THE CHARACTERIZATION OF A VIDEO CODEC FOR CATV APPLICATION

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Abstract

The use of modern digital techniques is rapidly approaching a dominant role in the field of color television. An effective interface between the analog and digital worlds is of critical importance, and very often the quality of analog-to-digital (A/D) conversion is the primary limiting factor in overall system performance.

This paper describes a codec, consisting of an A/D Converter, a D/A Converter, and appropriate low-pass filters for application to digital CATV application. Emphasis is placed on the description of hardware, and the several parameters of particular interest in the color video field.

Test methods are described along with actual test results. These results indicate the very high level of performance achievable with this state-of-the-art hardware.

Introduction

Digital signal processing technology is having a tremendous impact on the television industry. Digital techniques are now being utilized in such broadcast and studio applications as time base correction, frame synchronization, standards conversion, on-line monitoring of television signals and image enhancement; and in such CATV applications as transmission from studio to transmitter, closed circuit industrial transmission, and combination video/telephone channel links. The increasing proliferation of these digital "black boxes" into areas which have been predominately analog has led to the definition of the term "codec". A block diagram of a typical digital device in its simplest form is shown in Figure 1. The term "codec" applies to the combination of a single A/D Converter followed by a single D/A Converter.

Various subjective tests such as those reported by Goldberg and others[5-7] have placed recommended sampling rates and resolution requirements on the video codec. It is generally agreed sampling at either three or four times the color subcarrier frequency is desirable. However, for some CATV applications, other sampling rates in the 10.74 to 18 MHz are dictated. For the NTSC composite video signal with a 3.58 MHz color subcarrier, the popular sampling frequencies are 10.74 MHz and 14.32 MHz, respectively. While the major emphasis of this paper will be on sampling at multiples of the NTSC subcarrier frequency, the concepts are equally applicable to other closely related sampling frequencies. Test results have also indicated that 8-bits of resolution are adequate for encoding the composite video signal without noticeable degradation. The present state-of-the-art in video codecs is 10 bits of resolution at sampling rates to 20 MHz.

The intention of this paper is to present methods which may be used to characterize such a codec in terms of parameters commonly measured by video test equipment. Test methods will be presented and characteristics peculiar to digital systems, as opposed to analog systems, will be discussed. A testing philosophy is developed which makes maximum use of existing video test equipment. The following characterization tests will be described:

- DC Linearity and Accuracy
- Bandwidth
- AC Linearity
- Signal-to-Noise Ratio
- Differential Gain and Phase
- 2T Pulse Response
- 12T Modulated Sin^2 Pulse Response
- Color Bar Response.

The practical characterization procedures presented should assist newcomers to digital video in evaluating A/D and D/A conversion equipment for use in CATV systems. The test results also indicate the high degree of performance that is achievable with properly designed state-of-the-art hardware.

Description of Eight-Bit Codec Hardware

A block diagram of the codec used in the tests described in this paper is shown in Figure 2. The input signal is passed through a 6.5 MHz low-pass filter to prevent aliasing errors when sampling at 14.32 MHz (four times the NTSC color subcarrier frequency). A similar filter is used on the D/A Converter output. These video low-pass filters provide a high degree of phase linearity throughout the passband. The test results presented in this paper apply primarily to 14.32 MHz sampling. For sampling at 10.74 MHz (three times the NTSC color subcarrier frequency), a lower cutoff frequency of about 5 MHz would be required to prevent aliasing errors. Similar test results are obtained for the 10.74 MHz case as are shown for 14.32 MHz sampling.

The A/D Converter utilized for these tests is the Computer Labs' MATV-0816, an 8-bit Converter capable of operating at sampling rates up to 16 MHz. (For sampling rates to 18 MHz, the CLI MOD-818 may be employed.)

The modular construction of the MATV-0816 A/D Converter is shown in Figure 3. The volume of this Converter is approximately 22 cubic inches, and the power dissipation is 10 watts. The MATV-0816 A/D Converter uses a combination of the serial Gray code technique and the all-parallel technique of A/D conversion. A block diagram of the converter is shown in Figure 4. The six most significant bits are derived from serial Gray encoders. Each Gray encoder is contained in a TO-8 integrated circuit package. The "residue" output of the sixth Gray encoder is applied to a 2-bit parallel encoder which derives the two least significant bits. The module is self-contained and includes an input buffer amplifier, track-and-hold amplifier, timing generator, and TTL-compatible output registers. The unit accepts the standard 0 to +1 Volt video input level at an input impedance of 75 ohms.

The D/A Converter used in the test codec is a Computer Labs' MDD-0820A modular deglitched D/A Converter. As shown in the block diagram of Figure 5, the D/A Converter contains an input register, 8-bit current output D/A Converter, deglitcher, output buffer amplifier, and necessary timing circuits. The output signal amplitude is the standard video level of 1 volt full scale into 75 ohms.

The source of encode command for the A/D Converter is derived from either the multiplied 3.58 MHz subcarrier output of the video test signal generator (for "locked" measurements) or from the adjustable 14.32 MHz crystal oscillator (for "unlocked" measurements).

A discussion of test methods and results follow in the next sections.

DC Linearity and Accuracy

The DC linearity error of a properly designed codec should be no more than ±1/2 of the weight of the least significant bit (LSB). This error may be in addition to the inherent ±1/2 LSB quantization error. Thus, the total error in the overall codec transfer function should not exceed ±1 LSB, or 2 LSB's peak-to-peak. However, the test results presented will show that properly designed video codecs can be expected to give considerably better performance.

The codec DC accuracy and DC linearity can be measured using the test setup shown in Figure 6. This test shows the codec errors due to encoding a 400 usec full scale ramp voltage input obtained from a standard function generator. The resulting error waveform provides a means of viewing the full scale DC performance of the codec. The difference amplifier may also be implemented by using two channels of a dual-trace oscilloscope in the "subtract" mode if care is taken not to overdrive either of the two inputs. Results for the test codec are presented in Figure 7. An ideal error waveform would have the characteristic 1 LSB peak-to-peak sawtooth waveform. If the combined accuracy and linearity specification of the codec is 0.2% of full scale ±1/2 LSB, then the error waveform should never encompass a band wider than 2 LSB's.

Note that the actual error waveform shown for the test codec in Figure 7 is well within this limit.

A video test signal which is particularly useful in evaluating codec linearity is available on some of the newer signal generators and is shown in Figure 8. This is known commonly as the "unmodulated ramp", and traverses the black-to-white level in 40 usec. The codec output can be observed on an oscilloscope for nonlinearities and missing codes. The dual-trace oscilloscope subtraction technique previously described can be utilized to check the actual error waveform. If the codec output is applied to a picture monitor, any step discontinuity in the codec transfer characteristic will appear as a vertical line on the screen. If the brightness level is adjusted on the monitor, any portion of the sawtooth can be examined. Incidentally, if the D/A Converter has signal-related "glitches" at the bit transition points, these will also be visible as vertical lines on the screen.

Bandwidth

The bandwidth of the NTSC color television is approximately 4.2 MHz.

In practice, color television signals contain little energy above 4 MHz.

The overall frequency response of the codec output follows a (sin X)/X curve. This is due to the reconstruction process in the D/A Converter, where the output can be considered a series of rectangular pulses whose width is equal to the reciprocal of the sampling frequency. When this pulse stream is applied to a low-pass filter, the attenuation at a frequency f with a sampling rate of f_s can be expressed as:

$$A_f = \frac{\sin\left(\frac{\pi f}{f_s}\right)}{\pi \frac{f}{f_s}}$$

This curve has been plotted in dB (Figure 9) for the cases of three and four times subcarrier sampling rates. Any bandwidth measurements on the codec must consider this theoretical rolloff unless compensation has been provided within the codec.

The "multiburst" test waveform is useful in making bandwidth measurements on video systems and is generally available on most video test signal generators. This waveform consists of a series of constant amplitude bursts at 0.5 MHz, 1.25 MHz, 2.0 MHz, 3.0 MHz, 3.58 MHz, and 4.1 MHz. More accurate frequency response characteristics can be obtained, of course, by input/output measurements with an oscillator and a RMS voltmeter.

The multiburst response of the test codec is shown in Figure 10 for a sampling rate of 14.32 MHz. Note that the 4.1 MHz burst is attenuated by about 14%, or 1.3 dB, as theory predicts.

AC Linearity

The ability of a codec to reproduce a spectrally pure sinewave is a measure of AC linearity. For an 8-bit system with a dynamic range of 48 dB, the signal-related harmonics should be at least 51 dB below full scale. In a sampled system, harmonics of the fundamental may show up as inband intermodulation products when they beat with the sampling frequency. For example, the third harmonic of a 3 MHz sinewave would appear at 9 MHz, and 5.32 MHz, for a system where the sample rate is 14.32 MHz. Note that the product at 5.32 MHz actually falls inside the video bandwidth.

Signal-related harmonics are greatly reduced by adding a "deglitcher" circuit in the D/A Converter (Figure 5). The deglitcher in the D/A Converter consists of a type of track-and-hold circuit which is placed in "hold" immediately before a new digital input word is applied to the D/A Converter current switches. The deglitcher track-and-hold remains in "hold" until the current switches have settled to their final value. When the switches have settled, the track-and-hold automatically returns to the "track" condition and slews to the new analog output established by the most recent digital input. In this way, the track-and-hold "masks out" the signal-related transients which occur at the bit transition points.

The effects of the deglitcher are seen in Figure 11(A), where the photograph shows a spectrum analyzer display of the codec output when a 1 MHz full scale sinewave is applied. The sampling rate is 14.32 MHz. Note the increase in harmonic content of Figure 11 (B), without the D/A deglitcher.

With no deglitching, excess noise is seen as vertical lines on the television screen when a black-to-white test ramp is encoded and reconstructed. These vertical lines appear where the ramp passes through the major bit transition regions. Figure 12 is a multiple exposure of an expanded portion of a digitized and reconstructed "unmodulated ramp" test signal. The left-hand trace is the output of a non-deglitched unfiltered D/A Converter. The center trace shows the effects of adding a low-pass filter to the D/A output. Note that the magnitude of the vertical glitches has been reduced; however, they are still apparent and have the same relative amplitude, and would be clearly visible on a picture monitor as vertical stripes. The right-hand trace shows the further improvement achieved by adding both a deglitcher and a low-pass filter.

Signal-to-Noise Ratio

A common method for measuring signal-to-noise ratio in analog video systems consists of measuring the amount of noise on the flat portion of a constant luminance test signal. Unfortunately, this test signal only exercises the codec if the peak value of the test signal is in the transition zone between two adjacent codes.

For digital systems, a full scale sinewave loading test has been developed which gives a better measure of the true signal-to-noise ratio. The test configuration is shown in Figure 13.

A "pure" full scale sinewave of about 500 KHz is processed by the codec. The level of the reconstructed sinewave is measured with the bandstop filter switched out. The bandstop filter is then switched in, removing the fundamental signal, and the RMS quantizing noise level is measured. For a perfect

N-bit codec with a full scale sinewave input, the theoretical RMS signal-to-noise ratio is (6N + 1.8) dB, or 49.8 dB for a perfect 8-bit system. The 8-bit codec under consideration measures within 2 dB of theoretical, or about 48 dB for the 500 KHz input signal. Tests have also been conducted using a 2.5 MHz input sinewave, and signal-to-noise ratios of about 46 dB are typical.

Differential Gain and Phase

Differential gain is defined as the percentage difference between the output amplitude of a small high-frequency sinewave at two stated levels of a low-frequency signal on which it is superimposed. Differential phase is the difference in the output phase of a small high-frequency sinewave at two stated levels of a low-frequency signal on which it is superimposed. Distortion-free processing of a color television signal requires that neither the amplitude nor the phase of the chrominance signal be significantly altered as a function of the associated luminance signal.

The most common test waveform used to measure differential gain and phase is shown in Figure 14 and is commonly referred to as the 10-step 20-IRE unit modulated staircase. Some of the newer video test signal generators have the capability of increasing the subcarrier amplitude to 40-IRE units. Another test waveform available on the newer equipment is shown in Figure 15 and is commonly called the 20-IRE unit modulated ramp. Again, the option is usually available to increase the subcarrier amplitude to 40-IRE units if desired. The system output being tested for differential gain and phase is usually measured on a vectorscope.

In a digital system, the standard 10-step 20-IRE unit modulated staircase test signal of Figure 14 will usually give misleading results on a vectorscope display of differential gain and phase, especially when sampling at a frequency locked to a multiple of the subcarrier frequency. Such a display is shown in Figure 16, where the differential gain is about 8% and the differential phase about 3°. These numbers, while probably unacceptable for a strictly analog system, are very consistent with the theoretical analysis developed for an ideal 8-bit system.

As Felix[4] points out, the traditional assumption underlying the analog differential gain and phase measurement is that a differential gain error of 8%, for a 20-IRE unit signal, would introduce the same 8% error for an 80-IRE unit signal. This assumption is incorrect, however, in a digital system. The quantizing errors have fixed peak values regardless of the signal being quantized. The 8% reading on a 20-IRE unit signal due to quantizing would reduce to 2% on an 80-IRE unit signal and to 1.6% for an 100-IRE unit signal. There would be a corresponding reduction in the differential phase reading.

When making these measurements on a digital system, the objective should be to devise methods to "see through" the "spikes" on the display caused by quantization noise, and to observe the differential gain and phase error due to analog distortions.

The situation can be improved by several methods which will be illustrated by actual vectorscope displays of the 8-bit codec.

The three things which can be done to give a more meaningful measurement are: (1) Increase the subcarrier amplitude to 40-IRE units, (2) use the modulated ramp test waveform of Figure 15, and (3) "unlock" the sampling rate by about 100 Hz from an exact multiple of the color subcarrier frequency.

The effects of performing the above are illustrated in Figures 17 through 23. The method which is preferred is shown in Figure 23 for the case of the <u>40-IRE unit modulated ramp with unlocked sampling</u>. The other results are presented for reference, however, to allow for all possible test waveforms. There are some cases where unlocked sampling is not practical, as in some CATV applications.

"2T" Pulse Response - "K" Factor

The 2T pulse has become widely accepted as a test signal to measure the short-time waveform distortion of a video signal. The 2T pulse consists of a sine-squared pulse with a half-amplitude duration of 2T. T is the transient time constant of the TV system and is defined as $T=1/(2\ f_u)$ where f_u is the upper video-frequency limit of 4 MHz and T=0.125 usec. There is no energy in this pulse above the video bandwidth of 4.2 MHz. Therefore, the pulse should pass undistorted through an ideal video system.

Distortions of the 2T pulse such as ringing, smearing, etc., are normally analyzed in terms of K factors utilizing special oscilloscope graticules. Figure 24 shows the 2T pulse after processing by the test codec. There is practically no distortion, and the corresponding K factor would be less than 1%.

"12.5T" Modulated Sin^2 Pulse Response

The luminance and chrominance components of a color signal should pass through an ideal system with their relative amplitudes and delays unchanged.

Variation in gain is called chrominance-to-luminance gain and variation in delay is called chrominance-to-luminance delay.

The modulated 12.5T pulse is often used to check thse parameters. Figure 25 shows this pulse after passing through the test codec. For a perfect system, the baseline should be flat. For the pulse in Figure 25, the baseline has a variation of 5% of peak amplitude. The shape of the baseline indicates there is no significant chrominance-to-luminance delay, but the 5% bend in the baseline indicates that the chrominance is attenuated by about 1 dB with respect to the luminance. This is exactly what is predicted by the (sin X)/X rolloff curve for four-times color subcarrier sampling (See Figure 9). Normally a high frequency "boost" circuit is incorporated in the system to compensate for this loss.

Color Bar Response

No testing program for a video codec would be complete without analyzing the codec response to a standard 75% amplitude full-field color bar test signal. A picture monitor is useful in analyzing color purity, and a vectorscope displays the color bars as individual vectors whose amplitude corresponds to the level of saturation and whose phase angle corresponds to the phase of the color with respect to the reference burst. The color bars should appear as distinct dots on the vectorscope screen and should fall within the calibrated squares on the graticule.

Figure 26 shows the vectorscope display obtained by applying the color bar signal to the test codec. For this measurement, the sampling frequency is "unlocked" from the multiple of the subcarrier frequency by about 100 Hz.

Summary

This paper has characterized an 8-bit codec in terms of test parameters of particular interest in CATV applications. The test results obtained in all cases indicate that the codec described is capable of meeting the particular demands of the video industry as a whole.

It is apparent the availability of this high performance hardware will attract more attention to the rapidly expanding area of digital television.

Acknowledgements

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6. A. A. Goldberg, "PCM Encoded NTSC Color Television Subjective Tests," Journal SMPTE, 82: 649-654, August 1973.

7. Charles P. Ginsburg, "Report of the SMPTE Digital Television Study Group," Journal SMPTE, 85: 150-153, March 1976.

FIG. 1 BASIC ELEMENTS OF A DIGITAL DEVICE

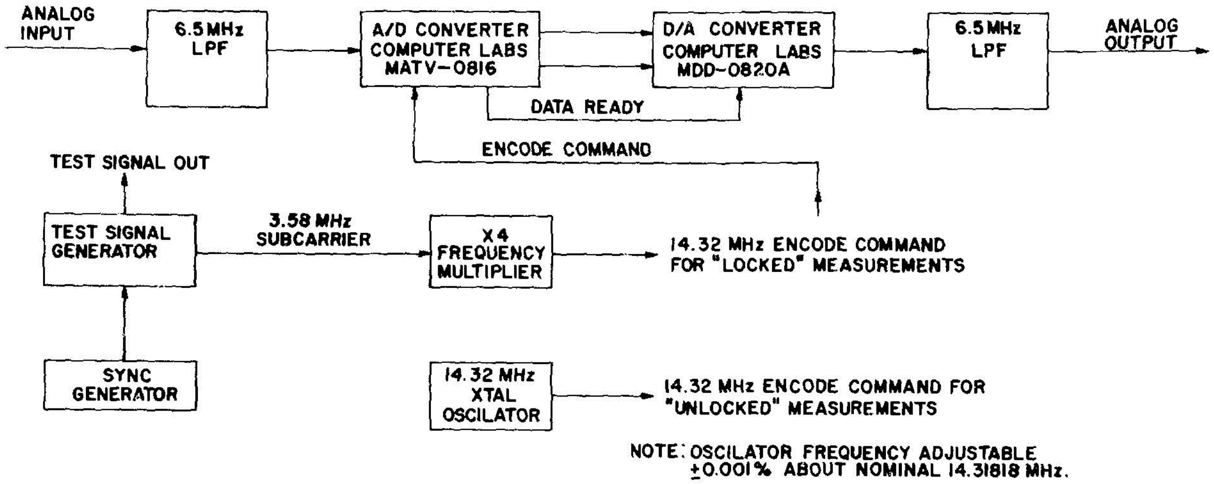
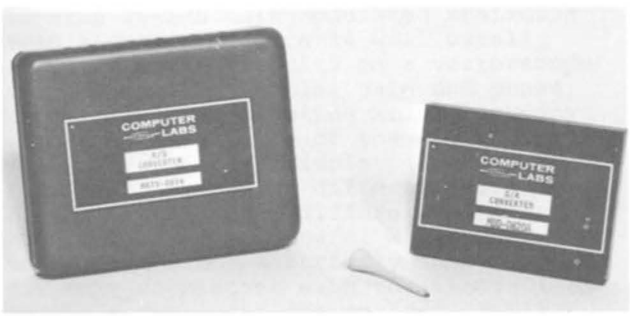
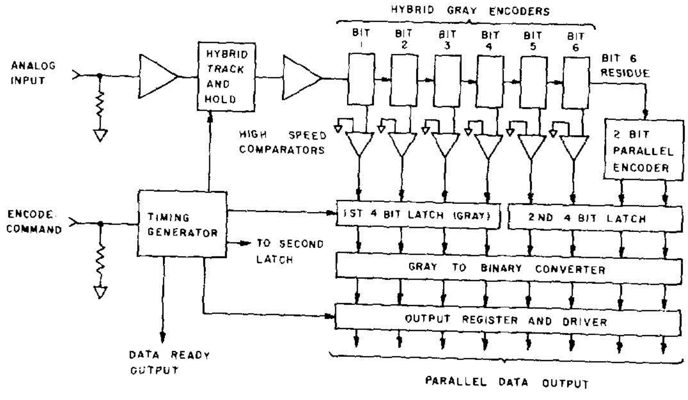


FIG. 2 CODEC BLOCK DIAGRAM





MATV SERIES A/D CONVERTER

FIG. 4

FIG. 3

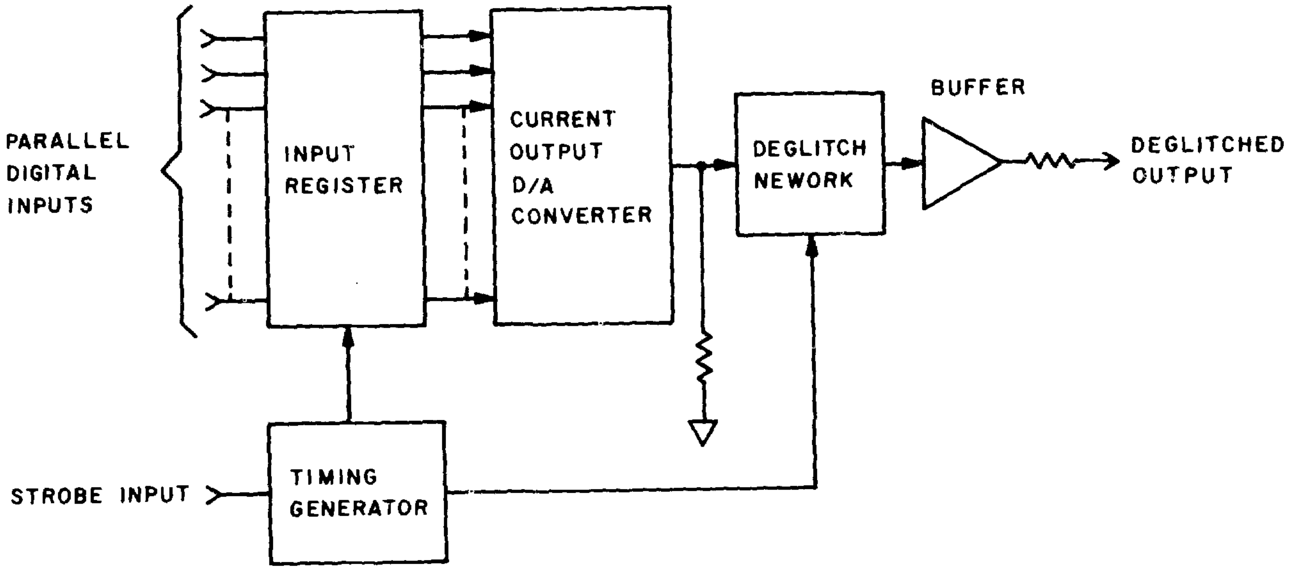


FIG. 5 DEGLITCHED D/A CONVERTER

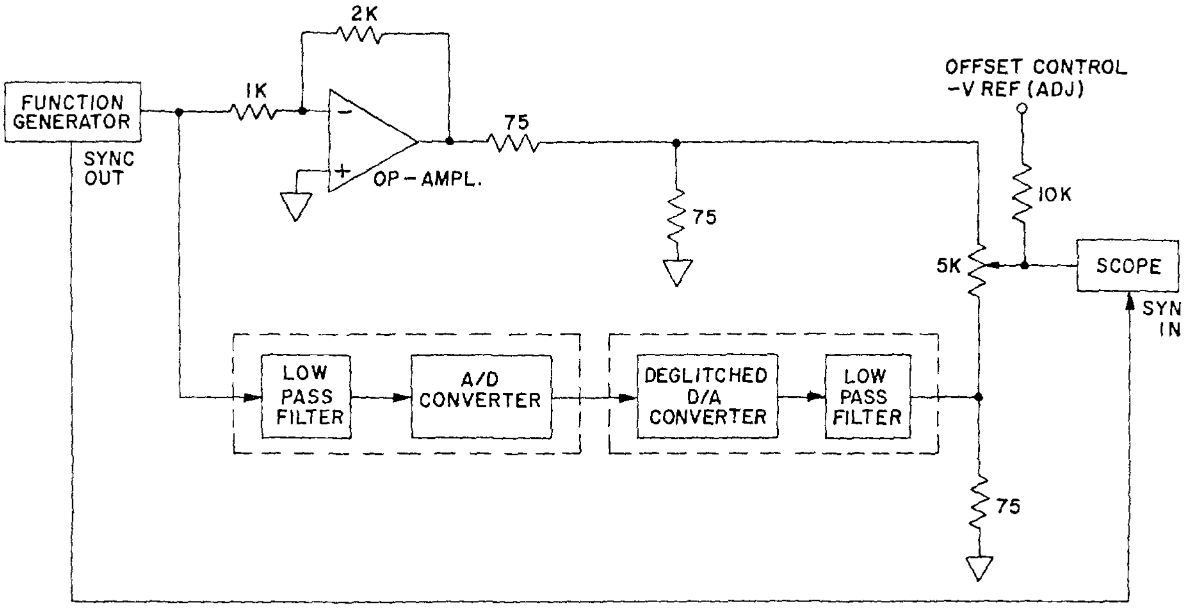
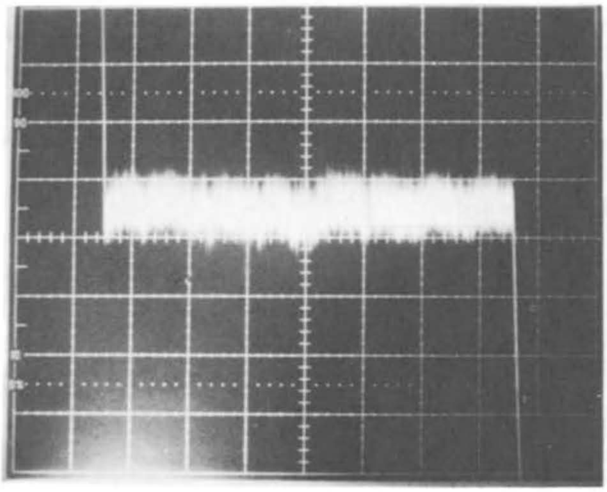
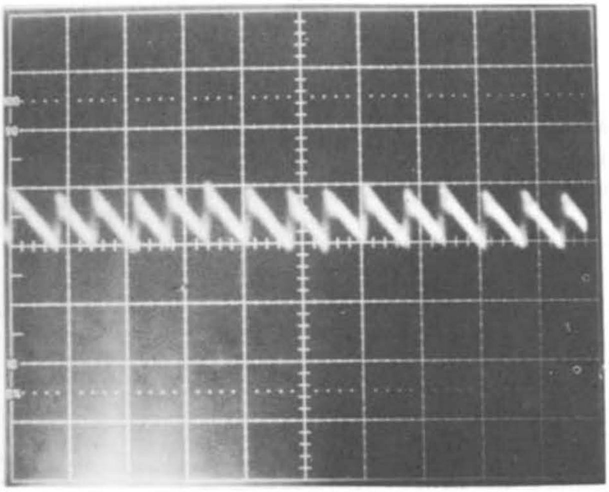


FIG. 6 RAMP LINEARITY TEST SETUP



(A) FULL RAMP ERROR DISPLAY
HORIZONTAL SCALE: 50 USEC/DIV.
VERTICAL SCALE: 1 LSB/DIV.



(B) EXPANDED DISPLAY
HORIZONTAL SCALE: 2 USEC/DIV.
VERTICAL SCALE: 1 LSB/DIV.

FIG. 7 RAMP LINEARITY DISPLAY FOR 400 USEC RAMP

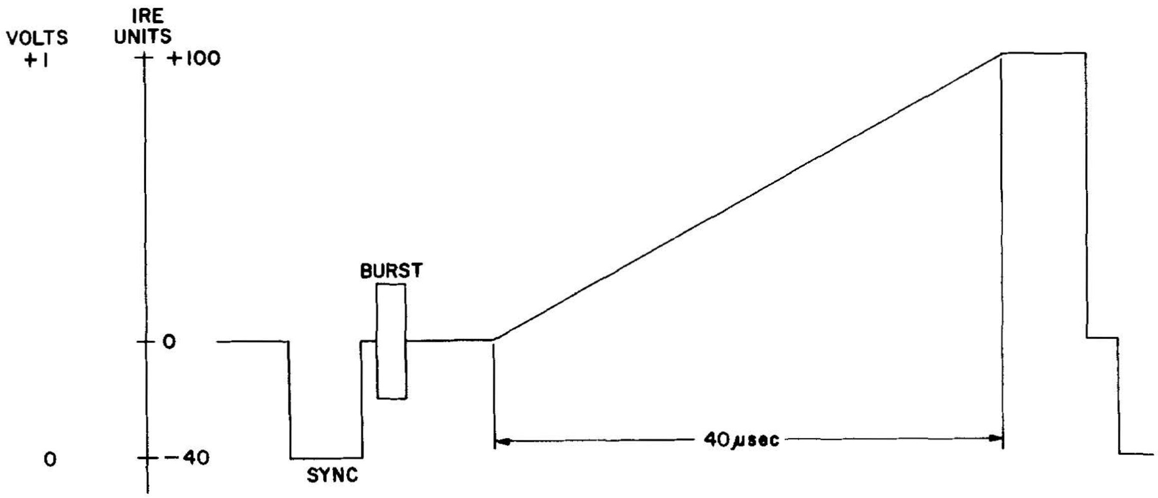
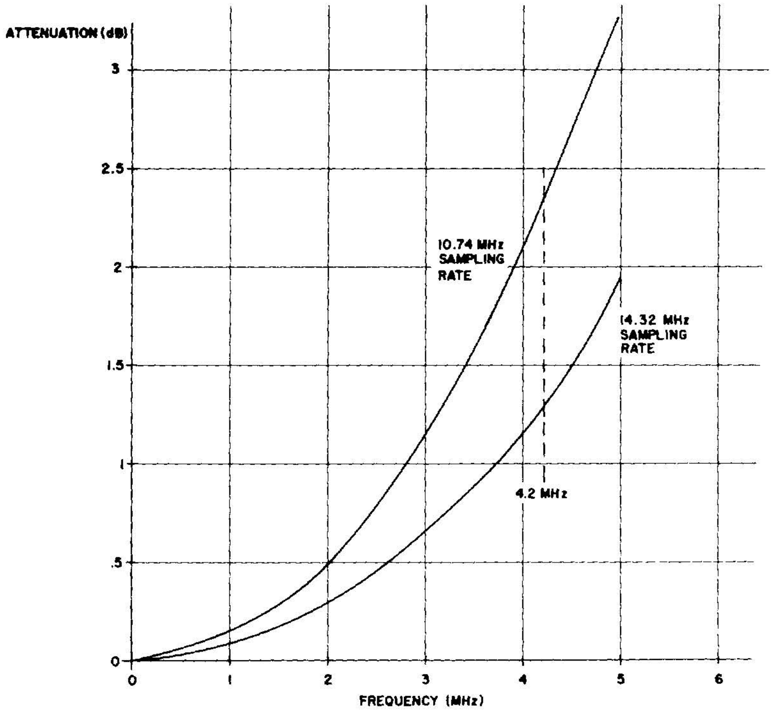
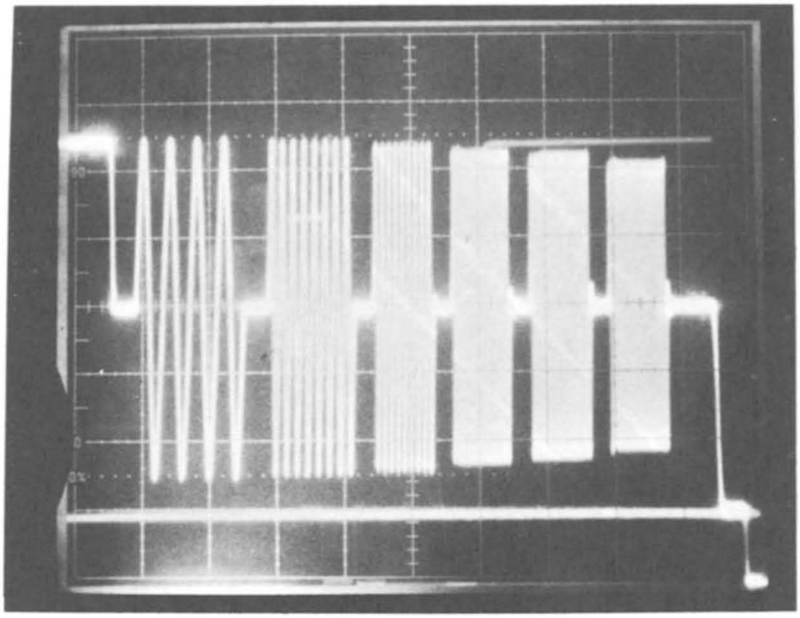


FIG. 8 LINEARITY TEST SIGNAL



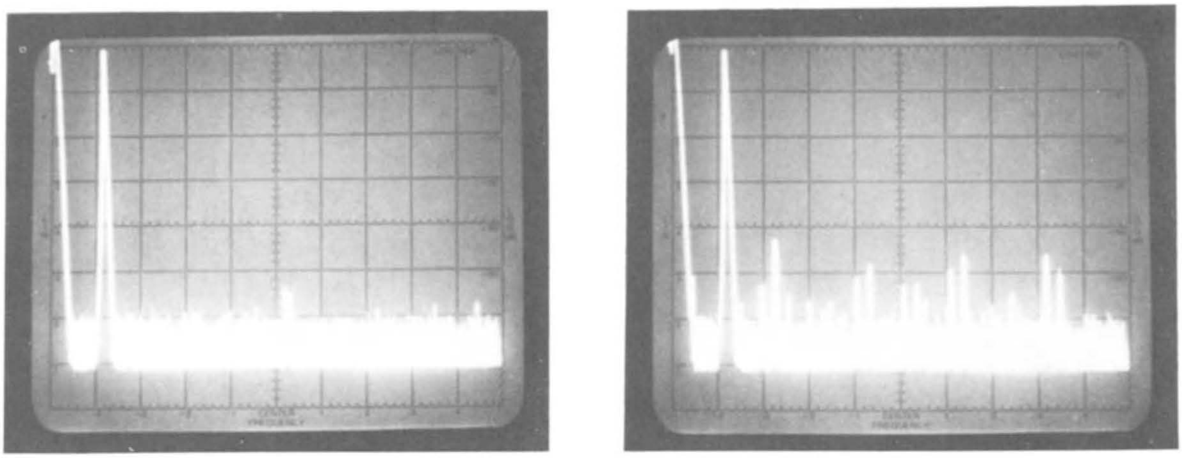
(SIN X)/X ROLLOFF IN dB

FIG. 9



CODEC MULTIBURST RESPONSE FOR
14.32 MHz SAMPLING RATE

FIG.10

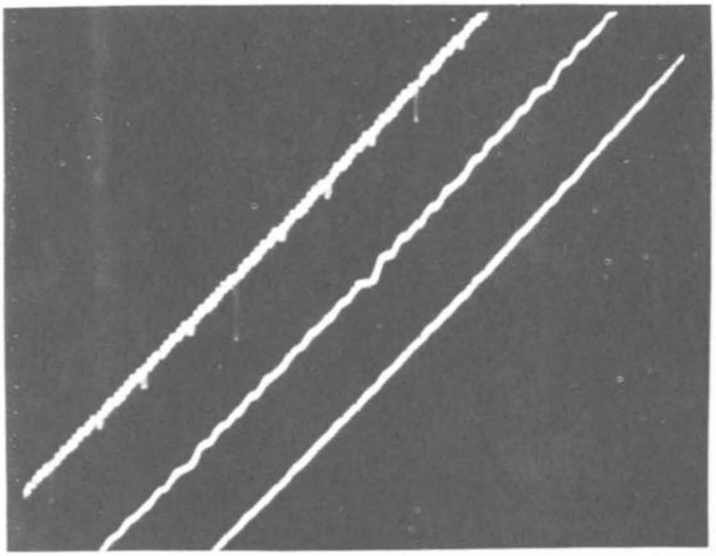


(A) WITH DEGLITCHING (B) WITHOUT DEGLITCHING

SPECTRAL OUTPUT OF CODEC FOR 1 MHz FULL SCALE
INPUT SINEWAVE (NO OUTPUT FILTER)
SAMPLED AT 14.32 MHz RATE

FIG. 11

HORIZONTAL SCALE: 1 MHz/DIV.
VERTICAL SCALE: 10dB/DIV.



EFFECTS OF FILTERING AND DEGLITCHING ON
RAMP TEST SIGNAL

LEFT-HAND TRACE: NO FILTERING, NO DEGLITCHING.
MIDDLE TRACE: ADDITION OF 6.5 MHz LOW-PASS FILTER.
RIGHT-HAND TRACE: ADDITION OF DEGLITCHER AND
6.5 MHz LOW-PASS FILTER.

FIG. 12

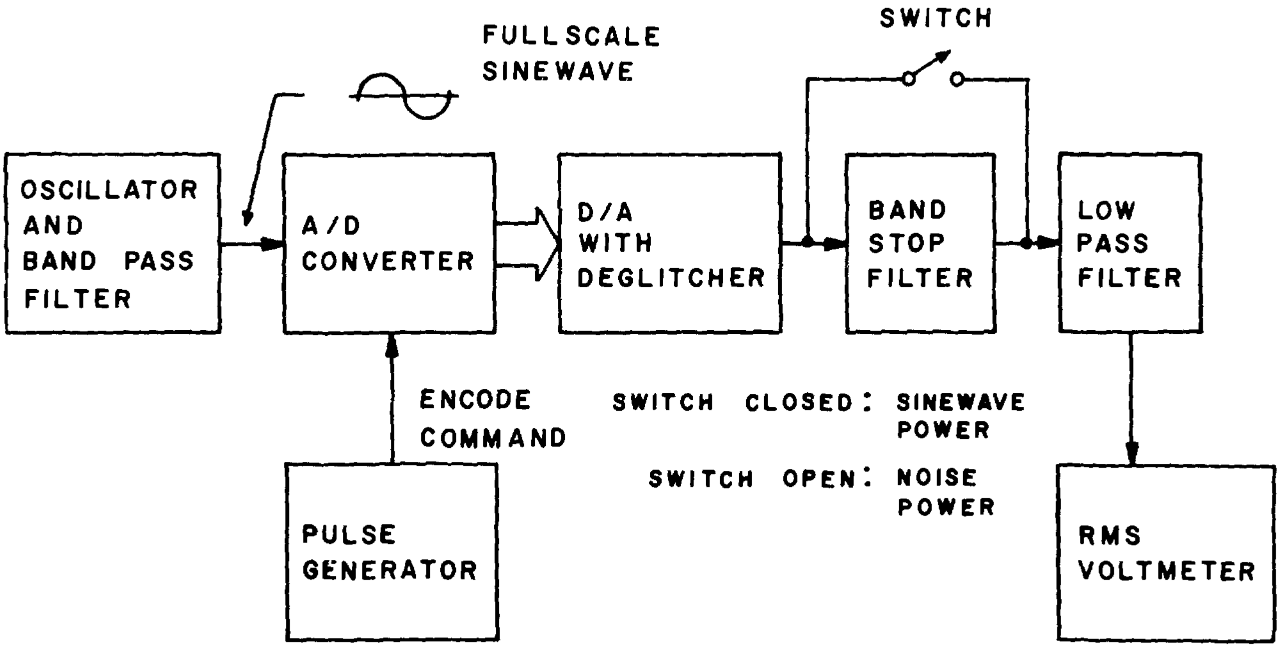


FIG. 13 **SIGNAL — TO — NOISE TEST SETUP**

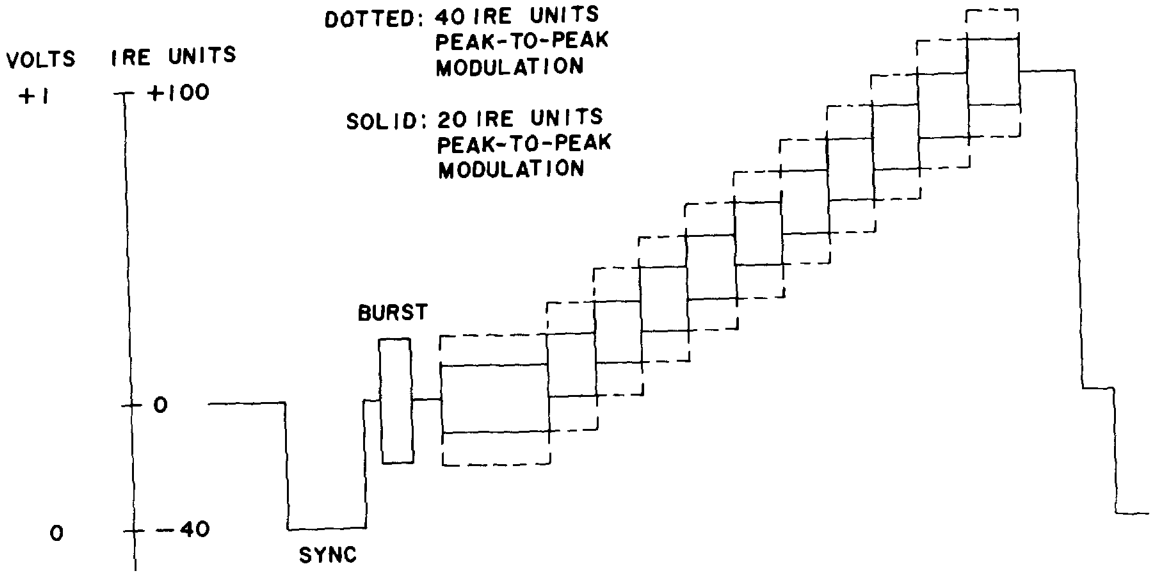
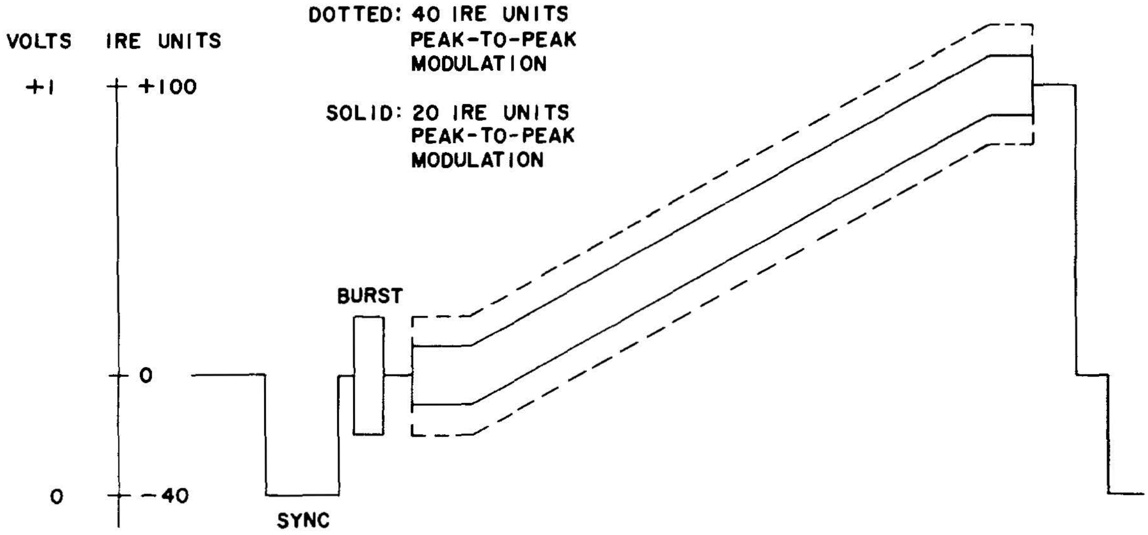
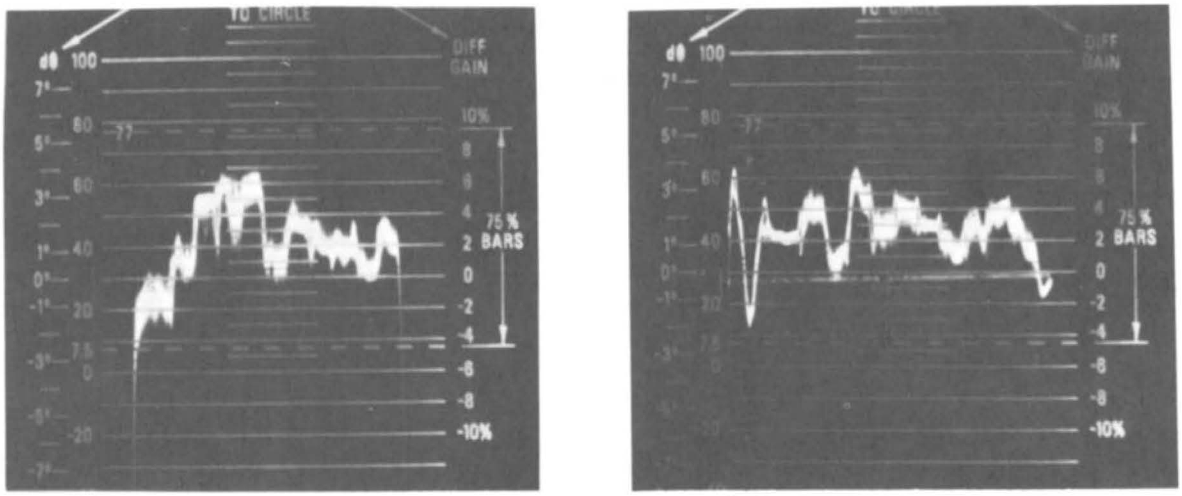


FIG. 14 10-STEP MODULATED STAIRCASE TEST SIGNAL



MODULATED RAMP TEST SIGNAL

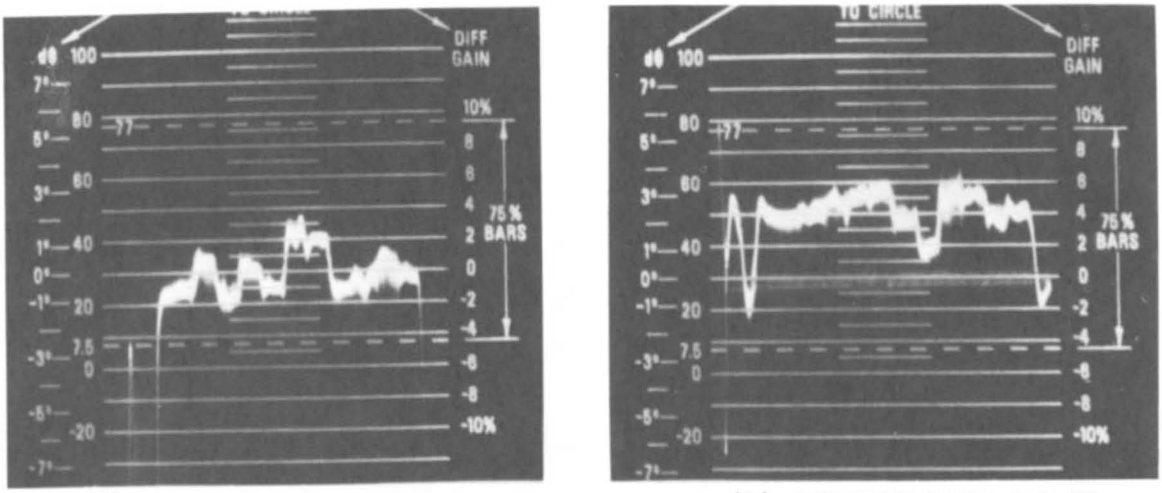
FIG.15



(A) DIFFERENTIAL GAIN (B) DIFFERENTIAL PHASE

TYPICAL CODEC DIFFERENTIAL GAIN AND PHASE DISPLAY
FOR 10-STEP, 20-IRE MODULATED STAIRCASE TEST
WAVEFORM - LOCKED SAMPLING (14.32 MHz)

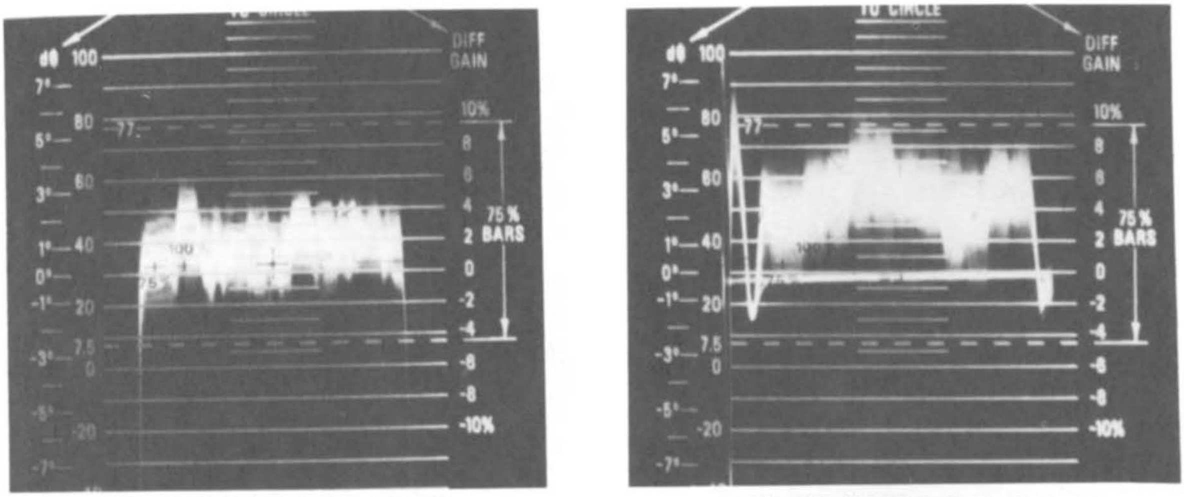
FIG. 16



(A) DIFFERENTIAL GAIN (B) DIFFERENTIAL PHASE

TYPICAL CODEC DIFFERENTIAL GAIN AND PHASE DISPLAY
FOR 10-STEP 40-IRE MODULATED STAIRCASE
TEST WAVEFORM - LOCKED SAMPLING (14.32 MHz)

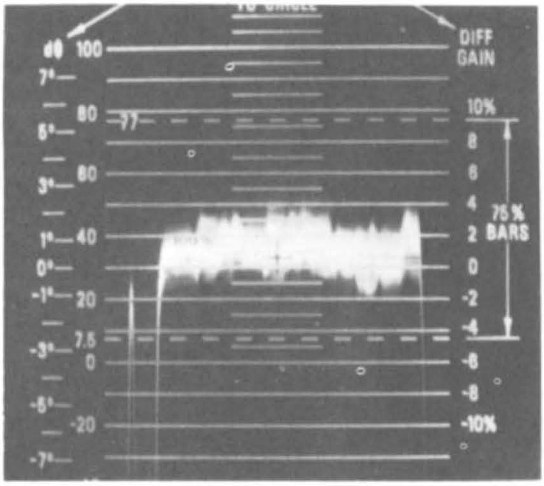
FIG. 17



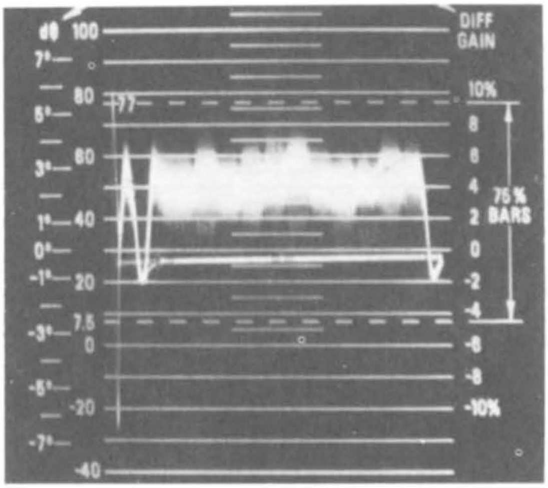
(A) DIFFERENTIAL GAIN (B) DIFFERENTIAL PHASE

TYPICAL CODEC DIFFERENTIAL GAIN AND PHASE DISPLAY
FOR 10-STEP 20-IRE MODULATED STAIRCASE
TEST WAVEFORM - UNLOCKED SAMPLING (14.32 MHz + Δf)

FIG. 18



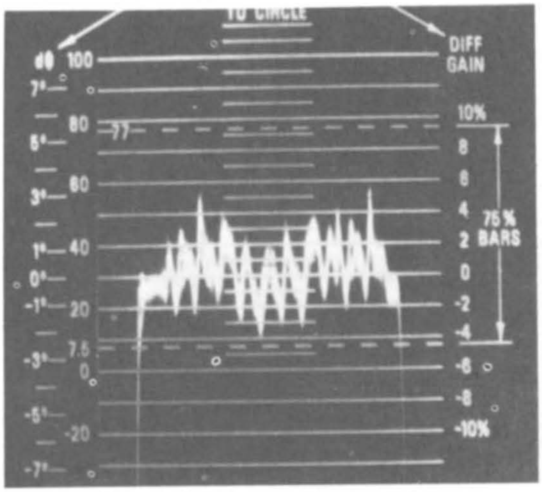
(A) DIFFERENTIAL GAIN



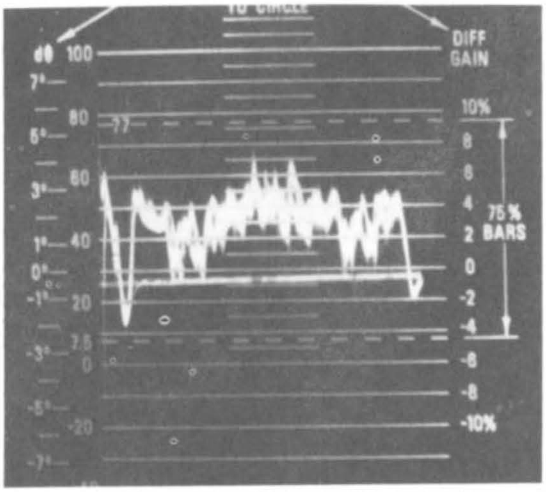
(B) DIFFERENTIAL PHASE

TYPICAL CODEC DIFFERENTIAL GAIN AND PHASE DISPLAY
FOR 10-STEP 40-IRE MODULATED STAIRCASE
TEST WAVEFORM - UNLOCKED SAMPLING (14.32 MHz + Δ f)

FIG. 19



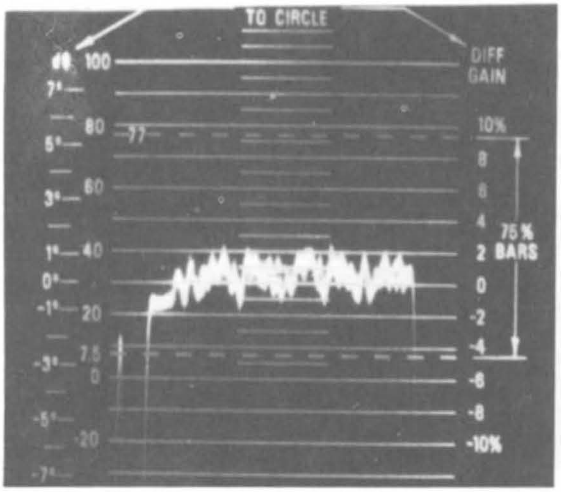
(A) DIFFERENTIAL GAIN



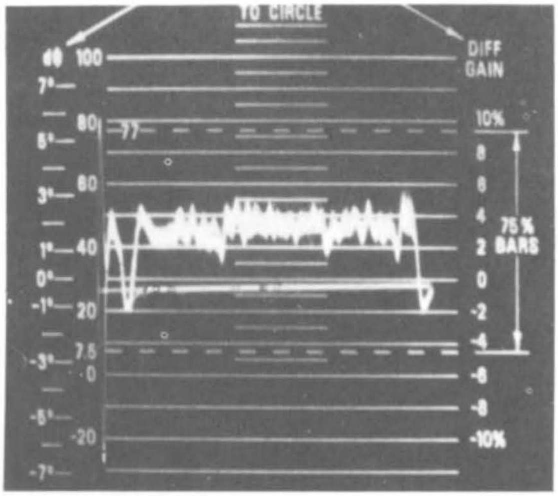
(B) DIFFERENTIAL PHASE

TYPICAL CODEC DIFFERENTIAL GAIN AND PHASE DISPLAY
FOR 20-IRE MODULATED RAMP TEST WAVEFORM -
LOCKED SAMPLING (14.32 MHz)

FIG. 20



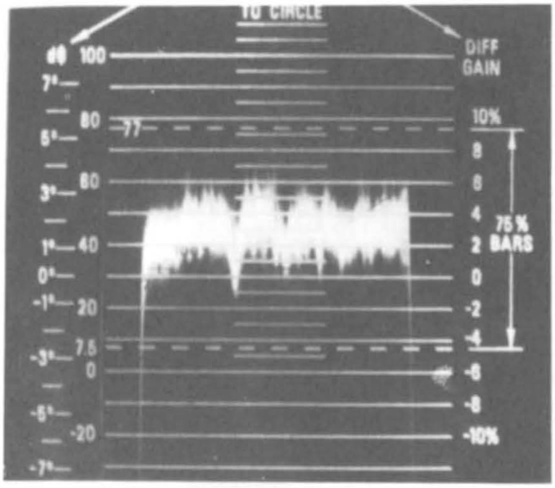
(A) DIFFERENTIAL GAIN



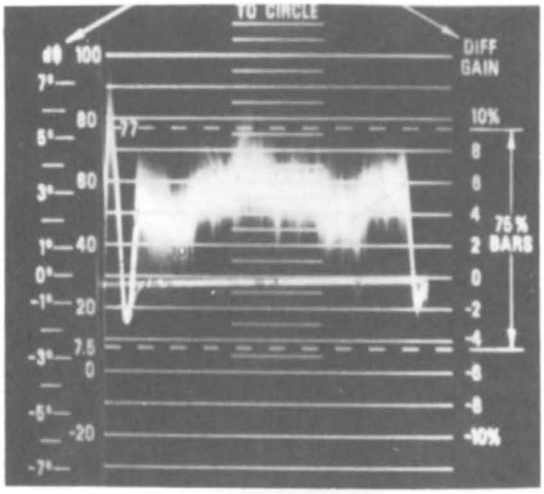
(B) DIFFERENTIAL PHASE

TYPICAL CODEC DIFFERENTIAL GAIN AND PHASE DISPLAY
FOR 40-IRE MODULATED RAMP TEST WAVEFORM
LOCKED SAMPLING (14.32 MHz)

FIG. 21



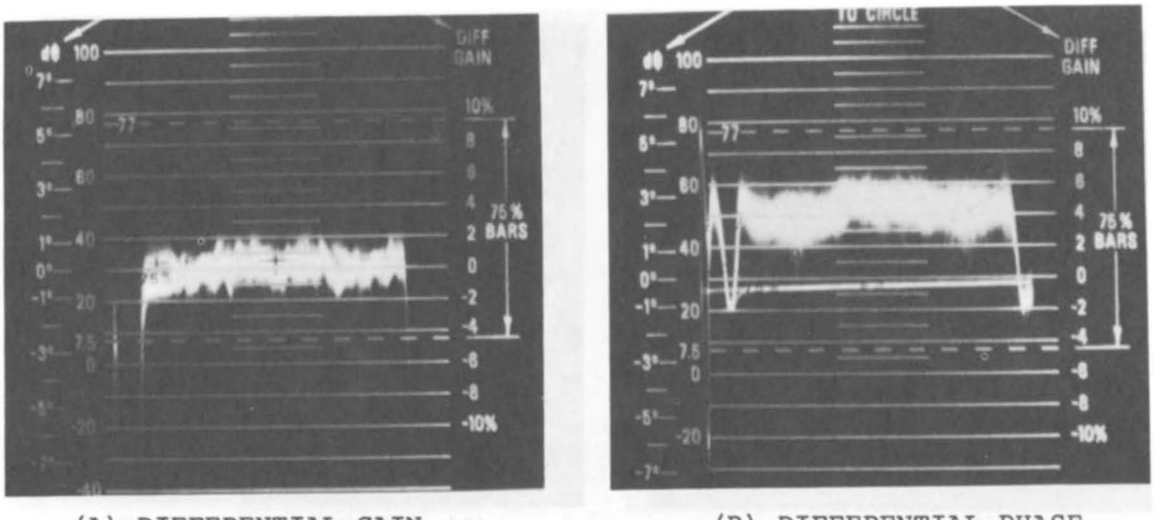
(A) DIFFERENTIAL GAIN



(B) DIFFERENTIAL PHASE

TYPICAL CODEC DIFFERENTIAL GAIN AND PHASE DISPLAY
FOR 20-IRE MODULATED RAMP TEST WAVEFORM
UNLOCKED SAMPLING (14.32 MHz $+\Delta f$)

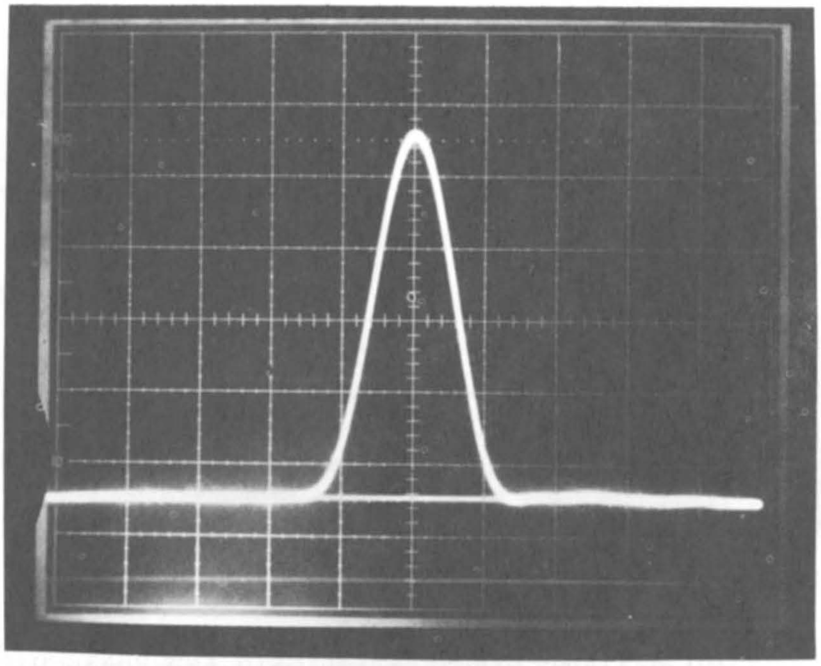
FIG. 22



(A) DIFFERENTIAL GAIN (B) DIFFERENTIAL PHASE

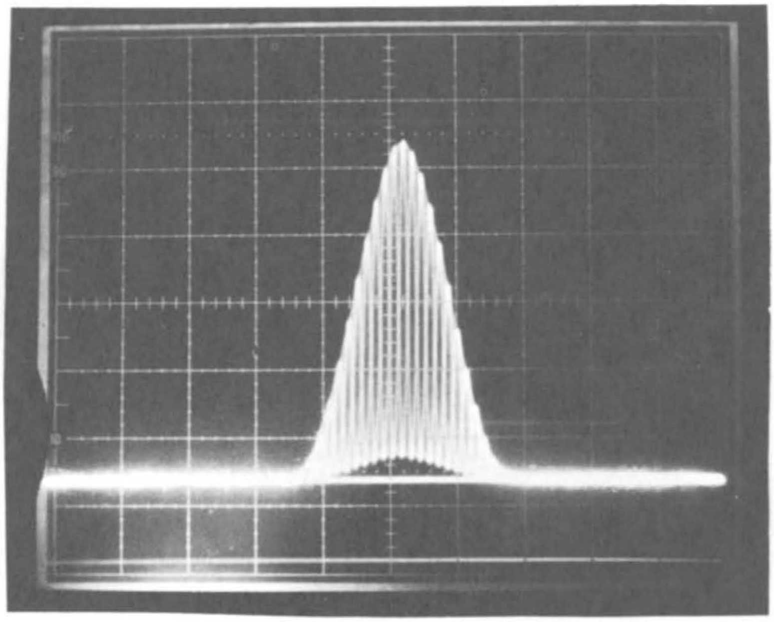
TYPICAL CODEC DIFFERENTIAL GAIN AND PHASE DISPLAY
FOR 40-IRE MODULATED RAMP TEST WAVEFORM
UNLOCKED SAMPLING (14.32 MHz + Δf)

FIG. 23



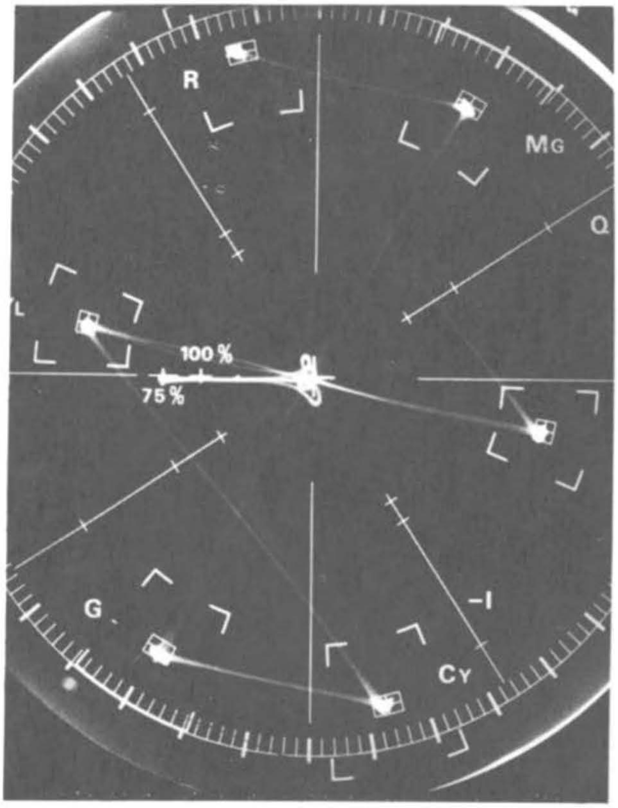
2T PULSE RESPONSE OF CODEC
HORIZONTAL SCALE: 200 NSEC/DIV.

FIG. 24



12.5T MODULATED SINE-SQUARED PULSE
RESPONSE OF CODEC FOR 14.32 MHz SAMPLING RATE
HORIZONTAL SCALE: 1 USEC/DIV.

FIG. 25



VECTORSCOPE DISPLAY OF CODEC
COLOR BAR RESPONSE - UNLOCKED
SAMPLING (14.32 MHz $+\Delta f$)

FIG. 26