'
           CALL FISTORE ('TIMEVIDEO.DAT',N2,'REAL',VIDEOSIGNAL)

C          Return to the current menu
           CALL WAIT_RET
           GOTO 200
        END IF

C=======================================================================
C
C MENU SELECTION #2:  GENERATE THE VIDEO SPECTRUM
C
C=======================================================================
        IF (CHOICE .EQ. 2) THEN

C          Enter the noise floor for the dft plot
           STATUS = LIB$ERASE_PAGE(1,1)
           TYPE*,'ENTER THE NOISE FLOOR FOR THE NORMALIZED LOG SPECTRA'
           TYPE114
114        FORMAT (T2,'THE DEFAULT IS -80.0 dB -----> ',$)
           ACCEPT130, NOISEFL
```

```
130       FORMAT (F10.3)
          IF (NOISEFL .EQ. 0.0) NOISEFL = -80.0

C         Generate the video spectra
          TYPE*,' '
          TYPE*,'GENERATING THE VIDEO SPECTRA'
          CALL FREQVIDEO

C         Store the video spectra
          TYPE*,' '
          TYPE*,'STORE THE VIDEO SPECTRA'
          CALL FISTORE ('FREQVIDEO.DAT',N2,'REAL',VIDEOSPECTRA)

C         Return to the current menu
          CALL WAIT_RET
          GOTO 200
       END IF

C===============================================================================
C
C MENU SELECTION #3:  STORE THE CURRENT NTSC PARAMETERS
C
C===============================================================================
       IF (CHOICE .EQ. 3) THEN
          CALL STOREPARA
          GOTO 200
       END IF

C===============================================================================
C
C MENU SELECTION #4:  RETURN TO THE FIRST MENU
C
C===============================================================================
       IF (CHOICE .EQ. 4) GOTO 100

C===============================================================================
C
C MENU SELECTION <RETURN>:  CONTINUE WITH THE SIMULATION
C
C===============================================================================

C*******************************************************************************
C
C DISPLAY THE MENU FOR SELECTION OF THE FM MODULATION AND DEMODULATION
C PARAMETERS
C
C*******************************************************************************
       STATUS = LIB$ERASE_PAGE(1,1)
       TYPE*,'BEGIN FM MODULATOR / DEMODULATOR SIMULATION'

C      Calculate the max and min of the current video signal
       CALL TIMEVIDEO
       CALL DATSTAT (VIDEOSIGNAL,N2,MAX,MIN,AVE)

C      Calculate the fm modulation constant km in mhZ per volt
       KM = 2.0 * FMPKDEV  / (MAX - MIN)

C      Calculate the dependent loop parameters
       WN = SQRT (KDKV / (T1 * 1.0E-9))
       FN = WN / (2.0 * PI * 1.0E6)
```

```
      DAMP = 0.5 * (1 + KDKV * T2 * 1.0E-9) / SQRT (KDKV * T1
     &        * 1.0E-9)

C       Display the fm modulator / pll parameter menu and let
C       the user edit the parameters
400     CALL MENFMPLL

C***********************************************************************
C
C CALCULATE THE RMS PHASE ERROR
C
C***********************************************************************

C       Integrate the dft coefficients for the luminance and chrominance
C       signals to obtain the phase coefficients.  Set the dc term of
C       the signal to zero and multiply the coefficients by KM
C       (rad/sec/volt) before the integration.
        DO I = 1,N
           PHALUM(I) = CMPLX (KM * 2.0 * PI * 1.0E6 , 0.0) * LUM (I)
           PHACHR(I) = CMPLX (KM * 2.0 * PI * 1.0E6 , 0.0) * CHR (I)
        END DO

C       Set the dc value to 0 before integration
        PHALUM (1) = (0.0 , 0.0)

        CALL INTEG (PHALUM, N, FH, 0.0)
        CALL INTEG (PHACHR, N, FH, FC)

C       Implement the error transfer function of the pll to obtain
C       the phase error coefficients
        DO I = 1,N
           ERRLUM (I) = PHALUM (I)
           ERRCHR (I) = PHACHR (I)
        END DO

        CALL ERRFUNC (ERRLUM, N, FH, 0.0, DAMP,FN,T1)
        CALL ERRFUNC (ERRCHR, N, FH, FC,  DAMP,FN,T1)

C       Compute the phase error
        CALL PHAERROR

C       Display the phase error
        TYPE*,'RMS PHASE ERROR = ',RMSERROR,' radians = ',RMSERROR *
     &          180.0 / PI,' degrees'

C       Set the time domain phase flag to .FALSE. indicating that the new
C       phase signal has not yet been generated
        PHAFLG = .FALSE.

        CALL WAIT_RET

C******************************************************************************
C
C       DISPLAY THE MENU FOR THE NEXT ACTION
C
C******************************************************************************
500     CALL MENNXT2 (CHOICE)

C==============================================================================
```

```
C
C MENU SELECTION #1:  COMPUTE THE TIME DOMAIN PHASE SIGNAL
C
C=============================================================================
        IF (CHOICE .EQ. 1) THEN

C          Set the phase flag to .TRUE. indicating that a new phase signal has
C          been generated
           PHAFLG = .TRUE.

C          Generate the phase signal
           STATUS = LIB$ERASE_PAGE(1,1)
           TYPE*,'GENERATING THE TIME DOMAIN PLL INPUT PHASE SIGNAL'
           CALL TIMEPHASE

C          Store the phase signal
           TYPE*,' '
           TYPE*,'STORE THE PHASE SIGNAL'
           CALL FISTORE ('PHASE.DAT',N4,'REAL',PHASE)

C          Return to the current menu
           CALL WAIT_RET
           GOTO 500
        END IF

C=============================================================================
C
C MENU SELECTION #2:  COMPUTE THE FM SPECTRA
C
C=============================================================================
        IF (CHOICE .EQ. 2) THEN

C          If the phase signal has already been generated, then their is no
C          need to generate it again.
           STATUS = LIB$ERASE_PAGE(1,1)

           IF (NOT(PHAFLG)) THEN
              TYPE*,'GENERATING THE TIME DOMAIN PLL INPUT PHASE SIGNAL'
              CALL TIMEPHASE
           END IF

C          Enter the noise floor for the FM spectra
           TYPE*,' '
           TYPE*,'ENTER THE NOISE FLOOR FOR THE NORMALIZED LOG SPECTRA'
           TYPE131
131        FORMAT (T2,'THE DEFAULT IS -60.0 dB -----> ',$)
           ACCEPT132, NOISEFL
132        FORMAT (F10.3)
           IF (NOISEFL .EQ. 0.0) NOISEFL = -60.0

C          Generate the FM spectra
           TYPE*,'GENERATING THE FM SPECTRA'
           CALL FMSPEC

C          Store the FM spectra
           TYPE*,' '
           TYPE*,'STORE THE FM SPECTRA'
           CALL FISTORE ('FMSPECTRA.DAT',N4,'REAL',FMSPECTRA)

C          Return to the current menu
```

```
            CALL WAIT_RET
            GOTO 500
         END IF

C=================================================================
C
C MENU SELECTION #3:  COMPUTE THE DEMODULATED SIGNAL
C
C=================================================================
         IF (CHOICE .EQ. 3) THEN

C           Compute the demodulated signal
            STATUS = LIB$ERASE_PAGE(1,1)
            TYPE*,'COMPUTING THE DEMODULATED SIGNAL'
            CALL PLLDEMOD

C           Store the demodulated signal
            TYPE*,' '
            TYPE*,'STORE THE DEMODULATED SIGNAL'
            CALL FISTORE ('DEMOD.DAT',N2,'REAL',DEMOD)

C           Return to the current menu
            CALL WAIT_RET
            GOTO 500
         END IF

C=================================================================
C
C MENU SELECTION #4:  RETURN TO THE FM MODULATOR / PLL PARAMETER MENU
C
C=================================================================
         IF (CHOICE .EQ. 4) GOTO 400

C=================================================================
C
C MENU SELECTION #5:  GO BACK TO THE NTSC GENERATOR MENU
C
C=================================================================
         IF (CHOICE .EQ. 5) GOTO 100

C=================================================================
C
C MENU SELECTION #6:  STORE THE CURRENT NTSC PARAMETERS
C
C=================================================================
         IF (CHOICE .EQ. 6) THEN
            CALL STOREPARA
            GOTO 500
         END IF

C=================================================================
C
C MENU SELECTION #7:  RECALL NTSC PARAMETERS FROM DISK
C
C=================================================================
         IF (CHOICE .EQ. 7) THEN
            CALL GETPARA
            GOTO 500
         END IF
```

```
C===========================================================================
C
C MENU SELECTION #8:  SHOW THE NTSC PARAMETERS STORED ON DISK
C
C===========================================================================
       IF (CHOICE .EQ. 8) THEN
          CALL SHOWPARA
          GOTO 500
       END IF

C===========================================================================
C
C MENU SELECTION <RETURN>:  STOP THE PROGRAM
C
C===========================================================================
       STOP
       END


C***************************************************************************
C
C
C      VAX-11 FORTRAN SOURCE FILENAME:          NTSCCOM.FOR
C
C      DEPARTMENT OF ELECTRICAL ENGINEERING     KANSAS STATE UNIVERSITY
C
C      REVISION         DATE                    PROGRAMMER(S)
C      --------         ----                    -------------
C       3.0             4/2/86                  DALE DUBBERT
C
C***************************************************************************
C
C  PURPOSE:
C
C      COMMON AREA FOR NTSC GENERATOR AND PLL SIMULATOR ROUTINE
C
C***************************************************************************
C
C  DESCRIPTION OF VARIABLES USED IN THE MAIN ROUTINE NTSC.FOR:
C
C     DATA ARRAYS:
C
C      LUM             The DFT coefficients of the video luminance signal l(w)
C                      (complex)
C
C      CHR             The DFT coefficients of the equivalent low pass
C                      chrominance signal c~(w) (complex)
C
C      PHALUM          The DFT coefficients of the luminance phase input of
C                      the phase locked loop
C
C      PHACHR          The DFT coefficients of the equivalent low pass
C                      chrominance phase input of the phase locked loop
C                      (complex)
C
C      ERRLUM          The DFT coefficients of the luminance PLL phase error
C                      (complex)
C
```

```
C       ERRCHR          The DFT coefficients of the equivalent low pass
C                       chrominance PLL phase error (complex)
C
C       DEMLUM          The DFT coefficients of the demodulated luminance
C                       signal (complex)
C
C       DEMCHR          The DFT coefficients of the equivalent low pass
C                       demodulated chrominance signal (complex)
C
C       CBUFFER         Temporary data buffer (complex)
C
C       RBUFFER         Temporary data buffer (real)
C
C       VIDEOSIGNAL     The NTSC color bar composite video signal (real)
C
C       VIDEOSPECTRA    The log magnitude spectra of the NTSC video signal
C                       (real)
C
C       PHASE           The time domain PLL input phase signal in radians (real)
C
C       FMSPECTRA       The log magnitude spectra of the PLL FM input (real)
C
C       DEMOD           The time domain PLL demodulated signal (real)
C
C       RMSERROR        The RMS value of the PLL error signal (real)
C
C
C   NTSC GENERATOR PARAMETERS:
C
C       YPOL            The number of poles for the luminance low pass filter
C
C       QPOL            The number of poles for the Q chrominance low pass filter
C
C       IPOL            The number of poles for the I chrominance low pass filter
C
C       YCUT            The cutoff frequency (MHz) for the luminance LPF
C
C       QCUT            The cutoff frequency (MHz) for the Q chrominance LPF
C
C       ICUT            The cutoff frequency (MHZ) for the I chrominance LPF
C
C       PREFLG          The 'Y' or 'N' flag for requesting preemphasis or no
C                       preemphasis
C
C       PERSAT          The percent color saturation for the NTSC color bar
C                       signal
C
C       NOISEFL         The noise floor (dB) for log magnitude plots
C
C
C  FM MODULATOR AND PLL DEMODULATOR PARAMETERS:
C
C       FMPKDEV         The peak deviation (MHz) for the FM signal
C
C       MAX             The maximum voltage of the FM transmitter input
C
C       MIN             The minimum voltage of the FM transmitter input
C
C       AVE             The average (dc) voltage of the FM transmitter input
C
```

```
C       KM              The modulation index for the FM transmitter (MHz/volt)
C
C       KDKV            The open loop gain of the phase locked loop (1/seconds)
C
C       WN              The natural frequency of the phase locked loop
C                       (radians/second)
C
C       FN              The natural frequency of the phase locked loop (MHz)
C
C       DAMP            The damping   coefficient of the phase locked loop
C
C       T1              The PLL loop filter pole time constant (nanoseconds)
C
C       T2              The PLL loop filter zero time constant (nanoseconds)
C
C
C  SYSTEM CONSTANTS:
C
C       FH              The horizontal scan frequency for a 525 line television
C                       system (Hz)
C
C       WH              The horizontal scan frequency for a 525 line television
C                       system (radians/second)
C
C       FC              The color subcarrier frequency for a 525 line
C                       television system (Hz)
C
C       WC              The color subcarrier frequency for a 525 line
C                       television system (radians/second)
C
C*****************************************************************************
C
C       COMMON BLOCKS
C
C*****************************************************************************

C       Data arrays:
        COMMON /DATA/ LUM,CHR,PHALUM,PHACHR,ERRLUM,ERRCHR,
     &                RBUFFER,VIDEOSIGNAL,VIDEOSPECTRA,PHASE,
     &                FMSPECTRA,CBUFFER,RMSERROR,DEMOD,DEMLUM,DEMCHR

C       NTSC signal generator parameters:
        COMMON /NTSCPAR/ YPOL,QPOL,IPOL,YCUT,QCUT,ICUT,PREFLG,PERSAT,
     &                   NOISEFL

C       FM transmitter and PLL demodulator parameters:
        COMMON /PLLPAR/ FMPKDEV,MAX,MIN,AVE,KM,KDKV,WN,FN,DAMP,T1,T2

C       System constants:
        COMMON /CONST/ FH,FC,WH,WC,PI,F0


C*****************************************************************************
C
C       DATA DECLARATION
C
C*****************************************************************************

        INTEGER N,N2,N4,N8,N16,I,YPOL,QPOL,IPOL
```

```
      INTEGER*4 STATUS

      PARAMETER (N=1024,N2=2048,N4=4096,N8=8192,N16=16384)

      REAL RBUFFER(N4),FH,FC,WH,WC,PI,F0,YCUT,QCUT,ICUT,
     &      PERSAT,VIDEOSIGNAL(N2),VIDEOSPECTRA(N2),NOISEFL,
     &      FMPKDEV,MAX,MIN,AVE,KM,KDKV,WN,FN,DAMP,T1,T2,
     &      PHASE(N4),FMSPECTRA(N4),RMSERROR,DEMOD(N2)

      CHARACTER*1 PREFLG

      COMPLEX LUM(N),CHR(N),PRELUM(N),PRECHR(N),PHALUM(N),PHACHR(N),
     &         ERRLUM(N),ERRCHR(N),DEMLUM(N),DEMCHR(N),ARG,
     &         CBUFFER(N4)



C*****************************************************************************
C
C
C
C       VAX-11 FORTRAN SOURCE FILENAME:          NTSCGEN.FOR
C
C       DEPARTMENT OF ELECTRICAL ENGINEERING     KANSAS STATE UNIVERSITY
C
C       REVISION        DATE                     PROGRAMMER(S)
C       --------        ----                     -------------
C        3.0            4/2/86                   DALE DUBBERT
C
C       PROJECT:  MS REPORT;  RMS PHASE ERROR OF A SECOND ORDER PHASE
C                             LOCKED LOOP EMPLOYED AS A SATELLITE FM
C                             VIDEO DEMODULATOR
C
C*****************************************************************************
C
C       RMS PHASE ERROR SIMULATION SIGNAL GENERATOR ROUTINES:
C
C       NTSCGEN         {NTSC COLOR BAR PATTERN GENERATOR}
C       TIMEVIDEO       {TIME DOMAIN VIDEO SIGNAL GENERATOR}
C       FREQVIDEO       {VIDEO SPECTRA GENERATOR}
C       TIMEPHASE       {PLL INPUT PHASE SIGNAL GENERATOR}
C       FMSPEC          {PLL FM INPUT SPECTRA GENERATOR}
C       PLLDEMOD        {PLL DEMODULATED SIGNAL GENERATOR}
C
C*****************************************************************************


C*****************************************************************************
C
C       NTSCGEN      {NTSC COLOR BAR SIGNAL GENERATOR ROUTINE}
C
C                    PROGRAMMER:  DALE DUBBERT
C
C*****************************************************************************
C
C  CALLING SEQUENCE:  CALL NTSCGEN
C
```

```
C  PURPOSE:
C
C       THIS ROUTINE GENERATES THE LUM AND CHR DATA ARRAYS
C
C  NOTE:  ALL ARGUMENTS ARE PASSED THROUGH THE COMMON AREA NTSCCOM.FOR
C
C*******************************************************************************

        SUBROUTINE NTSCGEN

        INCLUDE 'NTSCCOM.FOR'

        COMPLEX COLORBURST(N),ICHR(N),QCHR(N)

        REAL TIME,RED,GREEN,BLUE,BLANKING,CBPULSE

C===============================================================================
C
C       GENERATE THE NTSC LUMINANCE AND EQUIVALENT LOW PASS CHROMINANCE FREQ.
C       DOMAIN SIGNALS
C
C===============================================================================

C       Initialize the color burst vector

        DO I = 1,N
           COLORBURST(I) = CMPLX (0.0,0.0)
        END DO

C       Generate the I and Q chrominance, luminance and the color burst
C       and blanking signals

        DO I = 1,N

C          Calculate the time in microseconds

           TIME = 1.0E6 * FLOAT (I-1) / (FLOAT (N) * FH)

C          Find the red (r(t)), green (g(t)) and blue (b(t)) camera
C          signals, the color burst signal (u(t)) and the horizontal
C          sync + blanking signal (p(t)) for each iteration of time

           RED = 0.
           GREEN = 0.
           BLUE = 0.
           BLANKING = 0.
           CBPULSE = 0.

           IF ((11.0 .LE. TIME .AND. 26.0 .GT. TIME) .OR.
     &         (41.0 .LE. TIME .AND. 56.0 .GT. TIME))
     &         RED = 0.01 * PERSAT

           IF ((11.0 .LE. TIME .AND. 18.5 .GT. TIME) .OR.
     &         (26.0 .LE. TIME .AND. 33.5 .GT. TIME) .OR.
     &         (41.0 .LE. TIME .AND. 48.5 .GT. TIME) .OR.
     &         (56.0 .LE. TIME .AND. 63.6 .GT. TIME))
     &         BLUE = 0.01 * PERSAT

           IF  (11.0 .LE. TIME .AND. 41.0 .GT. TIME)
     &         GREEN = 0.01 * PERSAT
```

```
          IF ((0.0 .LE. TIME .AND. 1.5 .GT. TIME) .OR.
     &        (6.0 .LE. TIME .AND. 11.0 .GT. TIME))
     &        BLANKING = -0.083

          IF  (1.5 .LE. TIME .AND. 6.0 .GT. TIME)
     &        BLANKING = -0.083 - 0.33

          IF  (7.0 .LE. TIME .AND. 9.5 .GT. TIME)
     &        CBPULSE = 0.167

C         Implement the transformation matrix [A]
C         add the blanking signal (p(t)) to the luminance
C         signal (y(t))

          ICHR (I) = CMPLX (0.6 * RED - 0.377 * GREEN - 0.221 *
     &                      BLUE , 0.0)

          QCHR (I) = CMPLX (-0.191 * RED + 0.558 * GREEN - 0.368 *
     &                      BLUE , 0.0)

          LUM (I)  = CMPLX (0.299 * RED + 0.587 * GREEN + 0.114 *
     &                      BLUE + BLANKING , 0.0)

C         CALCULATE THE COLOR BURST SIGNAL (u(t))

          COLORBURST (I) =  CMPLX (CBPULSE , 0.0)

       END DO

C      DFT the I and Q chrominance signals

       CALL DFT (ICHR,N,0)
       CALL DFT (QCHR,N,0)

C      Filter the I (Hv(w)) and Q (Hq(w)) chrominance signals

       CALL BWLPF (ICHR,N,IPOL,1.0E6 * ICUT,FH,0.0)
       CALL BWLPF (QCHR,N,QPOL,1.0E6 * QCUT,FH,0.0)

C      DFT the color burst signal

       CALL DFT (COLORBURST,N,0)

C      Filter the color burst signal using the same filter parameters
C      as those specified for the luminance signal (Hv(w))

       CALL BWLPF (COLORBURST,N,YPOL,1.0E6 * YCUT,FH,0.0)

C      Compute the equivalent low pass chrominance + color burst
C      DFT coefficients

       DO I = 1,N
          CHR (I) = ICHR (I) - CMPLX (0.0 , 1.0)
     &              * (QCHR (I) - COLORBURST (I))
       END DO

C      Low pass filter the complex envelope of the chrominance signal
C      (Hv(w+wc)) to obtain the equivalent low pass chrominance
C      coefficients (c~(w))
```

```
      CALL BWLPF (CHR,N,YPOL,1.0E6 * YCUT,FH,FC)

C     DFT the luminance signal (y(t) + p(t))

      CALL DFT (LUM,N,0)

C     Filter the luminance signal (Hv(w)) to obtain the luminance
C     DFT coefficients (l(w))

      CALL BWLPF (LUM,N,YPOL,1.0E6 * YCUT,FH,0.0)

C=======================================================================
C
C     APPLY CCIR 405-1 FM PREEMPHASIS TO THE SIGNALS IF THE USER HAS
C     REQUESTED IT
C
C=======================================================================

      IF (PREFLG .EQ. 'Y') THEN
         CALL PREEMPH (LUM,N,FH,0.0,0)
         CALL PREEMPH (CHR,N,FH,FC,0)
      END IF

      RETURN
      END



C***********************************************************************
C
C     TIMEVIDEO      (SUBROUTINE TO GENERATE THE TIME DOMAIN NTSC VIDEO
C                     SIGNAL)
C
C***********************************************************************
C
C     CALLING SEQUENCE:  CALL TIMEVIDEO
C
C     PURPOSE:
C
C             THIS ROUTINE GENERATES THE VIDEOSIGNAL ARRAY.
C
C     NOTE:  ALL ARGUMENTS ARE PASSED IN THE COMMON BLOCK NTSCCOM.FOR.
C
C***********************************************************************

      SUBROUTINE TIMEVIDEO

      INCLUDE 'NTSCCOM.FOR'

      COMPLEX LUMINANCE(N),CHROMINANCE(N)

      REAL TIME,REALCHR,IMAGCHR

      INTEGER I2

C     Take the inverse DFT of the chrominance and luminance coefficients
```

```
      DO I = 1,N
         LUMINANCE(I)    = LUM(I)
         CHROMINANCE(I) = CHR(I)
      END DO
      CALL DFT (LUMINANCE,N,1)
      CALL DFT (CHROMINANCE,N,1)

      DO I = 1,N2

C        Calculate the n length counter
         I2 = (I + 1) / 2

C        Calculate the time in seconds
         TIME = FLOAT (I - 1) / (FH * FLOAT (N2))

C        Calculate the real and imaginary parts of the chrominance
C        signal for each iteration
         REALCHR = REAL  (CHROMINANCE (I2))
         IMAGCHR = AIMAG (CHROMINANCE (I2))

C        Check for illegal arguments in the ATAN2 function
         IF (REALCHR .EQ. 0.0 .AND. IMAGCHR .EQ. 0.0) REALCHR = 1.0E-30

C        Calculate the video signal for each iteration
         VIDEOSIGNAL(I) = CABS (CHROMINANCE(I2)) * COS (WC * TIME +
     &                    ATAN2 (IMAGCHR,REALCHR)) + REAL (LUMINANCE (I2))

      END DO

      RETURN
      END


C***************************************************************************
C
C     FREQVIDEO    (SUBROUTINE TO CALCULATE THE LOG MAGNITUDE SPECTRA
C                   OF THE NTSC VIDEO SIGNAL)
C
C***************************************************************************
C
C     CALLING SEQUENCE:  CALL FREQVIDEO
C
C     PURPOSE:
C
C            THIS ROUTINE GENERATES THE VIDEOSPECTRA ARRAY.
C
C     NOTE:  ALL ARGUMENTS ARE PASSED IN THE COMMON AREA NTSCCOM.FOR.
C
C***************************************************************************

      SUBROUTINE FREQVIDEO

      INCLUDE 'NTSCCOM.FOR'

      REAL RARG,HIGH,LOW,MID
      INTEGER COLORSC

C     Initialize the spectrum to a small value
```

```
      DO I = 1,N2
         VIDEOSPECTRA(I) = -1.0E20
      END DO

C     Generate the one sided spectra of the luminance signal
      DO I = 1,N2,4
         VIDEOSPECTRA(I) = 20.0 * LOG10 (CABS (LUM ((I + 3) / 4)))
      END DO

C     Calculate the color subcarrier pointer
      COLORSC = NINT ((4.0 * FC / FH) + 1.0)

C     Generate the high side spectra for the chrominance signal
      DO I = COLORSC,N2,4
         VIDEOSPECTRA(I) = 20.0 * LOG10
     &                     (CABS (CHR ((I - COLORSC + 4) / 4)))
      END DO

C     Generate the low side spectra for the chrominance signal
      DO I = COLORSC,3,-4
         VIDEOSPECTRA(I) = 20.0 * LOG10
     &                     (CABS (CHR ((I - COLORSC) / 4 + N)))
      END DO

C     Normalize the spectra
      CALL DATSTAT (VIDEOSPECTRA,N2,HIGH,LOW,MID)
      DO I = 1,N2
         VIDEOSPECTRA(I) = VIDEOSPECTRA(I) - HIGH
      END DO

C     Set the noise floor
      DO I = 1,N2
         IF (VIDEOSPECTRA(I) .LE. NOISEFL)
     &       VIDEOSPECTRA(I) = NOISEFL
      END DO

      RETURN
      END

C*******************************************************************************
C
C     TIMEPHASE    (SUBROUTINE TO CALCULATE THE PLL INPUT PHASE SIGNAL IN
C                   THE TIME DOMAIN)
C
C*******************************************************************************
C
C     CALLING SEQUENCE:  CALL TIMEPHASE
C
C     PURPOSE:
C
C             THIS ROUTINE GENERATES THE PHASE ARRAY.
C
C     NOTE:  ALL ARGUMENTS ARE PASSED THROUGH THE COMMON AREA NTSCCOM.FOR.
C
C*******************************************************************************

      SUBROUTINE TIMEPHASE

      INCLUDE 'NTSCCOM.FOR'
```

```
        REAL    TIME
        INTEGER I2

C       IDFT the phase coefficients
        CALL DFT (PHALUM,N,1)
        CALL DFT (PHACHR,N,1)

C       Calculate the phase signal from the time coefficients of the
C       chrominance and luminance phase signals
C       The phase signal contains 8192 data points
        DO I = 1,N4

           TIME = FLOAT (I-1) / (FH * FLOAT (N4))
           I2 = (I + 3) / 4

           PHASE (I) = REAL (CEXP (CMPLX (0.0 , WC * TIME)) *
     &                 PHACHR (I2)) + REAL (PHALUM (I2))

        END DO

C       Filter the time domain phase signal to eliminate the harmonics
C       produced by increasing the data file size from N to N4
C       Set the cutoff to 8 MHz and the number of poles to 5 for the
C       Butterworth low pass filter
        DO I = 1,N4
           CBUFFER (I) = CMPLX (PHASE (I), 0.0)
        END DO
        CALL DFT (CBUFFER, N4, 0)
        CALL BWLPF (CBUFFER, N4, 5, 8.0E6, FH, 0.0)
        CALL DFT (CBUFFER, N4, 1)

        DO I = 1,N4
           PHASE (I) = REAL (CBUFFER (I))
        END DO

C       DFT the phase coefficients
        CALL DFT (PHALUM,N,0)
        CALL DFT (PHACHR,N,0)

        RETURN
        END

C***********************************************************************
C
C       FMSPEC     (SUBROUTINE TO CALCULATE THE FM SPECTRA FROM THE TIME
C                   DOMAIN PHASE SIGNAL)
C
C***********************************************************************
C
C       CALL SEQUENCE:  CALL FMSPEC
C
C       PURPOSE:
C
C               THIS ROUTINE GENERATES THE FMSPECTRA ARRAY.
C
C       NOTE:  ALL ARGUMENTS ARE PASSED THROUGH THE COMMON AREA NTSCCOM.FOR.
C
C***********************************************************************
```

```
      SUBROUTINE FMSPEC

      INCLUDE 'NTSCCOM.FOR'
      REAL HIGH,LOW,MID

C     Compute the FM spectra from the phase signal
C     The FM spectra contains 8192 data points

      DO I = 1,N4
         CBUFFER(I) = CEXP (CMPLX (0.0 , PHASE(I)))
      END DO

      CALL DFT (CBUFFER,N4,0)

      DO I = 1,N4
         FMSPECTRA (I) = 20 * LOG10 (CABS (CBUFFER(I)))
      END DO

C     Shift the carrier frequency to the center of the sequence
      DO I = 1,N4 / 2
         RBUFFER(I) = FMSPECTRA(I + N4 / 2)
         FMSPECTRA(I + N4 / 2) = FMSPECTRA(I)
         FMSPECTRA(I) = RBUFFER(I)
      END DO

C     Normalize the data
      CALL DATSTAT (FMSPECTRA,N4,HIGH,LOW,MID)
      DO I = 1,N4
         FMSPECTRA(I) = FMSPECTRA(I) - HIGH
      END DO

C     Set the noise floor
      DO I = 1,N4
         IF (FMSPECTRA(I) .LE. NOISEFL)
     &         FMSPECTRA(I) = NOISEFL
      END DO

      RETURN
      END


C*****************************************************************************
C
C     PLLDEMOD    (SUBROUTINE TO CALCULATE THE TIME DOMAIN PLL DEMODULATED
C                  SIGNAL)
C
C*****************************************************************************
C
C     CALLING SEQUENCE:  CALL PLLDEMOD
C
C     PURPOSE:
C
C             THIS ROUTINE GENERATES THE DEMOD ARRAY
C
C     NOTE:  ALL ARGUMENTS ARE PASSED THROUGH THE COMMON AREA NTSCCOM.FOR.
C
C*****************************************************************************

      SUBROUTINE PLLDEMOD
```

```
      INCLUDE 'NTSCCOM.FOR'
      REAL W,TIME,REALCHR,IMAGCHR
      CHARACTER*1 RESPONSE

C     Filter the error coefficients with the loop filter transfer function
      DO I = 1,N
         DEMLUM(I) = ERRLUM(I)
         DEMCHR(I) = ERRCHR(I)
      END DO

      DO I = 1,N/2

         W = FLOAT (I - 1) * WH
         DEMLUM(I) = DEMLUM(I) * CMPLX(1.0, T2 * 1.0E-9 * W) /
     &               CMPLX(1.0, T1 * 1.0E-9 * W)

         W = -FLOAT (I) * WH
         DEMLUM(N+1-I) = DEMLUM(N+1-I)*CMPLX(1.0,T2*1.0E-9*W) /
     &               CMPLX(1.0, T1 * 1.0E-9 * W)

         W = FLOAT (I - 1) * WH + WC
         DEMCHR(I) = DEMCHR(I) * CMPLX(1.0, T2 * 1.0E-9 * W) /
     &               CMPLX(1.0, T1 * 1.0E-9 * W)

         W = -FLOAT (I) * WH + WC
         DEMCHR(N+1-I) = DEMCHR(N+1-I)*CMPLX(1.0,T2*1.0E-9*W) /
     &               CMPLX(1.0, T1 * 1.0E-9 * W)

      END DO

C     Ask for deemphasis
      TYPE111
111   FORMAT (/,T2,'APPLY DEEMPHASIS? (Y/N) ----> ',$)
      READ (6,112) RESPONSE
112   FORMAT (A1)

      IF (RESPONSE .EQ. 'Y' .OR. RESPONSE .EQ. 'y') THEN
         TYPE*,'APPLYING DEEMPHASIS'
         CALL PREEMPH (DEMLUM,N,FH,0.0,1)
         CALL PREEMPH (DEMCHR,N,FH,FC,1)
      END IF

C     Calculate the time domain demodulated signal
      CALL DFT (DEMLUM,N,1)
      CALL DFT (DEMCHR,N,1)

      DO I = 1,N2
         TIME = FLOAT(I-1) / (FLOAT(N2) * FH)
         I2 = (I + 1) / 2

         REALCHR = REAL  (DEMCHR(I2))
         IMAGCHR = AIMAG (DEMCHR(I2))

         IF (REALCHR.EQ.0.0.AND.IMAGCHR.EQ.0.0) REALCHR = 1.0E-30

         DEMOD(I) = CABS (DEMCHR(I2)) * COS (WC * TIME +
     &              ATAN2 (IMAGCHR,REALCHR)) + REAL (DEMLUM(I2))

      END DO
```

```
      CALL DFT (DEMLUM,N,0)
      CALL DFT (DEMCHR,N,0)

      RETURN
      END


C***************************************************************************
C
C     VAX-11 FORTRAN SOURCE FILENAME:          NTSCFIL.FOR
C
C     DEPARTMENT OF ELECTRICAL ENGINEERING     KANSAS STATE UNIVERSITY
C
C     REVISION         DATE                    PROGRAMMER(S)
C     --------         ----                    -------------
C      4.0             5/31/86                 DALE DUBBERT
C
C     PROJECT:  MS REPORT;  RMS PHASE ERROR FOR A SECOND ORDER PHASE LOCKED
C                           LOOP EMPLOYED AS A SATELLITE FM VIDEO DEMODULATOR
C
C***************************************************************************
C
C      RMS PHASE ERROR SIMULATION FREQUENCY DOMAIN FILTER SUBROUTINES:
C
C      DFT        (DISCRETE FOURIER TRANSFORM)
C      BWLPF      (BUTTERWORTH LOW PASS FILTER)
C      PREEMPH    (FM PREEMPHASIS / DEEMPHASIS)
C      INTEG      (INTEGRATION)
C      ERRFUNC    (LINEAR PLL ERROR TRANSFER FUNCTION)
C
C***************************************************************************


C***************************************************************************
C
C     DFT     (DISCRETE FOURIER TRANSFORM SUBROUTINE)
C
C             PROGRAMMER:  STEPHEN A. DYER
C
C***************************************************************************
C
C     CALLING SEQUENCE:
C
C             CALL DFT (X,NOPTS,INV)
C
C     PURPOSE:
C             This routine implements the FFT algorithm to compute
C             the DFT coefficients of a complex-valued data sequence
C             of NOPTS points, where NOPTS is an integer power of 2.
C
C     ARGUMENT(S) REQUIRED FROM THE CALLING ROUTINE:
C
C             X       = complex-valued data/transform sequence
C             NOPTS   = number of data points in X.  NOPTS must
C                       be an integer power of 2.
C             INV     = flag for forward/inverse transform
```

```
C                       INV = 0:  forward DFT
C                       INV = 1:  inverse DFT
C
C      ARGUMENT(S) SUPPLIED  TO  THE CALLING ROUTINE:
C
C              X       = complex-valued data/transform sequence
C                        resulting from the transform operation.
C
C******************************************************************************
C
C      NOTE 1: This routine was adapted from a FORTRAN subroutine
C              presented on page 79 of Ahmed and Rao, Orthogonal
C              Transforms for Digital Signal Processing, Springer-
C              Verlag, 1975.  For a derivation of the algorithm, see:
C
C                  Kahaner, D. K., "Matrix Description of the Fast
C                    Fourier Transform," IEEE Trans. Audio and
C                    Electroacoustics Vol. AU-18, 1970, pp. 442-452.
C
C******************************************************************************

      SUBROUTINE DFT (X,NOPTS,INV)

      IMPLICIT NONE
      INTEGER I,INDEX,INDEX2,INDEX3,INV,ITER,J,J1,J2,
     1     K,N1,N2,NOPTS,NPAR,NPAR2,REM
      REAL ARG,FN,SIGN,WPOWER
      COMPLEX CMPLX,T,W,X(*)

*     Calculate the number of iterations.
      ITER = 0
      REM  = NOPTS/2
      DO WHILE (REM.NE.0)
          REM  = REM/2
          ITER = ITER + 1
      ENDDO

      SIGN = -1.0
      IF (INV.NE.0) SIGN = 1.0

      NPAR2 = NOPTS
      DO INDEX = 1,ITER

*         Computation for each iteration.
*         NPAR is the number of points in a partition
*         NPAR2 is NPAR/2

          NPAR   = NPAR2
          NPAR2  = NPAR/2
          WPOWER = 3.1415926/FLOAT(NPAR2)

          DO INDEX2 = 1,NPAR2

*             Calculate the multiplier.
              ARG = FLOAT(INDEX2 - 1)*WPOWER
              W   = CMPLX(COS(ARG),SIGN*SIN(ARG))

                  DO INDEX3 = NPAR,NOPTS,NPAR

*                     Computation for each partition.
```

```
                    J1    = INDEX3 - NPAR + INDEX2
                    J2    = J1 + NPAR2
                    T     = X(J1) - X(J2)
                    X(J1) = X(J1) + X(J2)
                    X(J2) = T * W
                ENDDO
          ENDDO
      ENDDO

*     Unscramble the bit-reversed DFT coefficients.
      N2 = NOPTS/2
      J  = 1
      DO I = 1,NOPTS - 1
          IF (I.LT.J) THEN
              T    = X(J)
              X(J) = X(I)
              X(I) = T
          ENDIF

          K = N2

          DO WHILE (K.LT.J)
              J = J - K
              K = K/2
          ENDDO

          J = J + K
      ENDDO

      IF (INV.EQ.0) THEN
          FN = 1.0/FLOAT(NOPTS)
          DO I = 1,NOPTS
              X(I) = X(I) * FN
          ENDDO
      ENDIF

      RETURN
      END


C*****************************************************************************
C
C       BWLPF   (SUBROUTINE TO BUTTERWORTH LOW PASS FILTER A COMPLEX DATA
C                ARRAY)
C
C               PROGRAMMER:  DALE DUBBERT
C
C*****************************************************************************
C
C  CALLING SEQUENCE: CALL BWLPF(ARRAY,N,POL,F3,FH,FC)
C
C  PARAMETERS SUPPLIED TO THE SUBROUTINE:
C
C        ARRAY  The complex data array to be filtered
C
C        N      The number of data points in the array
```

```
C
C        POL    The number of poles in the desired transfer
C               function (POL=1,2,3,4 or 5).  If POL = 0 then no
C               filtering is done on the data.
C
C        F3     The 3dB cutoff frequency in Hz
C
C        FH     The frequency increment between the data points
C               in Hz
C
C        FC     Is the frequency offset (in Hz) for the filtering
C               of a complex envelope with a carrier freq. of FC
C
C  ARGUMENTS RETURNED TO THE CALLING ROUTINE:
C
C       ARRAY   The complex filtered data array
C
C  FUNCTIONS CALLED BY THIS ROUTINE:
C
C       BUTTER  Function to compute the complex butterworth coefficient
C               given a normalized frequency and the number of poles for
C               the filter
C
C*******************************************************************************

        SUBROUTINE BWLPF(ARRAY,N,POL,F3,FH,FC)

        INTEGER         N,       POL,     ITER
        REAL            F3,      FH,      FC
        COMPLEX         ARRAY(*),         BUTTER

C       If POL = 0 then return to the calling routine (no filtering)
        IF(POL.EQ.0) GOTO 100

C       Filter the complex data array
        DO ITER=1,N/2
           ARRAY(ITER)=ARRAY(ITER)*BUTTER((FLOAT(ITER-1)*FH+FC)
     &             /F3,POL)
           ARRAY(N+1-ITER)=ARRAY(N+1-ITER)*BUTTER(((0.-FLOAT(ITER))
     &                 *FH+FC)/F3,POL)
        END DO


C       Set the nyquist coefficient to zero
        ARRAY(N/2+1)=CMPLX(0.,0.)

100     RETURN
        END


C*******************************************************************************
C
C       BUTTER     (FUNCTION TO CALCULATE THE DISCRETE BUTTERWORTH FILTER
C                   COEFFICIENT FOR A GIVEN NORMALIZE FREQUENCY)
C
C                  PROGRAMMER:  DALE DUBBERT
C
C*******************************************************************************
C
```

```
C  CALLING SEQUENCE:  BUTTER(NFREQ,POL)
C
C  ARGUMENTS SUPPLIED TO THE FUNCTION:
C
C       NFREQ   The ratio of the frequency of interest to
C               the filter 3dB cutoff frequency.
C
C       POL     The number of filter poles. (POL=1,2,3,4 or 5)
C
C  ARGUMENTS RETURNED TO THE CALLING ROUTINE:
C
C       BUTTER  The complex butterworth filter coefficient
C
C*****************************************************************************

        FUNCTION BUTTER(NFREQ,POL)

        INTEGER         ITER,   POL
        REAL            NFREQ
        COMPLEX         BUTTER

C       Compute the butterworth coefficient corrosponding to the number
C       of poles
        GOTO (1,2,3,4,5), POL
1       BUTTER=CMPLX(1.0,NFREQ)
        GOTO 9
2       BUTTER=CMPLX((1.0-NFREQ)**2,1.41421*NFREQ)
        GOTO 9
3       BUTTER=CMPLX(1.0-2.0*NFREQ**2,2.0*NFREQ-NFREQ**3)
        GOTO 9
4       BUTTER=CMPLX(NFREQ**4-3.414*NFREQ**2+1,2.6131*NFREQ-
     &          2.6131*NFREQ**3)
        GOTO 9
5       BUTTER=CMPLX(1.0-5.236*NFREQ**2+3.236*NFREQ**4,
     &          3.236*NFREQ-5.236*NFREQ**3+NFREQ**5)

9       BUTTER=(1.0,0.0)/BUTTER

        RETURN
        END


C*****************************************************************************
C
C       PREEMPH    (SUBROUTINE TO APPLY FM PREEMPHASIS OR DEEMPHASIS TO A
C                   COMPLEX DATA ARRAY AS PER CCIR RECOMMENDATION 405-1)
C
C                  PROGRAMMER:  DALE DUBBERT
C
C*****************************************************************************
C
C  CALLING SEQUENCE:  CALL PREEMPH(ARRAY,N,FH,FC,PRE_DE)
C
C  ARGUMENTS SUPPLIED TO THE SUBROUTINE:
C
C       ARRAY   The complex data array
C
C       N       The size of array
```

```
C
C       FH      The frequency increment between the data points in the array
C               in Hz
C
C       FC      The carrier frequency in Hz for filtering an equivalent low
C               pass signal
C
C       PRE_DE  The preemphasis/deemphasis specifier
C
C                           PRE_DE=0  (PRE-EMPHASIS)
C                           PRE_DE=1  (DE-EMPHASIS)
C                           PRE_DE=-1 (NO FILTERING)
C
C  ARGUMENTS RETURNED TO THE CALLING ROUTINE:
C
C       ARRAY   The complex filtered data array
C
C  ROUTINES CALLED BY THIS ROUTINE:
C
C       PRE     Function to calculate the discrete preemphasis coefficient
C               for a given frequency
C
C       DE      Function to calculate the discrete deemphasis coefficient
C               for a given frequency
C
C*******************************************************************************

        SUBROUTINE PREEMPH(ARRAY,N,FH,FC,PRE_DE)

        INTEGER         N,      ITER,   PRE_DE
        REAL            FH,     FC
        COMPLEX         ARRAY(*),       PRE,    DE

C       Return to the calling routine if no filtering is requested
        IF (PRE_DE .EQ. -1) GOTO 100

C       Apply preemphasis if requested
        IF(PRE_DE.EQ.0)THEN
           DO ITER=1,N/2
              ARRAY(ITER)=ARRAY(ITER)*PRE((FLOAT(ITER-1)*FH+FC))
              ARRAY(N+1-ITER)=ARRAY(N+1-ITER)*PRE((0.-FLOAT(ITER))*
     &                        FH+FC)
           END DO
        ELSE

C       Apply deemphasis if requested
           DO ITER=1,N/2
              ARRAY(ITER)=ARRAY(ITER)*DE((FLOAT(ITER-1)*FH+FC))
              ARRAY(N+1-ITER)=ARRAY(N+1-ITER)*DE((0.-FLOAT(ITER))*
     &                        FH+FC)
           END DO
        END IF

100     RETURN
        END


C*******************************************************************************
C
```

```
C       PRE      (FUNCTION TO CALCULATE THE DISCRETE PREEMPHASIS COEFFICIENTS
C                 FOR A GIVEN FREQUENCY)
C
C                PROGRAMMER:  DALE DUBBERT
C
C*****************************************************************************
C
C  ARGUMENTS SUPPLIED TO THE FUNCTION:
C
C       W        The frequency in Hz
C
C  ARGUMENTS RETURNED TO THE CALLING ROUTINE:
C
C       PRE      The complex preemphasis coefficient
C
C*****************************************************************************

        FUNCTION PRE(W)

        REAL    W,       R,       R1,      R3,      C,      L
        COMPLEX Z1,      Z2,      PRE

C       Convert the frequency to radians/second
        W=2.*3.141593*W

C       Check for W = 0.0
        IF (W .EQ. 0.0) W = 1.0E-30

C       Set the component values for CCIR recommendation 405-1 preemphasis
        R=75.
        R1=275.8
        R3=20.4
        L=17.35E-6
        C=3085.E-12

C       Calculate the preemphasis coefficient
        Z1=R1/CMPLX(1.,W*C*R1)
        Z2=CMPLX(R3,W*L)
        PRE=.25*((2.+R/Z2)*(R/Z1)+1.)/((1.+R/Z1)*(1.+R/Z2))

        RETURN
        END


C*****************************************************************************
C
C       DE     (FUNCTION TO CALCULATE THE DISCRETE DEEMPHASIS COEFFICIENT FOR
C               A GIVEN FREQUENCY)
C
C              PROGRAMMER:  DALE DUBBERT
C
C*****************************************************************************
C
C  ARGUMENTS SUPPLIED TO THE FUNCTION:
C
C       W        The frequency in Hz
C
```

```
C  ARGUMENTS RETURNED TO THE CALLING ROUTINE:
C
C       DE      The complex deemphasis coefficient
C
C*****************************************************************************

        FUNCTION DE(W)

        REAL    W,      R,      R1,     R3,     C,      L
        COMPLEX Z1,Z2,DE

C       Convert the frequency to radians/second
        W = 2.0 * 3.141593 * W

C       Check for W = 0.0
        IF (W .EQ. 0.0) W = 1.0E-30

C       Set the component values for CCIR recommendation 405-1 deemphasis
        R=75.
        R1=275.8
        R3=20.4
        L=50.16E-6
        C=8917.E-12

C       Calculate the deemphasis coefficient
        Z1=R1/CMPLX(1.,-R1/(W*L))
        Z2=CMPLX(R3,-1.0/(W*C))
        DE=.25*((2.+R/Z2)*(R/Z1)+1.)/((1.+R/Z1)*(1.+R/Z2))

        RETURN
        END


C*****************************************************************************
C
C       INTEG    {SUBROUTINE TO INTEGRATE A COMPLEX DATA ARRAY OF DFT
C                 COEFFICIENTS}
C
C                PROGRAMMER:  DALE DUBBERT
C
C*****************************************************************************
C
C  CALLING SEQUENCE:  CALL INTEG(ARRAY,N,FH,FC)
C
C  ARGUMENTS SUPPLIED TO THE SUBROUTINE:
C
C       ARRAY   The complex data array
C
C       N       The array size
C
C       FH      The frequency increment between the data points in Hz
C
C       FC      The carrier frequency in Hz for integrating an equivalent
C               low pass data array
C
C  ARGUMENTS RETURNED TO THE CALLING ROUTINE:
C
C       ARRAY   The complex integrated array
```

```
C
C******************************************************************************
C
C NOTE:  This routine does not change the dc value of the input
C        (ARRAY(1)) where W + WC = 0.0
C
C******************************************************************************

      SUBROUTINE INTEG(ARRAY,N,FH,FC)

      INTEGER          N,      ITER
      REAL             FH,     FC,     WH,     WC,     W
      COMPLEX          ARRAY(*)

C     Calculate the frequencies in radians/second
      WH=2.0 * 3.141593 * FH
      WC=2.0 * 3.141593 * FC

C     Integrate the DFT coefficients
      DO ITER=1,N/2

         W = FLOAT(ITER-1)*WH+WC
         IF (W .NE. 0.0) THEN
            ARRAY(ITER)=ARRAY(ITER)/CMPLX(0.,W)
         END IF

         W = -FLOAT(ITER)*WH+WC
         IF (W .NE. 0.0) THEN
            ARRAY(N+1-ITER)=ARRAY(N+1-ITER)/CMPLX(0.,W)
         END IF

      END DO

      RETURN
      END


C******************************************************************************
C
C     ERRFUNC    (SUBROUTINE TO IMPLEMENT THE ERROR TRANSFER FUNCTION
C                 OF A SECOND ORDER LINEAR PHASE LOCKED LOOP)
C
C                PROGRAMMER:  DALE DUBBERT
C
C******************************************************************************
C
C  CALLING SEQUENCE:  CALL ERRFUNC (ARRAY,N,FH,FC,DAMP,FN,T1)
C
C  ARGUMENTS SUPPLIED TO THE SUBROUTINE:
C
C     ARRAY  The complex data array representing the PLL phase input DFT
C            coefficients
C
C     N      The size of the complex array
C
C     FH     The frequency increment between the data points in Hz
C
C     FC     The carrier frequency in Hz for filtering an equivalent low
```

```
C               pass signal
C
C       DAMP    The   damping coefficient of the 2nd order PLL linear model
C
C       FN      The natural frequency of the PLL model in MHz
C
C       T1      The pole time constant of the loop filter in nanoseconds
C
C  ARGUMENTS RETURNED TO THE CALLING ROUTINE:
C
C       ARRAY   The DFT coefficients representing the PLL phase error
C
C*****************************************************************************

        SUBROUTINE ERRFUNC (ARRAY,N,FH,FC,DAMP,FN,T1)

        COMPLEX ARRAY(*)
        INTEGER N,      I
        REAL    FH,     FC,     DAMP,   FN,     T1
        REAL    WH,     WC,     WN,     T,      W

C       Convert the external parameters to their internal values
        WH = 2.0 * 3.141593 * FH
        WC = 2.0 * 3.141593 * FC
        WN = 2.0 * 3.141593 * FN * 1.0E6
        T  = T1 * 1.0E-9

C       Implement the error function on the complex array
        DO I = 1,N/2

           W = FLOAT(I - 1) * WH + WC
           ARRAY(I) = ARRAY(I) * CMPLX (-W**2 , W / T) /
     &                CMPLX(WN**2 - W**2 , 2.0 * DAMP * WN * W)

           W = -FLOAT(I) * WH + WC
           ARRAY(N+1-I) = ARRAY(N+1-I) * CMPLX (-W**2 , W / T) /
     &                CMPLX(WN**2 - W**2 , 2.0 * DAMP * WN * W)

        END DO

        RETURN
        END




C****************************************************************************
C
C
C       VAX-11 FORTRAN SOURCE FILENAME:         NTSCAUX.FOR
C
C       DEPARTMENT OF ELECTRICAL ENGINEERING    KANSAS STATE UNIVERSITY
C
C       REVISION        DATE                    PROGRAMMER(S)
C       --------        ----                    -------------
C        4.0            4/26/86                 DALE DUBBERT
C
C       PROJECT:  MS REPORT;  RMS PHASE ERROR OF A SECOND ORDER PHASE
```

```
C                                   LOCKED LOOP EMPLOYED AS A SATELLITE FM
C                                   VIDEO DEMODULATOR.
C
C*****************************************************************************
C
C  AUXILIARY SUBROUTINES FOR THE NTSC PHASE ERROR SIMULATION:
C
C     DATA STORAGE AND RETRIEVAL:
C
C        FIGET
C        FISTORE
C
C     MENU GENERATORS:
C
C        MENGET
C        MENGEN
C        MENNXT1
C        MENFMPLL
C        MENNXT2
C
C     PARAMETER STORAGE AND RETRIEVAL:
C
C        GETPARA
C        SHOWPARA
C        STOREPARA
C
C     MISC:
C
C        DATSTAT
C        PHAERROR
C        WAIT_RET
C
C*****************************************************************************


C*****************************************************************************
C
C        DATSTAT       (SUBROUTINE TO COMPUTE THE MAXIMUM, MINIMUM AND THE
C                       AVERAGE VALUE OF A REAL DATA ARRAY)
C
C*****************************************************************************
C
C  CALLING SEQUENCE:  CALL DATSTAT (ARRAY,N,MAX,MIN,AVE)
C
C  ARGUMENTS SUPPLIED TO THE SUBROUTINE:
C
C        ARRAY   The real data array
C
C        N       The length of the data array
C
C  ARGUMENTS RETURNED TO THE CALLING ROUTINE:
C
C        MAX     The maximum value in the array
C
C        MIN     The minimum value in the array
C
C        AVE     The average value of the array
C
C******************************************************************************
```

```fortran
      SUBROUTINE DATSTAT(ARRAY,N,MAX,MIN,AVE)

      INTEGER N,ITER
      REAL ARRAY(*),MAX,MIN,AVE

      MAX=ARRAY(1)
      MIN=ARRAY(1)
      AVE=ARRAY(1)

      DO ITER=2,N
         IF(ARRAY(ITER).GT.MAX) MAX=ARRAY(ITER)
         IF(ARRAY(ITER).LT.MIN) MIN=ARRAY(ITER)
         AVE=AVE+ARRAY(ITER)
      END DO

      AVE=AVE/FLOAT(N)

      RETURN
      END

C******************************************************************************
C
C PHAERROR    (SUBROUTINE TO CALCULATE THE RMS PHASE ERROR OF THE LINEAR PLL
C              GIVEN THE CHROMINANCE AND LUMINANCE PHASE ERROR DFT
C              COEFFICIENTS)
C
C******************************************************************************
C
C  CALLING SEQUENCE:  CALL PHAERROR
C
C  NOTE:  ALL ARGUMENTS ARE PASSED THROUGH THE COMMON AREA NTSCCOM.FOR
C
C******************************************************************************

      SUBROUTINE PHAERROR

      INCLUDE 'NTSCCOM.FOR'

C     IDFT the error coefficients
      CALL DFT (ERRLUM,N,1)
      CALL DFT (ERRCHR,N,1)

C     Compute the phase error from the ERRLUM and ERRCHR time coefficients
      RMSERROR = 0.0
      DO I = 1,N
         RMSERROR = RMSERROR + 0.5 * CABS(ERRCHR(I))**2 +
     &                               CABS(ERRLUM(I))**2
      END DO
      RMSERROR = SQRT(RMSERROR/FLOAT(N))

C     DFT the error coefficients
      CALL DFT (ERRLUM,N,0)
      CALL DFT (ERRCHR,N,0)

      RETURN
      END
```

```
C*****************************************************************************
C
C       FISTORE    (SUBROUTINE TO STORE A DATA ARRAY TO AN EXTERNAL FILE)
C
C*****************************************************************************
C
C  CALLING SEQUENCE:  CALL FISTORE(DEFAULT,NUM,TYPE,VECTOR)
C
C  PARAMETERS SUPPLIED TO THE SUBROUTINE:
C
C       DEFAULT          The default file name which is used if the user
C                        specifies no file name (character)
C
C       NUM              The number of data elements in the array (integer)
C
C       TYPE             The array type ('REAL' or 'COMPLEX')
C
C       VECTOR           The internal data array
C
C  PARAMETERS RETURNED TO THE CALLING ROUTINE:
C
C       NONE
C
C*****************************************************************************
C
C  SUBROUTINES CALLED BY THIS ROUTINE:
C
C      SGOPEN:  Routine to open an external file for data storage
C               or retrieval
C
C      SGTRAN:  Routine to transfer data between an external file
C               and an internal array
C
C*****************************************************************************

        SUBROUTINE FISTORE(DEFAULT,NUM,TYPE,VECTOR)

        INTEGER          NUM
        CHARACTER*15     FINAME
        CHARACTER*(*)    DEFAULT,        TYPE
        REAL             VECTOR(*)

C       Prompt for entry of and read the data file name

        TYPE*,'ENTER THE FILE NAME (15 CHARACTERS MAX)'
        TYPE111, DEFAULT
111     FORMAT (T2,'THE DEFAULT IS ',A,' ----> ',$)
        READ (6,5) FINAME
5       FORMAT (A15)

C       Use default file name if no name is specified by the user

        IF(FINAME.EQ.'               ') FINAME=DEFAULT

C       Check for valid data type.  if type not valid then print
C       an error message and return to the calling routine.

        IF(TYPE.EQ.'COMPLEX'.OR.TYPE.EQ.'REAL')GOTO 50
        TYPE*,'****INVALID DATA TYPE***'
```

```
        TYPE*,'*****NO FILES READ******'
        GOTO 40

C       Open the external data file and store the data array

50      CALL SGOPEN(1,'WRITE','NOPROMPT',FINAME,TYPE,NUM)
        CALL SGTRAN(1,'WRITE',TYPE,VECTOR,NUM)

C       Display the file name, type and the number of data elements

        TYPE10,FINAME,TYPE,NUM
10      FORMAT(' THE ',A,' FILE IS ',A,' AND HAS ',I5,' ELEMENTS')

40      RETURN
        END


C***************************************************************************
C
C       FIGET    (SUBROUTINE TO RETRIEVE A DATA ARRAY FROM AN EXTERNAL FILE)
C
C***************************************************************************
C
C  CALLING SEQUENCE:  CALL FIGET (DEFAULT,NUM,TYPE,VECTOR)
C
C  PARAMETERS SUPPLIED TO THE SUBROUTINE:
C
C       DEFAULT         The default file name which is used if the user
C                       specifies no file name (character)
C
C  PARAMETERS RETURNED TO THE CALLING ROUTINE:
C
C       NUM             The number of data elements in the array (integer)
C
C       TYPE            The array type ('REAL' or 'COMPLEX')
C
C       VECTOR          The internal data array
C
C***************************************************************************
C
C  SUBROUTINES CALLED BY THIS ROUTINE:
C
C      SGOPEN:  Routine to open an external file for data storage
C               or retrieval
C
C      SGTRAN:  Routine to transfer data between an external file
C               and an internal array
C
C***************************************************************************

        SUBROUTINE FIGET(DEFAULT,NUM,TYPE,VECTOR)

        INTEGER NUM
        CHARACTER*15 FINAME
        CHARACTER*(*) DEFAULT,TYPE
        REAL VECTOR(*)

C       Prompt for entry of and read the data file name
```

```
      TYPE*,'ENTER THE FILE NAME (15 CHARACTERS MAX)'
      TYPE111, DEFAULT
111   FORMAT (T2,'THE DEFAULT IS ',A,' ----> ',$)
      READ (6,5) FINAME
5     FORMAT (A15)

C     Use default file name if no name is specified by the user

      IF(FINAME.EQ.'               ') FINAME = DEFAULT

C     Open and read the external data file

      CALL SGOPEN(1,'READ','NOPROMPT',FINAME,TYPE,NUM)
      CALL SGTRAN(1,'READ',TYPE,VECTOR,NUM)

C     Display the file name, type and number of data elements read

      TYPE10,FINAME,TYPE,NUM
10    FORMAT(' THE ',A,' FILE IS ',A,' AND HAS ',I5,' ELEMENTS')

      RETURN
      END


C******************************************************************************
C
C     MENGET   (SUBROUTINE TO GENERATE THE MENU FOR SELECTION OF THE SOURCE
C               OF THE DFT COEFFICIENTS FOR THE PHASE ERROR SIMULATION)
C
C******************************************************************************
C
C  CALLING SEQUENCE:  CALL MENGET
C
C******************************************************************************

      SUBROUTINE MENGET(CHOICE)

      INTEGER CHOICE
      INTEGER*4 STATUS

C     Output the menu to the terminal

      STATUS = LIB$ERASE_PAGE(1,1)

      TYPE*,'MENU:  GET NTSC COEFFICIENTS'
      TYPE*,' '
      TYPE*,'1.  GENERATE THE NTSC DFT COEFFICIENTS'
      TYPE*,'2.  RECALL STORED DFT COEFFICIENTS'
      TYPE*,' '
100   TYPE111
111   FORMAT (T2,'ENTER SELECTION ----> ',$)

C     Read the menu selection and return to the calling routine if
C     the menu selection is valid
      READ (6,1) CHOICE
1     FORMAT (I2)
```

```
      IF (CHOICE.LT.1.OR.CHOICE.GT.2) THEN
         TYPE*,' INVALID SELECTION, TRY AGAIN'
         GOTO 100
      END IF

      RETURN
      END


C***********************************************************************
C
C     MENGEN   (SUBROUTINE TO DISPLAY AND EDIT THE NTSC COLOR BAR GENERATOR
C               AND PREEMPHASIS PARAMETERS)
C
C***********************************************************************
C
C  CALLING SEQUENCE:  CALL MENGEN
C
C  NOTE:  ALL PARAMETERS ARE PASSED THROUGH THE COMMON AREA NTSCCOM.FOR
C
C***********************************************************************

      SUBROUTINE MENGEN

      INCLUDE 'NTSCCOM.FOR'

      INTEGER PENTRY,CHOICE
      REAL RENTRY
      CHARACTER*1 CHENTRY

C     Display the ntsc generator parameter menu and prompt the
C     user for a selection

100   STATUS = LIB$ERASE_PAGE(1,1)

      TYPE*,' MENU:  NTSC SIGNAL GENERATOR PARAMETER SELECTION'
      TYPE*,' '
      TYPE1,' 1.  # OF POLES FOR Y LUMINANCE SIGNAL   =',YPOL
      TYPE1,' 2.  # OF POLES FOR Q CHROMINANCE SIGNAL =',QPOL
      TYPE1,' 3.  # OF POLES FOR I CHROMINANCE SIGNAL =',IPOL
1     FORMAT(A,3X,I1)
      TYPE2,' 4.  BANDWIDTH FOR Y LUMINANCE FILTER    =',YCUT,'MHz'
      TYPE2,' 5.  BANDWIDTH FOR Q CHROMINANCE FILTER  =',QCUT,'MHz'
      TYPE2,' 6.  BANDWIDTH FOR I CHROMINANCE FILTER  =',ICUT,'MHz'
2     FORMAT(A,1X,F7.3,1X,A)
      TYPE3,' 7.  CCIR 405-1 PREEMPHASIS? (Y/N)       =',PREFLG
3     FORMAT(A,3X,A)
      TYPE4,' 8.  PERCENTAGE COLOR SATURATION         =',PERSAT,'%'
4     FORMAT(A,1X,F7.3,1X,A)
      TYPE*,' '
      TYPE111
111   FORMAT (T2,'ENTER SELECTION, <RETURN> TO CONTINUE ----> ',$)

200   READ (6,10) CHOICE
10    FORMAT(I1)

C     Check for out of range selection
C     If out of range then read keyboard again
```

```
      IF (CHOICE.LT.0.OR.CHOICE.GT.8) THEN
         TYPE*,' INVALID SELECTION, TRY AGAIN'
         GOTO 200
      END IF

C=======================================================================
C
C     MENU SELECTIONS 1,2 OR 3:  CHANGE A POLE SPECIFICATION
C
C=======================================================================

      IF (CHOICE.GE.1.AND.CHOICE.LE.3) THEN
         TYPE*,'ENTER NUMBER OF POLES (1 TO 5, 0 = NO FILTERING)'
         TYPE112
112      FORMAT (T2,'----> ',$)
250      READ (6,20) PENTRY
20       FORMAT (I1)

C        Check for out of range pole specification
C        If out of range, then read keyboard again
         IF (PENTRY.LT.0.OR.PENTRY.GT.5) THEN
            TYPE*,' OUT OF RANGE, VALID ENTRY = 0 TO 5'
            GOTO 250
         END IF

C        Set the proper pole parameter to the value entered
         IF (CHOICE.EQ.1) YPOL = PENTRY
         IF (CHOICE.EQ.2) QPOL = PENTRY
         IF (CHOICE.EQ.3) IPOL = PENTRY

C        Return to the parameter menu display
         GOTO 100

      END IF

C=======================================================================
C
C     MENU SELECTIONS 4,5 OR 6:  CHANGE A FILTER BANDWIDTH SPECIFICATION
C
C=======================================================================

      IF (CHOICE.GE.4.AND.CHOICE.LE.6) THEN
         TYPE113
113      FORMAT (T2,'ENTER THE BANDWIDTH IN MHz ----> ',$)
         READ (6,*) RENTRY
         RENTRY = ABS(RENTRY)

C     Set the corresponding bandwidth parameter to the entry
C     value
         IF (CHOICE.EQ.4) YCUT = RENTRY
         IF (CHOICE.EQ.5) QCUT = RENTRY
         IF (CHOICE.EQ.6) ICUT = RENTRY

C     Return to the parameter menu
         GOTO 100

      END IF

C=======================================================================
C
```

```
C       MENU SELECTION 7:  CHANGE THE PREEMPHASIS REQUEST FLAG
C
C===========================================================================

        IF (CHOICE.EQ.7) THEN
           TYPE114
114        FORMAT (T2,'APPLY PREEMPHASIS? (Y/N) ----> ',$)
300        READ (6,40) CHENTRY
40         FORMAT (A)

C          Check for invalid entry
C          If invalid then read the keyboard again
           IF (CHENTRY.NE.'Y'.AND.CHENTRY.NE.'N'.AND.CHENTRY.NE.'y'
     &         .AND.CHENTRY.NE.'n') THEN
              TYPE*,' INVALID ENTRY, ENTER ''Y'' OR ''N'''
              GOTO 300
           END IF

C          Set the preemphasis flag to its proper upper case value
           IF (CHENTRY.EQ.'Y'.OR.CHENTRY.EQ.'y') PREFLG = 'Y'
           IF (CHENTRY.EQ.'N'.OR.CHENTRY.EQ.'n') PREFLG = 'N'

C          Return to the parameter menu
           GOTO 100

        END IF

C===========================================================================
C
C       MENU SELECTION 8:  CHANGE THE PERCENTAGE COLOR SATURATION
C
C===========================================================================

        IF (CHOICE.EQ.8) THEN
           TYPE*,'ENTER THE PERCENTAGE SATURATION (0. TO 200.)'
           TYPE115
115        FORMAT (T2,'----> ',$)
350        READ (6,*) RENTRY
           RENTRY = ABS(RENTRY)

C          Check for out of range entry
C          If entry is out of range then read the keyboard again
           IF (RENTRY.GT.200.) THEN
              TYPE*,'ENTRY OUT OF RANGE, TRY AGAIN'
              GOTO 350
           END IF

C          Set the percentage saturation to the value entered
           PERSAT = RENTRY

C          Return to the parameter menu
           GOTO 100

        END IF

C===========================================================================
C
C       RETURN TO THE CALLING ROUTINE IF SELECTION = 0
C
C===========================================================================
```

```
      IF (CHOICE.EQ.0) RETURN

      END

C*****************************************************************************
C
C     MENNXT1     (SUBROUTINE TO DISPLAY THE MENU FOR THE NEXT ACTION
C                  AFTER GENERATING THE CHROMINANCE AND LUMINANCE DFT
C                  COEFFICIENTS)
C
C*****************************************************************************
C
C  CALLING SEQUENCE: CALL MENNXT1 (CHOICE)
C
C  ARGUMENT SUPPLIED TO THE CALLING ROUTINE:
C
C     CHOICE      The integer menu selection
C
C*****************************************************************************

      SUBROUTINE MENNXT1 (CHOICE)

      INTEGER CHOICE

C     Display the menu
      TYPE*,'MENU:  GENERATE VIDEO SIGNALS'
      TYPE*,' '
      TYPE*,'1.  GENERATE THE TIME DOMAIN VIDEO SIGNAL'
      TYPE*,'2.  GENERATE THE LOG MAGNITUDE SPECTRA OF THE VIDEO SIGNAL'
      TYPE*,'3.  STORE THE CURRENT NTSC PARAMETERS (NTSCPARA.TXT)'
      TYPE*,'4.  RESTART THE PROGRAM'
      TYPE*,' '
      TYPE*,'ENTER SELECTION OR PRESS <RETURN> TO CONTINUE WITH THE PHASE'
      TYPE111
111   FORMAT (T2,'ERROR SIMULATION ----> ',$)

10    READ(6,1) CHOICE
1     FORMAT(I2)

C     Check for out of bounds entry
      IF (CHOICE .LT. 0 .OR. CHOICE .GT. 4) THEN
         TYPE*,'INVALID SELECTION, TRY AGAIN'
         GOTO 10
      END IF

      RETURN
      END

C*****************************************************************************
C
C     MENFMPLL     (SUBROUTINE TO GENERATE THE MENU TO EDIT THE FM
C                   TRANSMITTER AND PLL DEMODULATOR PARAMETERS)
C
C*****************************************************************************
C
C   CALLING SEQUENCE:  CALL MENFMPLL
```

```
C
C   NOTE:  ALL PARAMETERS ARE PASSED THROUGH THE COMMON AREA NTSCCOM.FOR
C
C*****************************************************************************
        SUBROUTINE MENFMPLL

        INCLUDE 'NTSCCOM.FOR'

        INTEGER CHOICE

C       Display the menu
100     STATUS = LIB$ERASE_PAGE(1,1)

        TYPE*,'MENU:  FM MODULATOR (VCO) / DEMODULATOR (PLL) PARAMETERS'
        TYPE*,' '
        TYPE1,' VIDEO STATUS:  MAXIMUM = ',MAX
1       FORMAT (A,F10.4)
        TYPE1,'                MINIMUM = ',MIN
        TYPE1,'                AVERAGE = ',AVE

        TYPE*,' '
        TYPE*,'FM MODULATOR (VCO)'
        TYPE*,'------------------'

        TYPE2,' 1.  PEAK FREQUENCY DEVIATION  = ',FMPKDEV,' MHz'
2       FORMAT (A,F10.4,A)

        TYPE2,' 2.  MODULATION INDEX Km       = ',KM     ,' MHz/volt'

        TYPE*,' '
        TYPE*,'FM DEMODULATOR (LINEAR PLL)'
        TYPE*,'---------------------------'

        TYPE3,' DEPENDENT PARAMETERS:  NATURAL FREQ. Fn  = ',FN,' MHz'
3       FORMAT (A,F10.4,A)

        TYPE4,'                        DAMPING    FACTOR = ',DAMP
4       FORMAT (A,F10.5)

        TYPE*,' '
        TYPE5,' 3.  POLE TIME CONSTANT T1     = ',T1     ,' nsec'
5       FORMAT (A,F10.5,A)

        TYPE5,' 4.  ZERO TIME CONSTANT T2     = ',T2     ,' nsec'

        TYPE6,' 5.  OPEN LOOP GAIN KdKv       = ',KDKV   ,' 1/sec'
6       FORMAT (A,E10.4,A)

        TYPE*,' '
        TYPE*,'ENTER SELECTION OR <RETURN> TO CONTINUE WITH '
        TYPE116
116     FORMAT (T2,'THE PHASE ERROR CALCULATION ----> ',$)

20      READ (6,10) CHOICE
10      FORMAT (I2)

C       Check for an out of range selection

        IF (CHOICE .LT. 0 .OR. CHOICE .GT. 5) THEN
```

```
            TYPE*,'INVALID SELECTION, TRY AGAIN'
            GOTO 20
         END IF

C==========================================================================
C
C        MENU SELECTION #1:  CHANGE THE PEAK FREQUENCY DEVIATION
C
C==========================================================================
         IF (CHOICE .EQ. 1) THEN

            TYPE*,'ENTER THE PEAK FREQUENCY DEVIATION (MHz)'
            TYPE117
117         FORMAT (T2,'----> ',$)
            READ (6,*) FMPKDEV

C           Calculate KM in MHz/volt
            KM = 2.0 * FMPKDEV / (MAX - MIN)

            GOTO 100

         END IF

C==========================================================================
C
C        MENU SELECTION #2:  CHANGE THE MODULATION INDEX Km
C
C==========================================================================
         IF (CHOICE .EQ. 2) THEN

            TYPE118
118         FORMAT (T2,'ENTER Km (MHz/volt) ----> ',$)
            READ (6,*) KM

C           Calculate the peak deviation in MHz
            FMPKDEV = KM * (MAX - MIN) / 2.0

            GOTO 100

         END IF

C==========================================================================
C
C        MENU SELECTION #3:  CHANGE THE POLE TIME CONSTANT T1
C
C==========================================================================
         IF (CHOICE .EQ. 3) THEN

            TYPE119
119         FORMAT (T2,'ENTER T1 (nsec) ----> ',$)
            READ (6,*) T1

C           Calculate Fn (MHz), Wn (rad/sec), and the dampening factor
            WN = SQRT (KDKV / (T1 * 1.0E-9))
            FN = WN / (2.0 * PI * 1.0E6)
            DAMP = 0.5 * (1.0 + KDKV * T2 * 1.0E-9) / SQRT (KDKV * T1
     &            * 1.0E-9)

            GOTO 100
```

```
      END IF
C=========================================================================
C
C     MENU SELECTION #4:  CHANGE THE ZERO TIME CONSTANT T2
C
C=========================================================================
      IF (CHOICE .EQ. 4) THEN

         TYPE120
120      FORMAT (T2,'ENTER T2 (nsec) ----> ',$)
         READ (6,*) T2

C        Calculate the dampening factor
         DAMP = 0.5 * (1.0 + KDKV * T2 * 1.0E-9) / SQRT (KDKV * T1
     &          * 1.0E-9)

         GOTO 100

      END IF

C=========================================================================
C
C     MENU SELECTION #5:  CHANGE THE OPEN LOOP GAIN KdKv
C
C=========================================================================
      IF (CHOICE .EQ. 5) THEN

         TYPE121
121      FORMAT (T2,'ENTER KdKv (1/sec) ---> ',$)
         READ (6,*) KDKV

C        Calculate Fn (MHz), Wn (rad/sec), and the dampening factor
         WN = SQRT (KDKV / (T1 * 1.0E-9))
         FN = WN / (2.0 * PI * 1.0E6)
         DAMP = 0.5 * (1.0 + KDKV * T2 * 1.0E-9) / SQRT (KDKV * T1
     &          * 1.0E-9)

         GOTO 100

      END IF

C=========================================================================
C
C     <RETURN> ENTERED
C
C=========================================================================

      RETURN
      END


C*************************************************************************
C
C     MENNXT2    (SUBROUTINE TO DISPLAY THE MENU FOR THE NEXT ACTION
C                 AFTER THE RMS PHASE ERROR CALCULATION)
C
C*************************************************************************
C
```

```
C   CALLING SEQUENCE:  CALL MENNXT2 (CHOICE)
C
C   ARGUMENT RETURNED TO THE CALLING ROUTINE:
C
C       CHOICE     The user menu selection (integer)
C
C******************************************************************************

        SUBROUTINE MENNXT2 (CHOICE)

        INTEGER CHOICE

C       Display the menu
        STATUS = LIB$ERASE_PAGE(1,1)

        TYPE*,'MENU:  DISPLAY PHASE, FM SPECTRA AND DEMODULATED'
        TYPE*,'       SIGNAL'
        TYPE*,' '
        TYPE*,'1.  GENERATE THE PLL INPUT PHASE SIGNAL'
        TYPE*,'2.  GENERATE THE PLL INPUT FM SPECTRA'
        TYPE*,'3.  GENERATE THE PLL DEMODULATED SIGNAL'
        TYPE*,'4.  SELECT NEW FM MODULATOR / PLL PARAMETERS'
        TYPE*,'5.  SELECT NEW NTSC SIGNAL GENERATOR PARAMETERS'
        TYPE*,'6.  STORE THE CURRENT PARAMETERS (NTSCPARA.TXT)'
        TYPE*,'7.  RECALL THE STORED NTSC PARAMETERS (NTSCPARA.TXT)'
        TYPE*,'8.  DISPLAY THE STORED NTSC PARAMETERS (NTSCPARA.TXT)'
        TYPE*,' '
        TYPE122
122     FORMAT (T2,'ENTER SELECTION OR <RETURN> TO QUIT ----> ',$)

10      READ (6,1) CHOICE
1       FORMAT (I2)

C       Check for an out of range entry
        IF (CHOICE .LT. 0 .OR. CHOICE .GT. 8) THEN
           TYPE*,'INVALID SELECTION, TRY AGAIN'
           GOTO 10
        END IF

        RETURN
        END


C******************************************************************************
C
C       WAIT_RET    (SUBROUTINE TO WAIT UNTIL THE USER HITS <RETURN>)
C
C******************************************************************************
C
C   CALLING SEQUENCE:  CALL WAIT_RET
C
C******************************************************************************

        SUBROUTINE WAIT_RET

        CHARACTER*1 DUMMY

        TYPE111
111     FORMAT (T2,'PRESS <RETURN> TO CONTINUE',$)
```

```
      READ(6,1) DUMMY
1     FORMAT(A1)

      RETURN
      END



C*************************************************************************
C
C     SHOWPARA     (SUBROUTINE TO TYPE THE NTSC PARAMETER FILE (NTSCPARA.TXT)
C                   ON THE SCREEN)
C
C*************************************************************************
C
C  CALLING SEQUENCE:  CALL SHOWPARA
C
C************************************************************************

      SUBROUTINE SHOWPARA

      CHARACTER*1 DUMMY
      CHARACTER*80 LINE(22)

C     Open the parameter text file
      OPEN (UNIT=1,STATUS='OLD',FILE='NTSCPARA.TXT')

C     Read the text in the file 'NTSCPARA.TXT'
      REWIND (UNIT=1)

      DO I = 1,22
         READ(1,1) LINE(I)
1        FORMAT (T1,A80)
      END DO

C     Clear the screen and output the text
      STATUS=LIB$ERASE_PAGE(1,1)

      DO I = 1,22
         TYPE2,LINE(I)
2        FORMAT (X,A80)
      END DO

C     Close the text file
      CLOSE (UNIT = 1)

C     Prompt for a <RETURN> to continue
      TYPE3
3     FORMAT (T2,'PRESS <RETURN> TO CONTINUE',$)
      READ (6,4) DUMMY
4     FORMAT (A1)

      RETURN
      END
```

```
C*****************************************************************************
C
C       GETPARA     {SUBROUTINE TO READ THE DEFAULT NTSC PARAMETERS FROM
C                    THE NTSCPARA.TXT FILE}
C
C*****************************************************************************
C
C  CALLING SEQUENCE:  CALL GETPARA
C
C  NOTE:  ALL PARAMETERS ARE PASSED THROUGH THE COMMON AREA NTSCCOM.FOR
C
C*****************************************************************************

        SUBROUTINE GETPARA

        INCLUDE 'NTSCCOM.FOR'

C       Open the text file
        OPEN (UNIT=1,STATUS='OLD',FILE='NTSCPARA.TXT')

C       Read the ntsc generator parameters
        REWIND (UNIT=1)
        READ(1,10) YCUT,QCUT,ICUT,YPOL,QPOL,IPOL,PREFLG,PERSAT
10      FORMAT (////////,T3,3(F7.4,3X),T34,3(I1,6X),T58,A1,T70,F7.3)

C       Read the fm modulator parameters
        READ(1,11) FMPKDEV,KM
11      FORMAT (/////,T14,F7.3,T54,F7.3)

C       Read the pll demodulator parameters
        READ(1,12) KDKV,T1,T2,FN,DAMP
12      FORMAT (/////,T7,E10.4,T21,F9.3,T33,F9.3,T44,F9.3,T59,F8.5)

C       Calculate WN in rad/sec
        WN = 2.0 * PI * FN * 1.0E6

C       Close the text file
        CLOSE (UNIT = 1)

        RETURN
        END



C***************************************************************************
C
C       STOREPARA     {SUBROUTINE TO WRITE THE CURRENT NTSC PARAMETERS TO
C                      THE NTSCPARA.TXT FILE}
C
C***************************************************************************
C
C  CALLING SEQUENCE:  CALL STOREPARA
C
```

```
C  NOTE:  ALL PARAMETERS ARE PASSED THROUGH THE COMMON AREA NTSCCOM.FOR
C
C*****************************************************************************

        SUBROUTINE STOREPARA

        INCLUDE 'NTSCCOM.FOR'

        CHARACTER*80 LINE(22)

C       Open the old parameter file and read the text
        OPEN (UNIT=1,STATUS='OLD',FILE='NTSCPARA.TXT')
        REWIND (UNIT = 1)
        DO I = 1,22
           READ(1,1) LINE(I)
1          FORMAT (T1,A80)
        END DO

C       Close the old parameter file and open a new version
        CLOSE (UNIT = 1)
        OPEN (UNIT=1,STATUS='NEW',FILE='NTSCPARA.TXT')

C       Output the text and the parameter values to the new file
        DO I = 1,8
           WRITE(1,50) LINE(I)
50         FORMAT (T1,A)
        END DO

        WRITE (1,51) '|',YCUT,'|',QCUT,'|',ICUT,'|',YPOL,'|',
     &               QPOL,'|',IPOL,'|',PREFLG,'|',PERSAT,'|'
51      FORMAT (T1,A,T3,F7.4,T11,A,T13,F7.4,T21,A,T23,F7.4,T31,A,T34,I1,
     &      T38,A,T41,I1,T45,A,T48,I1,T52,A,T58,A,T66,A,T70,F7.3,T79,A)

        DO I = 10,14
           WRITE(1,50) LINE(I)
        END DO

        WRITE (1,52) '|',FMPKDEV,'|',KM,'|'
52      FORMAT (T1,A,T14,F7.3,T39,A,T54,F7.3,T79,A)

        DO I = 16,20
           WRITE(1,50) LINE(I)
        END DO

        WRITE (1,53) '|',KDKV,'|',T1,'|',T2,'|',FN,'|',DAMP,'|'
53      FORMAT (T4,A,T7,E10.4,T19,A,T21,F9.3,T31,A,T33,F9.3,T43,A,
     &        T44,F9.3,T54,A,T59,F8.5,T73,A)

        WRITE(1,50) LINE (22)

C       Close the file
        CLOSE (UNIT = 1)

        RETURN
        END
```

NTSCPARA.TXT

NTSC COLOR BAR GENERATOR

VIDEO FILTERS						PREEMPHASIS FLAG (Y/N)	PERCENT COLOR SATURATION
Cutoff Frequency (MHz)			# of Poles				
y(t)	q(t)	i(t)	y(t)	q(t)	i(t)		
4.2000	0.5000	1.5000	3	3	3	Y	100.000

FM TRANSMITTER (VCO)

PEAK FREQUENCY DEVIATION (MHz)	MODULATION INDEX Km (MHz/volt)
10.700	36.507

FM DEMODULATOR (LINEAR PLL MODEL)

KdKv (1/sec)	T1 (nsec)	T2 (nsec)	Fn (MHz)	Damping Factor
0.2310E+09	26.005	10.670	15.000	0.70682

Appendix 2. Program Operating Instructions

PROGRAM OPERATING INSTRUCTIONS FOR THE NTSC PLL PHASE ERROR SIMULATION

Program Description

The PLL phase error simulation program was written to perform the data generation, calculations and signal processing necessary to evaluate the performance of a second order PLL operating as an FM demodulator for standard NTSC video. The program was written in VAX-11 FORTRAN and structured primarily as a menu driven routine. Once the user understands the theory and the process for obtaining the phase error and related information, then the program operation is relatively straight forward.

Running the Simulation Program

The source code for the simulation is located in the following files:

NTSC.FOR
NTSCCOM.FOR
NTSCFIL.FOR
NTSCGEN.FOR
NTSCAUX.FOR

The text file which contains the default system parameters is

NTSCPARA.TXT

The program can be compiled and linked using the following VAX/VMS commands:

```
FORTRAN NTSC,NTSCFIL,NTSCGEN,NTSCAUX
LINK NTSC,NTSCFIL,NTSCGEN,NTSCAUX
```

To execute the program, enter:

```
RUN NTSC
```

The program will then display a series of command and parameter menus which control the execution of the simulation.

Menu Descriptions

The following menus are displayed in the order of appearance during execution of the program. A sequential flow of the program is achieved by using the <RETURN> key after each menu. Certain menus, however, provide the user with the capability of accessing previous menus for situations where multiple phase error or data calculations are required.

Generating the NTSC Test Signal

The first menu asks the user to specify the source of the DFT coefficients for the chrominance and luminance components of the simulation test signal.

```
MENU:  GET NTSC COEFFICIENTS

1.  GENERATE THE NTSC DFT COEFFICIENTS
2.  RECALL STORED DFT COEFFICIENTS

ENTER SELECTION ---->
```

A selection of #1 allows the user to specify the parameters for the NTSC color bar pattern generator routine. The NTSC parameter menu is as follows:

```
MENU:  NTSC SIGNAL GENERATOR PARAMETER SELECTION

1.  # OF POLES FOR Y LUMINANCE SIGNAL     =   3
2.  # OF POLES FOR Q CHROMINANCE SIGNAL =   3
3.  # OF POLES FOR I CHROMINANCE SIGNAL =   3
4.  BANDWIDTH FOR Y LUMINANCE FILTER     =   4.200 MHz
5.  BANDWIDTH FOR Q CHROMINANCE FILTER  =   0.500 MHz
6.  BANDWIDTH FOR I CHROMINANCE FILTER  =   1.500 MHz
7.  CCIR 405-1 PREEMPHASIS? (Y/N)        =   Y
8.  PERCENTAGE COLOR SATURATION          = 100.000 %

ENTER SELECTION, <RETURN> TO CONTINUE ---->
```

The initial defaults for this menu are located in the NTSCPARA.TXT file. Once the desired parameter values have been selected, the user hits <RETURN> to generate the NTSC test signal. The program then responds with:

```
GENERATING THE NTSC COEFFICIENTS
```

The generated chrominance and luminance files may be stored on disk if the user so desires. The following prompts and entries are for storage of the coefficients in the default files LUM.DAT and CHR.DAT:

```
STORE THE DFT COEFFICIENTS? (Y/N) -----> Y

STORE THE LUMINANCE DFT COEFFICIENTS (l(w))
ENTER THE FILE NAME (15 CHARACTERS MAX)
THE DEFAULT IS LUM.DAT ---->
THE LUM.DAT          FILE IS COMPLEX AND HAS  1024 ELEMENTS

STORE THE CHROMINANCE DFT COEFFICIENTS (c~(w))
ENTER THE FILE NAME (15 CHARACTERS MAX)
THE DEFAULT IS CHR.DAT ---->
THE CHR.DAT          FILE IS COMPLEX AND HAS  1024 ELEMENTS
PRESS <RETURN> TO CONTINUE
```

This program uses the same general procedure shown above for storage and retrieval of all data files. The user is given a default filename which can be used by pressing <RETURN> or a different filename can be entered. The program also responds with the data type and the length of the file for user reference.

Recalling the NTSC Signal Files From Disk

A selection of #2 from the GET NTSC COEFFICIENTS menu allows the user to input the complex, 1024 point data files from disk. The user is asked for the names of the chrominance and luminance files by the following prompts:

```
RECALL THE LUMINANCE DFT COEFFICIENTS:
ENTER THE FILE NAME (15 CHARACTERS MAX)
THE DEFAULT IS LUM.DAT ---->
THE LUM.DAT          FILE IS COMPLEX AND HAS  1024 ELEMENTS

RECALL THE CHROMINANCE DFT COEFFICIENTS:
ENTER THE FILE NAME (15 CHARACTERS MAX)
THE DEFAULT IS CHR.DAT ---->
THE CHR.DAT          FILE IS COMPLEX AND HAS  1024 ELEMENTS
PRESS <RETURN> TO CONTINUE
```

Default filenames of LUM.DAT and CHR.DAT are used in the cases shown above.

Generating the Time and Frequency Domain Video Signals

The time domain video signal v(t) or the log magnitude spectrum of the video signal may be calculated and stored on disk by using the following menu:

MENU: GENERATE VIDEO SIGNALS

1. GENERATE THE TIME DOMAIN VIDEO SIGNAL
2. GENERATE THE LOG MAGNITUDE SPECTRA OF THE VIDEO SIGNAL
3. STORE THE CURRENT NTSC PARAMETERS (NTSCPARA.TXT)
4. RESTART THE PROGRAM

ENTER SELECTION OR PRESS <RETURN> TO CONTINUE WITH THE PHASE ERROR SIMULATION ---->

A selection of #1 or #2 generates a 2048 point real data file which may be plotted using an external graphics routine. The user is prompted for a disk filename (or default) in each case.

When generating the log spectra of the video signal (Selection #2), the user is asked to specify a noise floor for the log data:

ENTER THE NOISE FLOOR FOR THE NORMALIZED LOG SPECTRA
THE DEFAULT IS -80.0 dB ----->

The default of -80.0 dB provides satisfactory results in most cases.

Selection #3 allows the user to store the current NTSC generator parameters on the permanent disk file NTSCPARA.TXT.

Selection #4 returns the program to the GET NTSC COEFFICIENTS menu. By pressing <RETURN>, control is then transferred to the FM modulator (VCO) and demodulator (PLL) parameter selection menu.

<u>FM Modulator/Demodulator Parameter Selection and Phase Error Calculation</u>

The following menu displays and edits the parameters for the FM modulator (VCO) and the phase-locked loop (PLL) demodulator:

```
MENU:  FM MODULATOR (VCO) / DEMODULATOR (PLL) PARAMETERS

VIDEO STATUS:  MAXIMUM =     0.4298
               MINIMUM =    -0.2825
               AVERAGE =     0.0464

FM MODULATOR (VCO)
------------------
1.  PEAK FREQUENCY DEVIATION   =    10.7000 MHz
2.  MODULATION INDEX Km        =    30.0440 MHz/volt

FM DEMODULATOR (LINEAR PLL)
---------------------------
DEPENDENT PARAMETERS:  NATURAL FREQ. Fn   =    15.0002 MHz
                       DAMPING  FACTOR    =    0.70682

3.  POLE TIME CONSTANT T1      =   26.00500 nsec
4.  ZERO TIME CONSTANT T2      =   10.67000 nsec
5.  OPEN LOOP GAIN KdKv        = 0.2310E+09 1/sec

ENTER SELECTION OR <RETURN> TO CONTINUE WITH
THE PHASE ERROR CALCULATION ---->
```

The FM modulator parameters (selections 1 and 2) are interdependent, i.e., by changing one, the other is recomputed based on the video status information provided above the menu.

The dependent PLL parameters are computed for each new selection of the independent PLL parameters (selections 3,4 and 5).

Once the desired parameters have been selected, a <RETURN> will continue with the RMS phase error calculation. A sample output for the aforementioned default parameters is

```
RMS PHASE ERROR = 0.1412961 radians = 8.095671 degrees
PRESS <RETURN> TO CONTINUE.
```

<u>Computing the Phase, FM Spectra and the Demodulated Test Signal</u>

After computing the phase error, the next menu provides the user with several options.

```
MENU:  DISPLAY PHASE, FM SPECTRA AND DEMODULATED
       SIGNAL

1.  GENERATE THE PLL INPUT PHASE SIGNAL
2.  GENERATE THE PLL INPUT FM SPECTRA
3.  GENERATE THE PLL DEMODULATED SIGNAL
4.  SELECT NEW FM MODULATOR / PLL PARAMETERS
5.  SELECT NEW NTSC SIGNAL GENERATOR PARAMETERS
6.  STORE THE CURRENT PARAMETERS (NTSCPARA.TXT)
7.  RECALL THE STORED NTSC PARAMETERS (NTSCPARA.TXT)
8.  DISPLAY THE STORED NTSC PARAMETERS (NTSCPARA.TXT)

ENTER SELECTION OR <RETURN> TO QUIT ---->
```

Menu selections #1, #2 and #3 each generate real data files representing the PLL input phase, the PLL input FM spectra and the PLL demodulated signal respectively. Selection #2 prompts the user for a noise floor (or default) for the log magnitude data. Selection #3 allows the user to specify FM deemphasis to restore the original signal characteristics. Selections #4 and #5 return control to the FM MODULATOR / DEMODULATOR PARAMETER and the GET NTSC COEFFICIENTS menus respectively. Menu selections #6, #7 and #8 are included for storage, retrieval and displaying of the system parameters. A sample screen display for menu selection #8 is shown below. The parameters are displayed as they appear in the text file NTSCPARA.TXT.

NTSC COLOR BAR GENERATOR

VIDEO FILTERS						PREEMPH. FLAG (Y/N)	PERCENT COLOR SAT.
Cutoff Freq. (MHz)			# of Poles				
y(t)	q(t)	i(t)	y(t)	q(t)	i(t)		
4.2000	0.5000	1.5000	3	3	3	Y	100.000

FM TRANSMITTER (VCO)

PEAK FREQ. DEVIATION (MHz)	MODULATION INDEX (MHz/volt)
10.700	36.507

FM DEMODULATOR (LINEAR PLL MODEL)

KdKv (1/sec)	T1 (nsec)	T2 (nsec)	Fn (MHz)	Damping Factor
0.2310E+09	26.005	10.670	15.000	0.70682

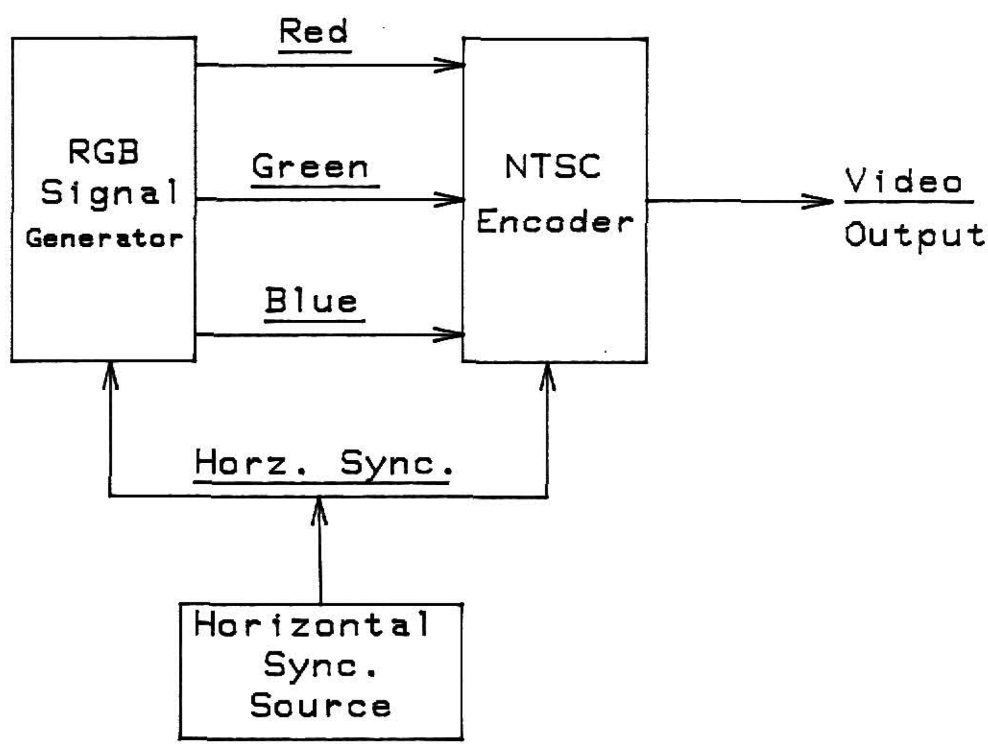
PRESS <RETURN> TO CONTINUE

The user may exit the program from the final menu by pressing <RETURN>. At any point in the program, the user may exit to the operating system by pressing CTRL-C.

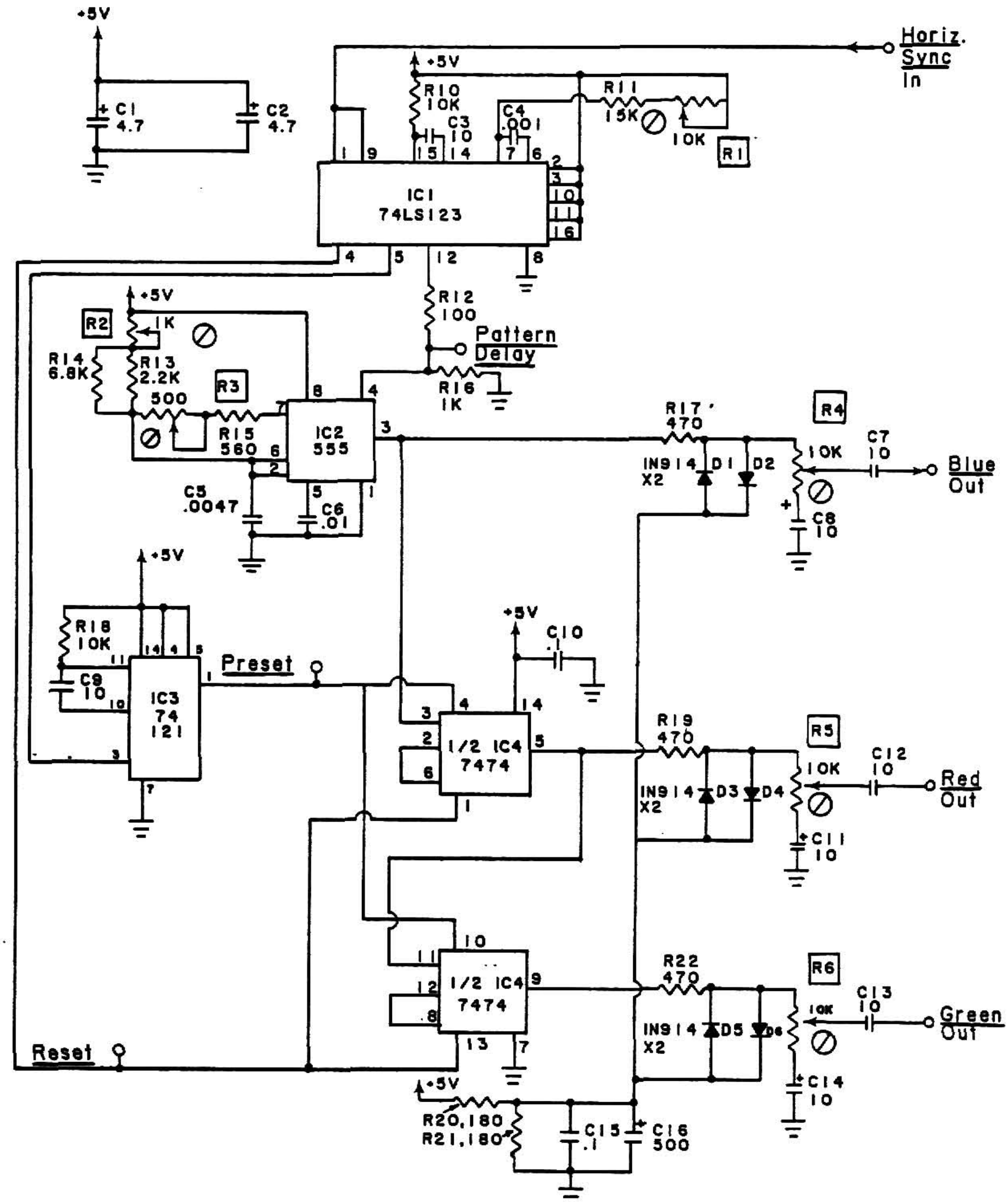
Appendix 3. Hardware Schematics

NTSC Color Bar Generator

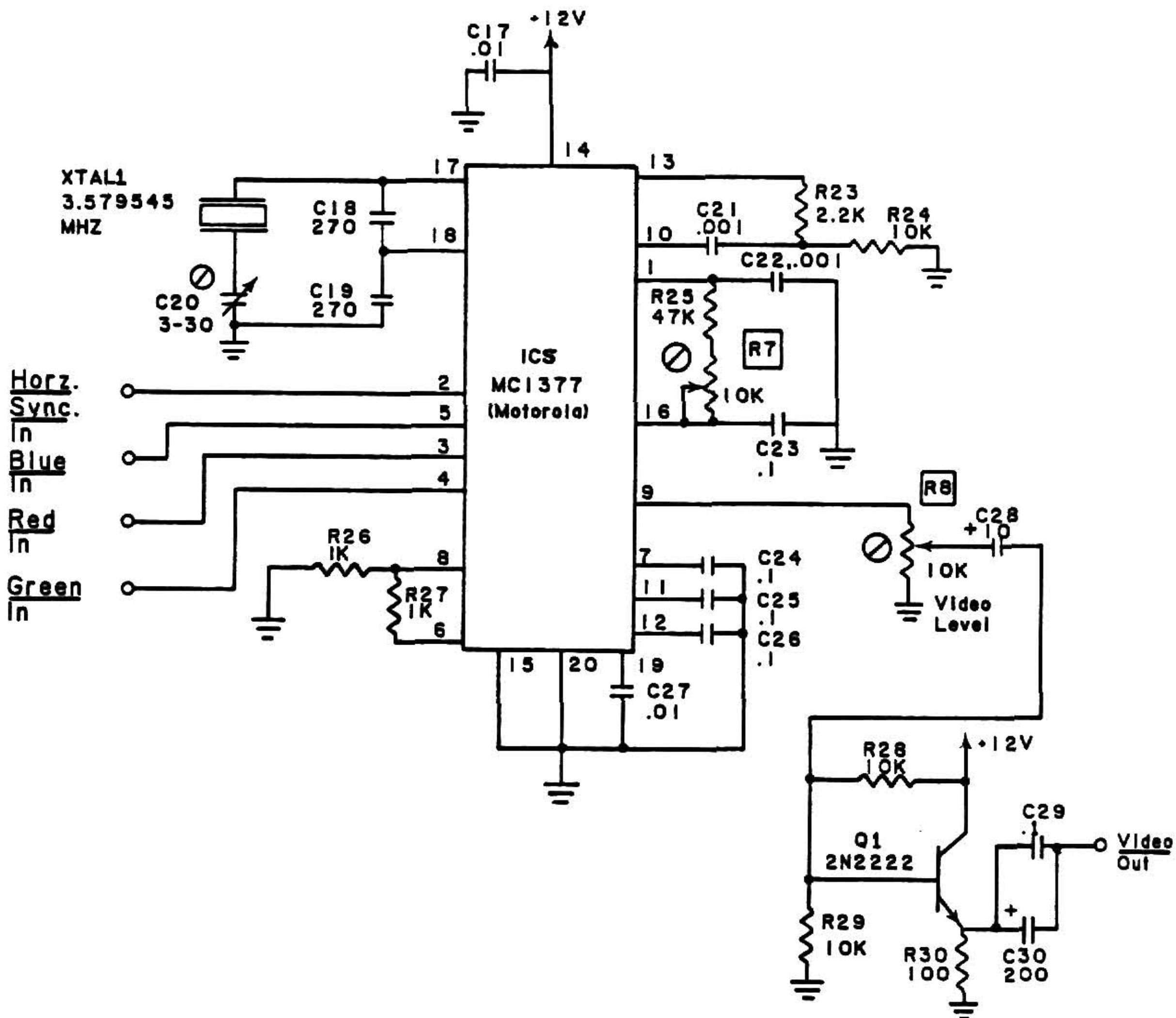
Block Diagram



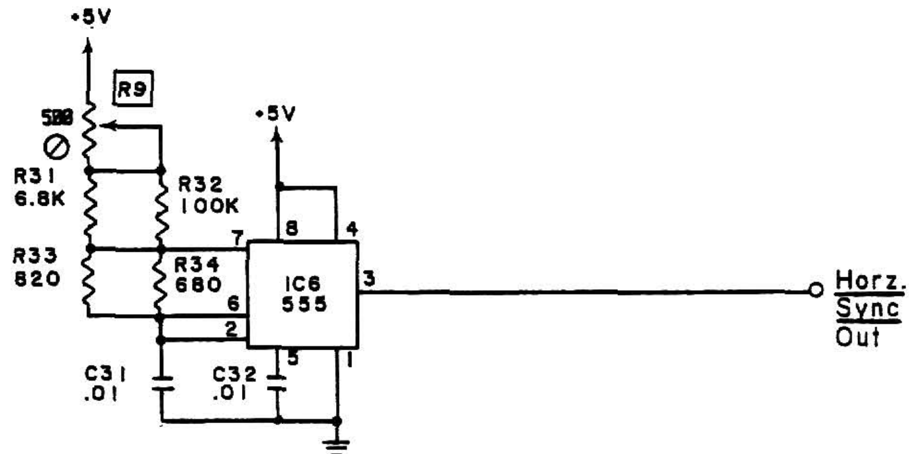
RGB Signal Generator



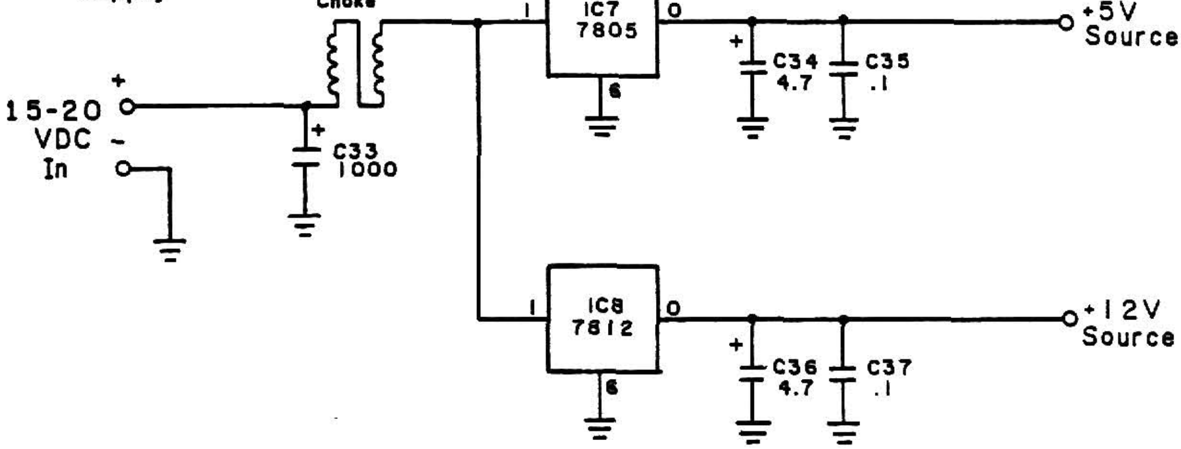
NTSC Encoder



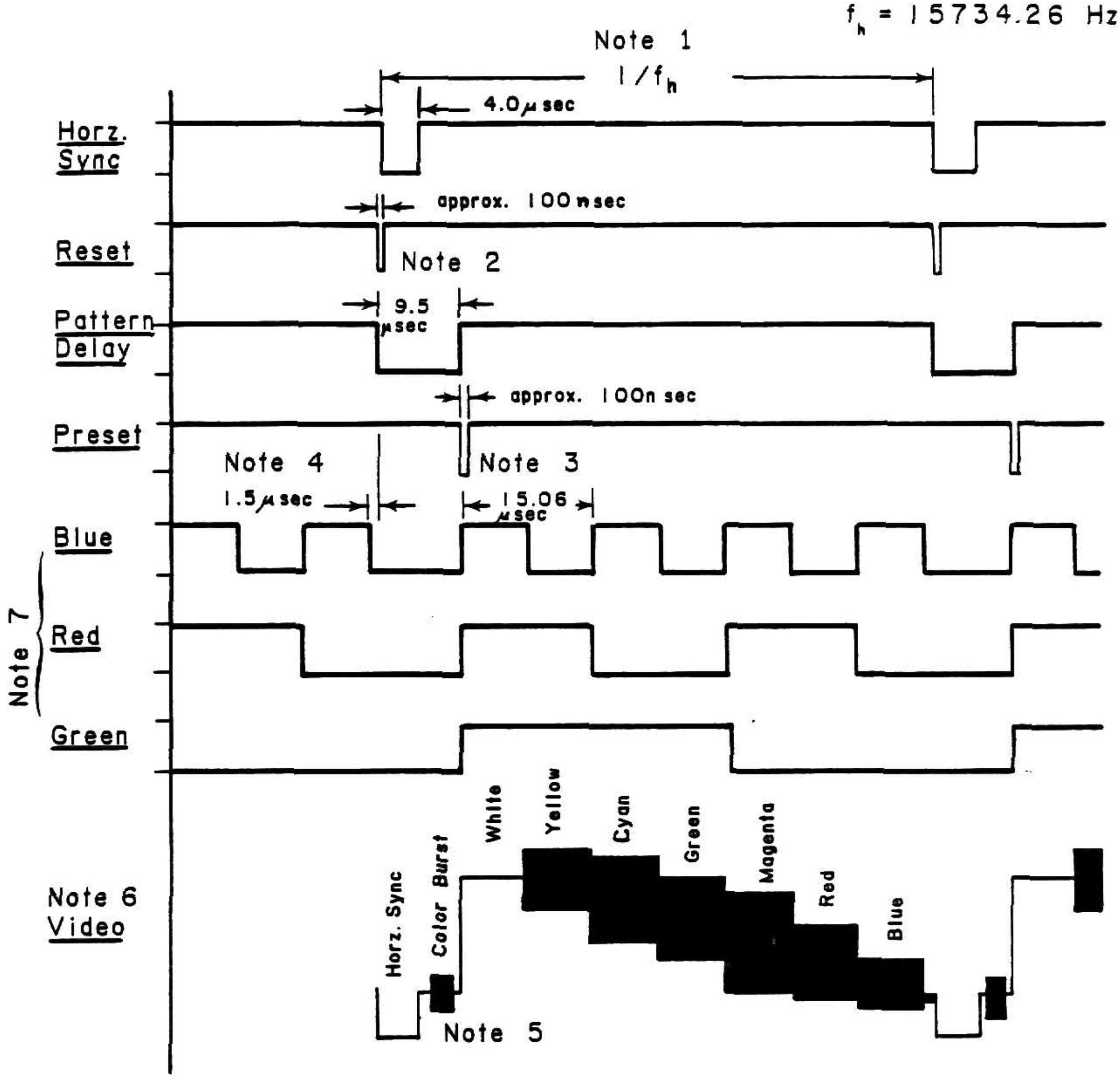
Horizontal
Sync.
Source



Power
Supply



Timing Diagram



Note 1: Adjust R9 for f_h=15734±10 Hz. Frequency may drift over time.

Note 2: Adjust R1 for approx. 9.5 μsec delay as shown.

Note 3: Adjust R2 and R3 for 66.4 KHz, 50% duty cycle square wave as shown.

Note 4: Adjustment of R2, R3 and R1 will vary this period which should be approx. 1.5 μsec. (not critical)

Note 5: Adjust R7 for proper color burst position.

Note 6: Adjust R8 for 1 to 1.5 volts peak-to-peak video output.

Note 7: Adjust R4,R5 and R6 for 1 volt peak-to-peak for 100% saturated color bars.

NTSC Color Bar Pattern Generator Parts List

Resistors: (1/4 watt carbon composition)

R1,R4,R5,R6,R7,R8	10K ohm trimmer
R2	1K ohm trimmer
R3,R9	500 ohm trimmer
R10,R18,R24,R28,R29	10K ohm
R11	15K ohm
R12,R30	100 ohm
R13,R23	2.2K ohm
R14	6.8K ohm
R15	560 ohm
R16,R26,R27	1K ohm
R17,R19,R22	470 ohm
R20,R21	180 ohm
R25	47K ohm

Capacitors:

C1,C2,C34,C36	4.7 µF tantalum
C3,C9	10 pF ceramic
C4,C21,C22	.001 µF ceramic
C5	4700 pF mica
C6,C17,C27,C32	.01 µF ceramic
C7,C8,C11,C12,C13,C14,C28	10 µF electrolytic
C10,C15,C23,C24,C25,C26,C29, C35,C37	.1 µF ceramic
C16	500 µF electrolytic
C18,C19	270 pF ceramic
C20	5-30 pF trimmer

C30	200 μF electrolytic
C31	.01 μF mylar
C33	1000 μF electrolytic

Inductors:

L1	RF choke (50 turns of # 32 wire on a T25-2 core)

Transistors:

D1,D2,D3,D4,D5,D6	1N914 silicon diode
Q1	2N2222 NPN general purpose

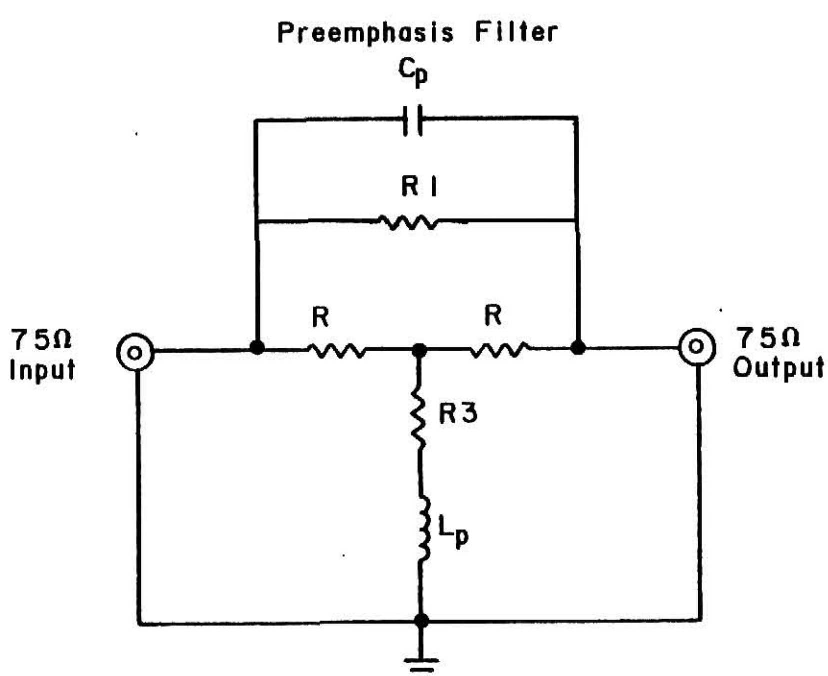
Integrated Circuits:

IC1	74LS123	dual monostable multivibrator
IC2,IC6	NE555	timer
IC3	74121	monostable multivibrator
IC4	7474	dual D flip-flop
IC5	MC1377	NTSC encoder (Motorola)
IC7	7805	+5 volt regulator
IC8	7812	+12 volt regulator

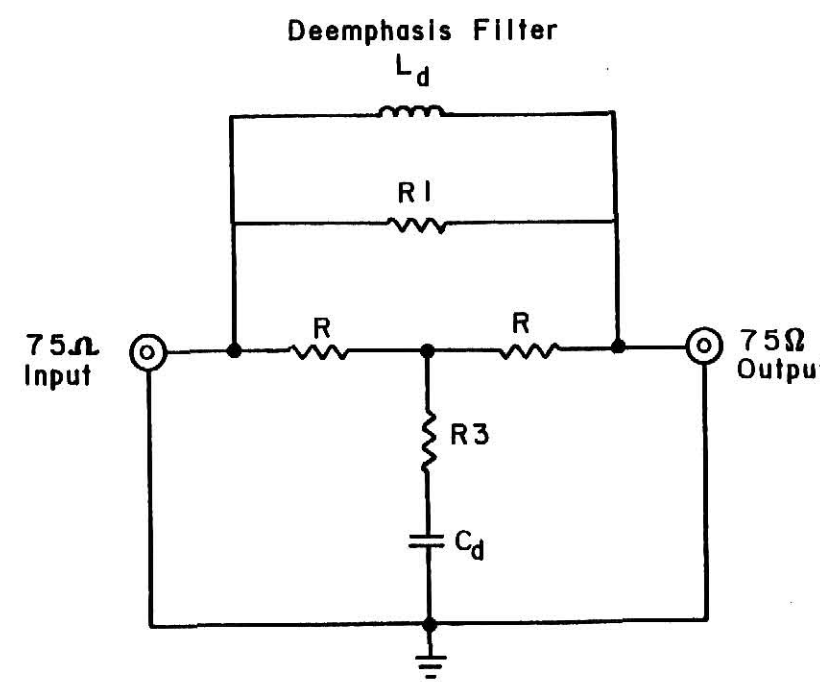
Miscellaneous:

XTAL1	3579545 Hz color burst crystal

CCIR Recommendation 4Ø5-1

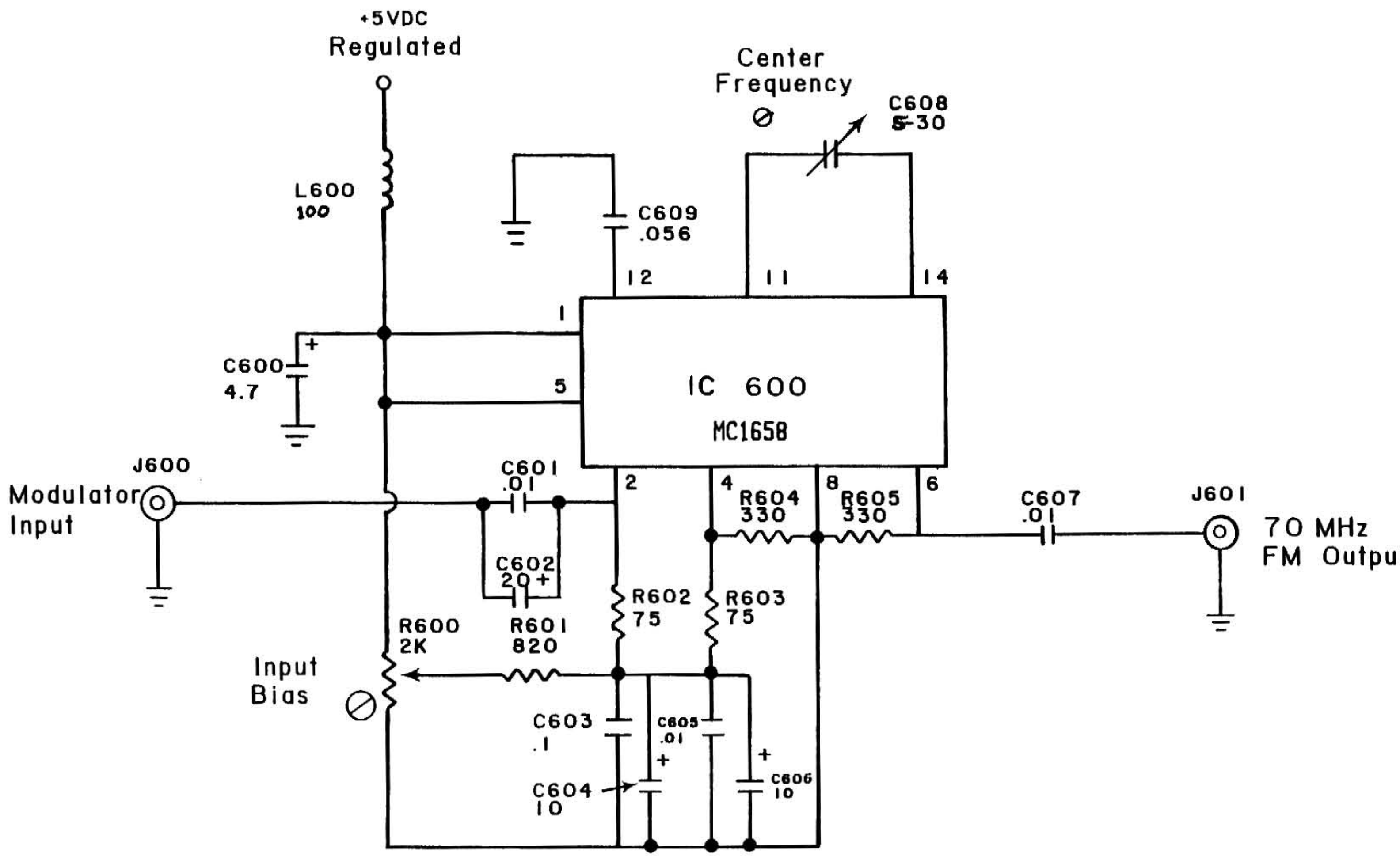


R	75Ω
R1	275.8Ω
R3	20.4Ω
C_p	308 5 pF
L_p	17.35 μH



R	75Ω
R1	275.8Ω
R3	20.4Ω
C_d	8917 pF
L_d	50.16 μH

FM Modulator



FM Modulator Parts List

Resistors: (1/4 watt carbon composition)

R600	2K ohm multiturn trimmer
R601	820 ohm
R602,R603	75 ohm
R604,R605	330 ohm

Capacitors:

C600	4.7 μF tantalum
C601,C605,C607	.01 μF ceramic
C602	20 μF tantalum
C603	.1 μF ceramic
C604,C606	10 μF 50V electrolytic
C608	5-30 pF trimmer
C609	.056 μF ceramic chip

Inductors:

L600	100 μH RF choke

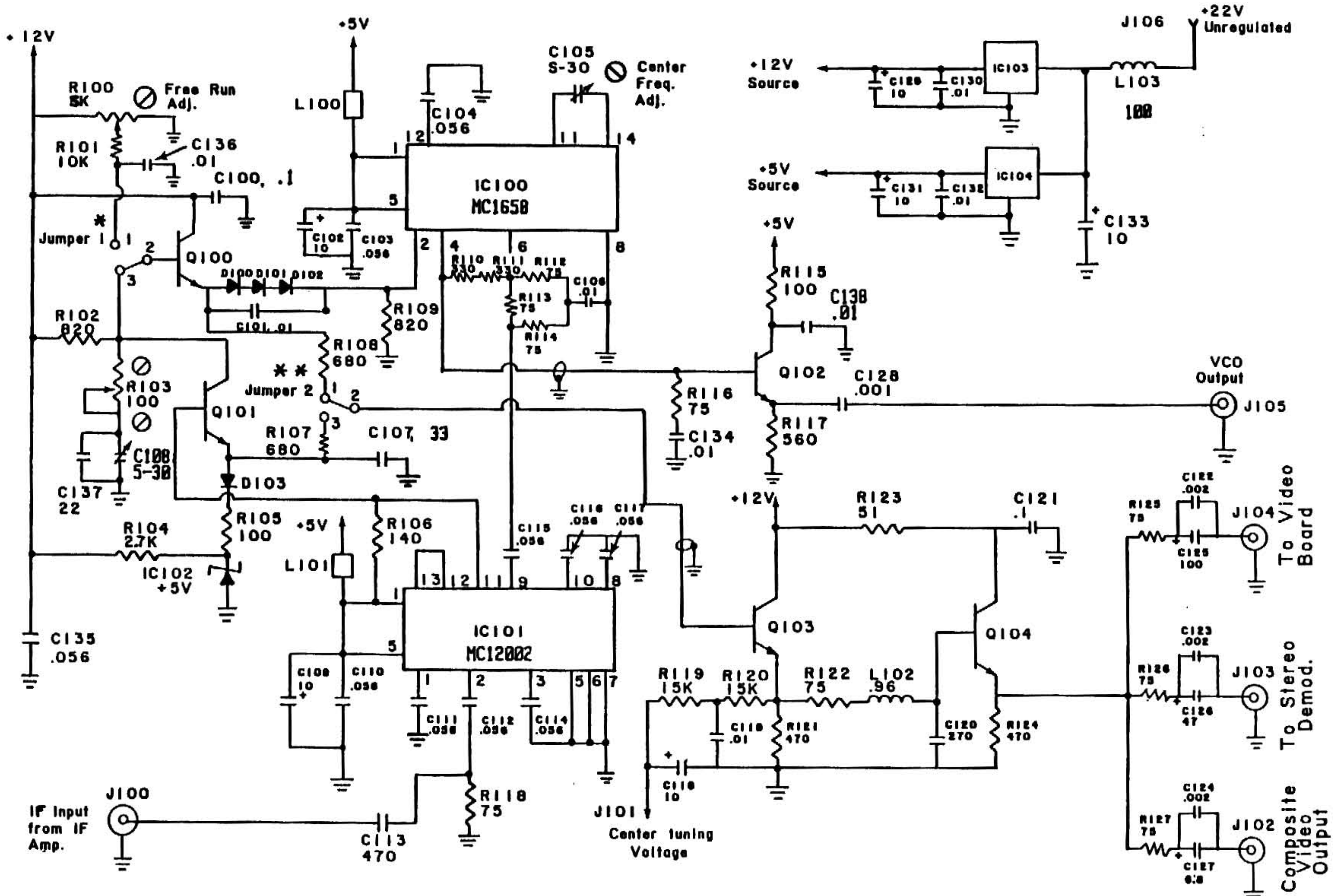
Integrated Circuits:

IC600	MC1658 voltage controlled multivibrator (Motorola)

Connectors:

J600,J601	BNC female

PLL Video Demodulator



*Jumper 1 shown in normal position. Connect 1 to 2 for free run, open loop testing.
**Jumper 2 shown in normal position. Connect 2 to 3 for phase error measurements.

PLL Video Demodulator Parts List

Resistors: (1/4 watt carbon composition)

R100	5K ohm trimmer
R101	10K ohm
R102,R109	820 ohm
R103	100 ohm trimmer
R104	2.7K ohm
R105,R115	100 ohm
R106	140 ohm
R107,R108	680 ohm
R110,R111	330 ohm
R112,R113,R114,R116,R118, R122,R125,R126,R127	75 ohm
R117	560 ohm
R119,R120	15K ohm
R121,R124	470 ohm
R123	51 ohm

Capacitors:

C100,C121	.1 µF ceramic
C101,C106,C119,C130,C132, C134,C136,C138	.01 µF ceramic
C102,C109,C118,C129,C131, C133	10 µF tantalum
C103,C104,C110,C111,C112, C114,C115,C116,C117,C135	.056 µF ceramic chip
C105,C108	5-30 pF trimmer
C107	33 pF ceramic
C113	470 pF ceramic

C120	270 pF ceramic
C122,C123,C124	2000 pF ceramic
C125	100 µF 50V electrolytic
C126	4.7 µF tantalum
C127	6.8 µF tantalum
C128	1000 pF ceramic
C137	22 pF silver mica

Inductors:

L100,L101	1/8" D, 1/4" L ferrite bead
L102	.96 µH (16 turns of #32 wire on a T25-2 core)
L103	100 µH RF choke

Transistors:

D100,D101,D102,D103	1N914 silicon diode
Q100,Q101,Q102	2N918 NPN high frequency
Q103,Q104	2N2222 NPN general purpose

Integrated Circuits:

IC100	MC1658 voltage controlled multivibrator (Motorola)
IC101	MC12002 analog mixer (Motorola)
IC102	LM336 precision +5 volt reference
IC103	LM7812 +12 volt regulator
IC104	LM7805 +5 volt regulator

Connectors:

J100	F coaxial female

J101,J106	Single conductor push-on
J102,J103,J104,J105	BNC female

THE RMS PHASE ERROR OF A PHASE-LOCKED LOOP FM DEMODULATOR FOR STANDARD NTSC VIDEO

by

DALE F. DUBBERT
B.S., Kansas State University, 1984

AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the
requirements for the degree

MASTER OF SCIENCE

Department of Electrical and Computer Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1986

Abstract

A second order phase-locked loop (PLL) is a well known scheme for the demodulation of FM signals. A major consideration in the design of a PLL FM demodulator is to keep the phase error relatively small thus assuring minimum demodulator output distortion due to phase detector nonlinearities and, in extreme cases, loss of phase lock. The loop bandwidth must be selected to both maintain a small phase error (wide loop bandwidth) and to keep the demodulator output signal to noise ratio as large as possible (narrow loop bandwidth). In the absence of a qualitative signal-to-noise ratio analysis, the procedure is to select the second order loop natural frequency to be as low as possible. Below this frequency, the loop phase error increases drastically.

This paper documents a study of the RMS phase error performance of a second order phase-locked loop employed as a satellite FM video demodulator. The phase error for the PLL was both computer calculated and experimentally measured using a standard NTSC color bar pattern as a test signal. The experimental and calculated results illustrate the relationship between RMS phase error and the second order PLL natural frequency. Both sets of results were found to be well correlated, thus providing important information needed for an optimum demodulator design.