A Sliding-Scale Direct-Feedback PCM Coder for Television

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A sliding-scale coder for television signals was built which extends the range of the quantizing scale by processing the input signal twice when the input signal exceeds a prescribed threshold. On the second pass the quantizing range is effectively moved outward to reduce the errors in coding large signals. Double processing nearly triples the number of quantizing levels of a basic three-bit coder. Measurements of the number of extra bits required, that is, those in excess of three-bits per sample show that they may be accomodated on a three-bit per sample transmission channel by reducing the sampling rate five percent. The experimental coder generates 19 *quantizing levels. Its performance approaches that of a seven-bit pulse code modulation coder. Busyness or streaking, common to most three-bit differential type coders, is eliminated. Acceptable pictures are reproduced with* ±5 *dB changes in the input signal's range. Over this range the signal-to-noise ratio of the reproduced pictures varies from* 47 *dB to* 54 *dB and the rise-time of a regenerated step-signal varies from* 1 *microsecond to* 1.45 *microsecond when the input signals rise-time is limited to* 1 *microsecond.*

I. INTRODUCTION

Differential, direct-feedback, and delta-modulation pulse code modulation systems take advantage of the television viewer's tolerance to brightness errors, especially in high detail areas of the picture.[1–5*] Analog signals must be quantized into a finite number of levels for conversion to digital signals. This quantization introduces errors in the reconstructed picture. These errors are lumped together under the name of quantizing noise which for differential pulse code modulation (PCM) systems is a function of the quantizer step size(s), the sampling rate, channel capacity, and filter characteristics. Quantizing noise may be classified into six visually subjective catagories: granular

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[*] This family of coders are hereafter referred to as differential coders.

noise, streaking, contouring, slope-overload, edge-busyness, and edge-stepping.

Granular noise is a high frequency noise, caused by individual sample errors, whose visibility is increased by amplitude differences from frame to frame. Contouring produces brightness steps in flat regions of the picture. Both of these defects may be decreased with proper filtering and decreasing the smaller step sizes. A reduction in contouring is usually made at the expense of increased granular noise.

Streaking results from mistracking between the coder and the decoder. The length is determined by the decoder's time constant.

Slope-overload, edge-busyness, and edge-stepping occur at large brightness boundaries which are not parallel to the scanning lines. These defects become increasingly visible as the brightness boundaries approach the vertical. Slope-overload appears as a smearing effect. This may be reduced by increasing the step size for large difference signals at the expense of increasing edge-busyness and edge-stepping. Edge-busyness appears as relatively large brightness errors jumping back and forth along the scanning line. This defect results from large errors at brightness boundaries whose jitter is increased with frame-to-frame amplitude differences and when the sweep rates are not locked to the digital processing rates. Edge-stepping appears as discontinuities in brightness boundaries because of amplitude differences along the continuum. This defect appears to crawl up and down the boundary when the sweep rates are not locked to the digital processing rates.

Some or all of these defects may be reduced, if not eliminated, through one or more of the following procedures:

(*i*) Companding the signal,
(*ii*) Increasing the number of levels and length of PCM words, and
(*iii*) Increasing the sampling and bit rate.

When the bandwidth and bit rate are fixed, more sophisticated techniques are required such as:

(*i*) Optimizing sampling rate or coder processing rate as a function of spatial frequency,

(*ii*) Adding levels as a function of slope amplitude.

(*iii*) Efficiently using time slots such as redundant signal areas and blanking periods.

Two types of sliding-scale differential coders were simulated on a computer.[6] The excellent results obtained in the simulation encouraged the building of a real-time sliding-scale coder.

The real-time sliding-scale coder was designed to process the input signal twice and introduce additional levels when the input signal exceeded a threshold. Double processing can increase the number of effective levels in a three-bit system to 22 at a moderate increase in circuit complexity. The additional information may be handled by reducing the sampling rate; or the additional information could be transmitted during the blanking period or in place of redundant signal components.

The experimental coder was limited to 19 levels. Its performance approached that of a 7-bit straight PCM coder. Slope-overload, edge-stepping, and granular noise were minimized. Edge-stepping was just perceptible when the sweep rates and the digital processing rates were unlocked. Edge-busyness and contouring were eliminated. Input signals varying over a ±5 dB range produced acceptable pictures. At midrange the peak-to-peak signal to root mean square noise was 50 dB; and with a 75 percent change in signal level, the rise-time increased from 1 to 1.15 μs. Over the input signal operating range of ±5 dB, a signal-to-noise ratio of 54 to 47 dB was obtained. Over the same operating range, and with a 75 percent change in signal level occurring in 1 μs, the rise-time of the output signal varied from 1 to 1.45 μs.

II. DIRECT-FEEDBACK CODING

The sliding-scale coder was built around a direct-feedback coder configuration. Briefly, direct-feedback coders function the same as DPCM coders, but the circuit is arranged to allow greater flexibility of filter design. Figure 1 is a schematic diagram of a direct-feedback

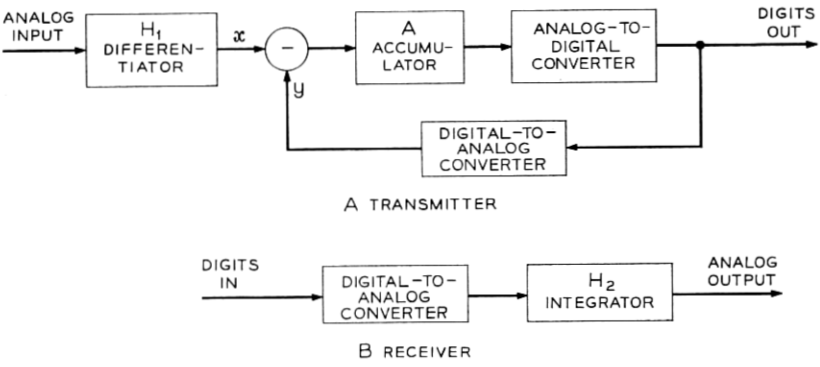


Fig. 1 — Block diagram of a direct-feedback PCM coder.

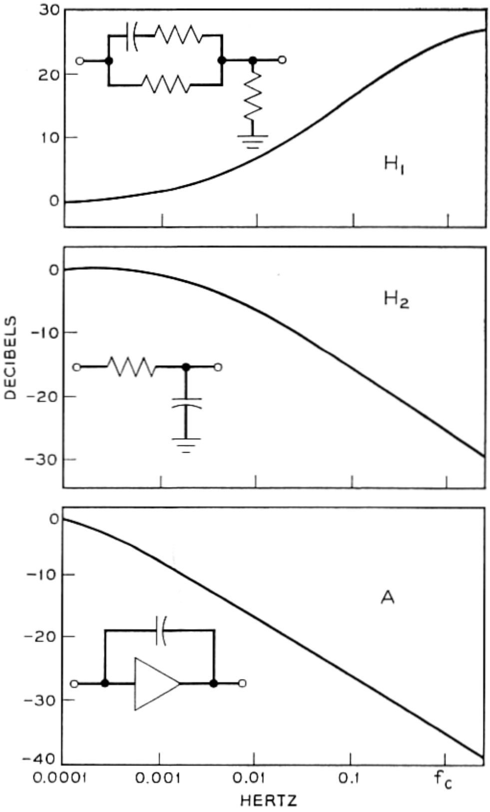


Fig. 2 — Filter characteristics of a direct-feedback PCM coder.

coder, and Fig. 2 shows typical filter characteristics. For television signals the preemphasis filter H_1 is a differentiating filter. The deemphasis filter H_2 is a short time integrator, approximately the inverse of H_1. The accumulator filter A in the feedback loop has a long time constant.

The feedback acts like a servomechanism trying to make the average value of the quantized signal, y, equal to the pre-emphasized input signal, x. The difference between x and y is accumulated in A and used to correct the quantized output.

Figure 3 shows a typical 8-level companded quantizer scale. The quantizer is tailored to the observer's perception; that is, fine quantum steps are used for small signal errors and coarse steps for large error signals. Optimally designed companded quantizers adhere to Max's rule for minimum distortion.[7] Max states that the decision levels must fall midway between the quantizer levels. In such a quantizer the error amplitude ranges between plus and minus half a quantum step over the range of the quantizer.

Even so, minimum distortion quantizers of three bits per sample or less are subject to considerable noise and are only marginally acceptable. The sliding-scale coder is an attempt to increase the subjective acceptability of predictive coders.

III. PRINCIPLES OF THE CODER

3.1 *Transmitter Coder*:

Figure 4a is a block diagram of a sliding-scale direct-feedback coder. It has the same functional blocks as a direct-feedback coder except for an AND gate and an elastic store. Assume a three-bit coder with the quantizer levels shown in Fig. 5. Switches S_1 and S_2 of Fig. 4a are closed at time t_1. The error signal out of the accumulator at time t_1 is quantized and fed back to the accumulator. If the quantizer output stays within the bounds of decision levels $+c$ and $-c$, the processing during that sample period is complete and one word describing

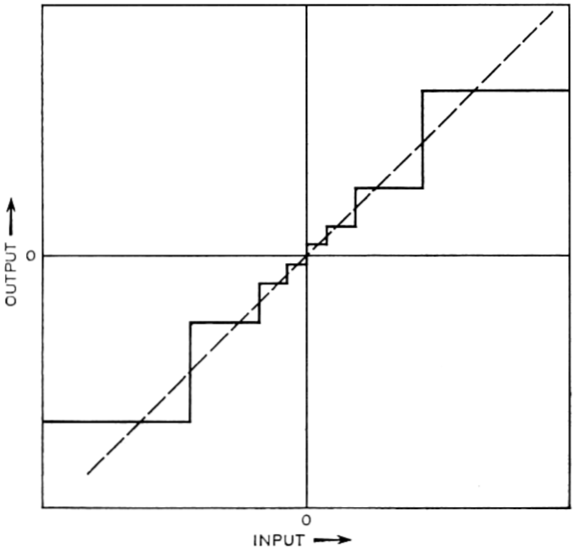


Fig. 3 — Typical eight-level companded quantizer scale.

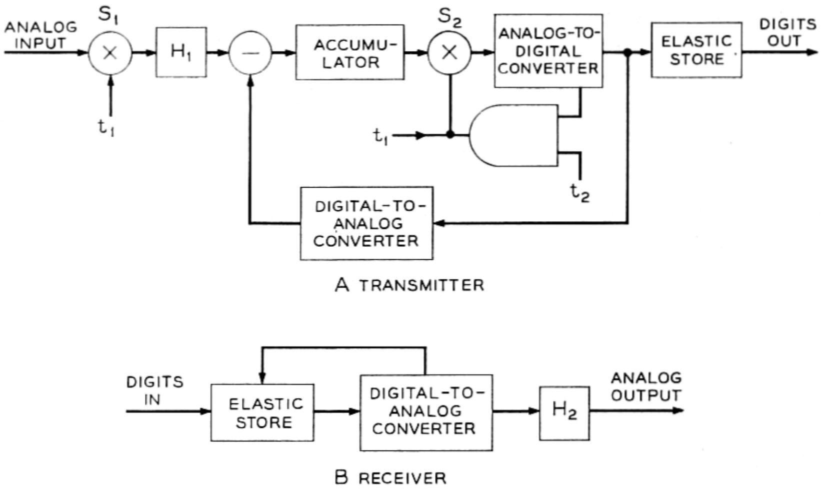


Fig. 4 — A sliding-scale direct-feedback PCM coder.

the error signal is generated. If decision levels $+d$ or $-d$ are generated they are also fed back to the accumulator; they reduce its error signal. In addition, levels $+d$ and $-d$ are used to open the AND gate. A pulse then passes through the AND gate at time t_2 closing switch S_2 during the same sample period. In so doing, the output of the accumulator, already coarsely corrected by level $+d$ or $-d$, has a fine correction applied to it during the sample period.

When levels $+d$ or $-d$ are generated, two words are produced in one sample period. To facilitate a uniform transmission rate the words are fed into an elastic store which feeds the transmission channel at a constant rate. The sampling rate may be reduced by an amount proportionate to the number of additional words so as not to exceed the channel bit rate capacity. When the sampling rate is reduced, the cutoff frequency of the low-pass filter must be reduced proportionately so as to reduce the effects of foldover (aliasing) and granular noise.

3.2 *Receiver Decoder*

Figure 4b is a functional block diagram of the receiver decoder. The output of the receiver elastic store is applied to the digital-to-analog converter. When a $+d$ or $-d$ level is detected by the digital-to-analog converter, a second word is taken out of the elastic store during that sampling period. The output of the decoder after integration by filter H_2 is a replica of the input analog signal at the transmitter.

3.3 *Quantizer Levels*

The technique of double processing the error signal may be thought of as one operation in which the quantizing scale's midpoint may occupy one of three positions: centered around zero, $+d$, or $-d$. Thus the midpoint of the quantizer scale slides up and down the scale as a function of the amplitude of the accumulator's error signal. For an 8-level quantizer six levels are available when the midpoint of the scale is centered around zero and 8 each when centered around level $+d$ or $-d$ as illustrated in Fig. 5b. For a three-bit coder operating in this mode, 22 levels are available during one sample interval if level $+d,-d$ is counted twice. Although the quantizing scale of Fig. 5b is not optimized, it is adequate for most television applications. The effectiveness of all 22 available levels may be increased by additional companding of the error signal, approximately the inverse of the initial companding, on the second pass.

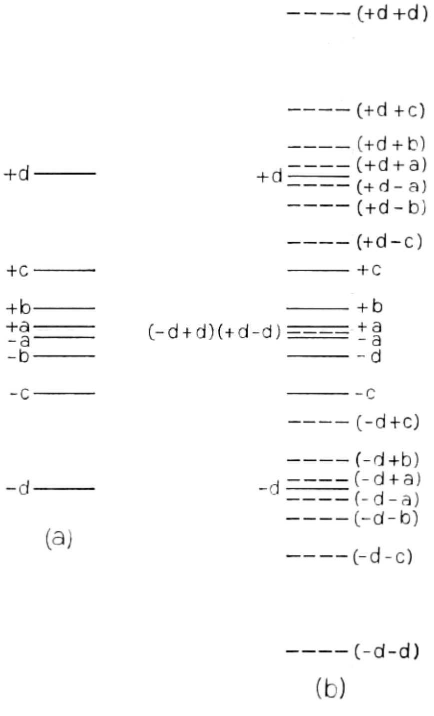


Fig. 5 — Quantizing scales: (a) an eight-level companded quantizing scale; (b) typical levels of a sliding-scale coder derived from the eight-level quantizing scale.

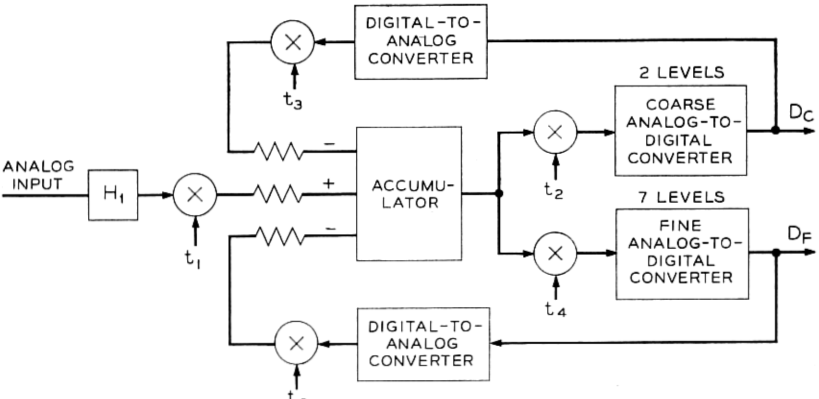
A general expression for the number of effective quantizer levels in a sliding-scale coder is

$$Q_L = (2^n - K) + (K2^m) \tag{1}$$

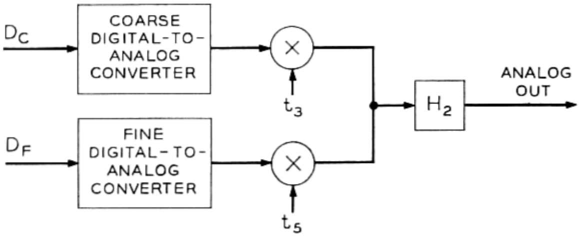
where 2^n is the number of levels the quantizer can generate, K is the number of levels which causes a double processing, and 2^m is the number of levels used when the midpoint of the quantizer scale is shifted from zero and where m usually equals n.

IV. EXPERIMENTAL SLIDING-SCALE CODER

Figure 6 is a block diagram of the experimental coder. This is a direct-feedback coder with the sliding-scale features added to it. This arrangement of the sliding-scale coder was used to increase its experimental versatility. The elastic stores were omitted since they do not directly relate to the quality of the picture if they have suf-



A TRANSMITTER



B RECEIVER

Fig. 6 — Experimental sliding-scale direct-feedback PCM coder.

ficient capacity. The design procedure of Brainard and Candy was followed for the direct-feedback coder.[3]

Two feedback paths were used, one for coarse and one for fine quantized levels. Several switches were used to control the timing of the operations. Each switch was closed for 50 ns with a 50 ns space between successive operations so that all operations were completed in the sampling period of 0.5 μs.

The companded quantizing scale for the experimental coder is shown in Fig. 7. The fine quantizer was designed with seven levels. Level a was set at zero volts. The five inner levels a, $\pm b$, and $\pm c$ satisfied Max's first rule for minimum distortion. The two outer levels, $+d$ and $-d$, of the fine quantizer were assigned the same code words as the two coarse quantizer levels, $+d'$ and $-d'$. (Notice that in Section III levels $+d$ and $-d$, and $+d'$ and $-d'$, respectively, have the same value).

The decision levels for $+d$ and $-d$ were set slightly higher than the decision levels for $+d'$ and $-d'$. Thus code words for levels $\pm d'$ will always preceed the code words for levels $\pm d$. This permits the receiver to identify and assign the correct level to the d words. Although the optimum quantizing scale was not determined, some information in this direction was obtained. The coder was not sensitive to changes in the fine quantizing scale when the $+d$ and $-d$ levels did not exceed ten percent of the peak input signal. The coarse levels $+d'$ and $-d'$ prefer to be slightly more than twice the value of $+d$ and $-d$.

Examination of the quantizing scale, Fig. 7, shows that the 19 levels are not efficiently used. For instance, levels $+d' \pm b$ and $-d' \pm b$ produce substantially the same results as the $\pm d' + a$ level with signal changes of this magnitude. Therefore, the effective number of levels is more like 15 instead of 19. Since excellent results were obtained with the fifteen "effective" levels the techniques which would permit the effective use of all 19 levels were not tried.

V. LARGE SIGNAL CHANGES

5.1 *Frequency of Occurrence*

The frequency of occurrence of the two outer levels, $\pm d'$, was measured for the two still pictures shown in Figs. 8a and c. The results are listed in Table I for three levels of input signal. Picture A refers to the picture shown in Fig. 8a and Picture C to the picture shown in Fig. 8c. The position of levels $\pm d'$ for picture A is shown in Fig. 9 for three levels of input signal.

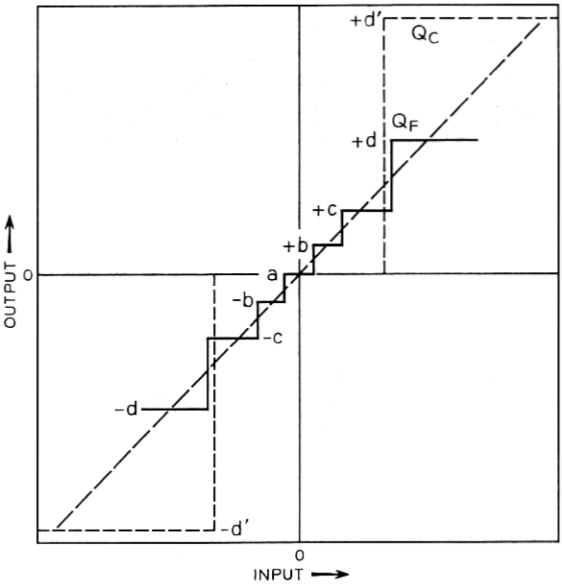


Fig. 7 — Companded quantizing scale of the experimental sliding-scale direct-feedback PCM coder.

5.2 *Capacity of Elastic Store*

The data of Table I provide a measure of the size of the elastic store that is required. Assuming that the average proportion of large changes per picture is the same as the average proportion for each line, an elastic store with a capacity of ten percent of the bits per line would be adequate to handle the three signal levels listed in Table

TABLE I—FREQUENCY OF OCCURRENCE OF LEVELS $\pm d'$ IN PERCENT OF TOTAL CHANGES FOR THREE INPUT SIGNAL LEVELS

Change in signal level	Picture A			Picture C		
	$-d'$	$+d'$	Total	$-d'$	$+d'$	Total
+5 dB	4.6	4.7	9.3	5.8	4.7	10.5
0 dB	1.1	1.2	2.3	1.6	1.8	3.4
−5 dB	0.4	0.6	1.0	0.4	0.4	0.8

Fig. 8 — Photographs of television pictures bandlimited to 1.0 MHz: (a) high detail picture without coding, (b) high detail coded picture with optimum input signal level, (c) low detail picture without coding, and (d) low detail coded picture with optimum input signal level. (The scan lines and printing screen in Figs. 8 through 11 cause moiré patterns that are not in the originals.)

I. If the average number of large changes per line exceeds ten percent, the coder degrades to an eight-level coder. This "graceful" degradation occurs at the edge of the picture which in most cases will not be noticed.

VI. EVALUATION OF CODER

6.1 *Coder Environment*

The signal source was a television system consisting of a 275 line, 2:1 line interlaced picture, displaying 30 frames per second. The television signal was bandlimited to 1 MHz and sampled at a 2 MHz rate. The transmission bit rate was 6 MHz with 3-bits per sample. The picture display was $5\frac{1}{2}$ inches by 5 inches and was viewed from $3\frac{1}{2}$

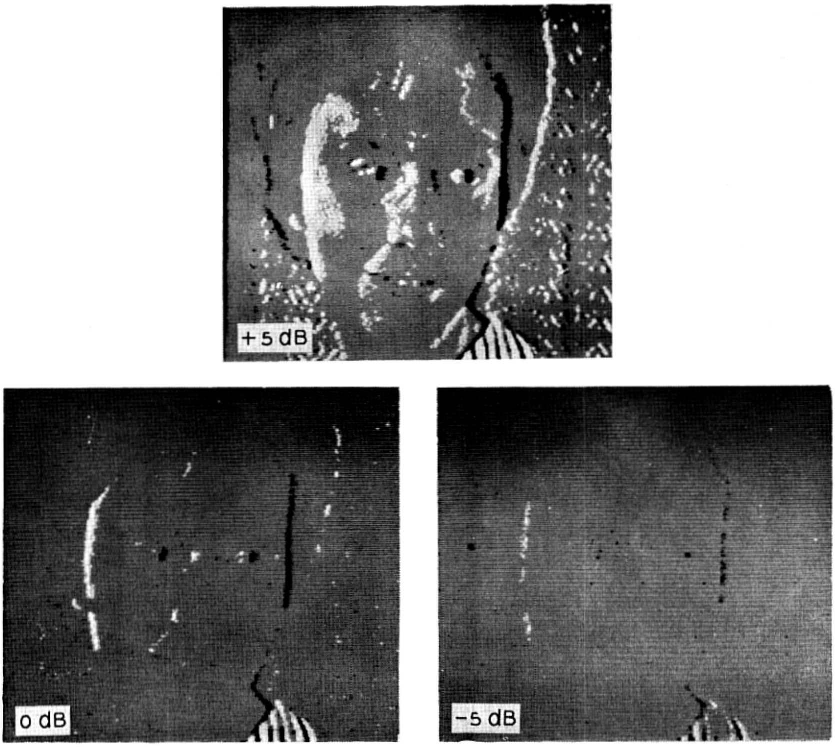


Fig. 9 — Television pictures showing where ±d' occurred for input signal level changes of —5dB, 0dB (optimum input level), and +5dB.

feet. The peak luminance was 70 foot lamberts and the room illumination was 100 foot candles.

6.2 *Picture Material*

Two types of still pictures (see Fig. 8) were used for the subjective evaluation; one with great detail and one with little detail. Evaluations were obtained for input signals which varied over a ±5 dB range. Figs. 8a and c show the uncoded pictures passed through the same low-pass filters as the coded pictures. Figs. 8b and d show coded pictures at the optimum input signal level. Fig. 10 shows the detailed picture with a −5 dB(a) and a +5 dB(b) change in input signal.

Photographs should be used with care in evaluating television presentations. Long exposures of photographs, compared with television frame time, will integrate noise and motion defects out of television pictures. The photographs of Fig. 8 may be compared except for the granular noise defects which appeared in Figs. 8b and c. The granular signal-to-noise ratio of these two pictures was 50 dB. Fig. 10a shows some of the effects of granular noise that appeared in the television picture. For this picture the input signal was reduced 5 dB from the reference level and had a granular signal-to-noise ratio of 47 dB. Fig. 10b illustrates slope-overload defects which occurred when the input signal was increased by 5 dB from the reference value. This defect is most apparent in the young woman's blouse. The granular signal-to-noise ratio in this case was 54 dB.

6.3 *Evaluation*

Evaluation of the coder using live subjects indicated that the defects listed in this section were more severe for the two still subjects. Therefore only the still subjects were used in the evaluation.

The six types of noise associated with differential type PCM coders were evaluated. The six types of noise are: granular noise, streaking, contouring, slope-overload, edge-busyness, and edge-stepping. These were evaluated subjectively by the author, except for slope-overload. The subjective evaluation was conducted on pictures when the sweep rates were locked to the digital processing rates and when they were not.

Contouring, edge-busyness, and streaking were not perceptible in either picture whether or not the sweep rates and the digital processing rates were locked. However, when the ratios between the outer levels,

Fig. 10 — Detailed coded picture at two input signal levels: (a) decrease of 5 dB from optimum; (b) increase of 5 dB from optimum.

$+d'$ and $-d'$, and the inner levels were different between the transmitter and receiver, streaking did occur. The threshold for streaking permitted a difference in ratios of ±4 percent. Worst case transmission errors which occur in the d' and $-d'$ words produce an error signal which decays exponentially to zero in 6 μs and appears as a streak about 0.05 inches long on the picture. The photographs in Fig. 11 show the effect of an error locked to the line rate in a $-d'$ and a $+d'$ word.

Edge-stepping was not perceptible when the sweep rates and the digital processing rates were locked. When they were unlocked, edge-stepping was just perceptible at large brightness boundaries.

Slope-overload was measured objectively. A slide which provided a 75 percent white to black transition along the scanning lines was placed in front of the camera. An oscilloscope was used to measure the transition time from white to black for several input levels at the input to the monitor. The results are shown in Fig. 12 and a typical waveform shown in Fig. 13. The rise-time varied from 1.0 to 1.45 μs over a 12.5 dB range of input signals, where the input signal was limited to a rise-time of 1.0 μs. At the optimum input signal level (0 dB), the rise-time increased to 1.15 μs. There was no measurable difference in the slope response when the sweep rates and the digital processing rates were unlocked.

Granular noise was measured subjectively by comparing the coded picture with an uncoded picture to which gaussian noise had been added. The granular noise resulting from coding was a high frequency

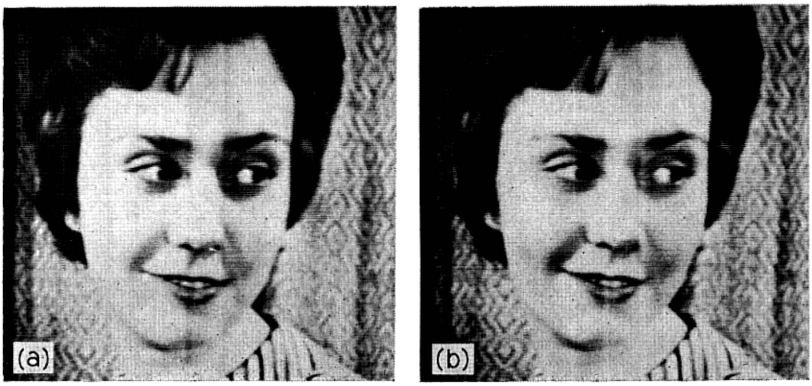


Fig. 11 — Effect of transmitting erroneous $\pm d'$ word when the erroneous word is locked to the scanning rates: (a) $-d'$ error, (d) $+d'$ error.

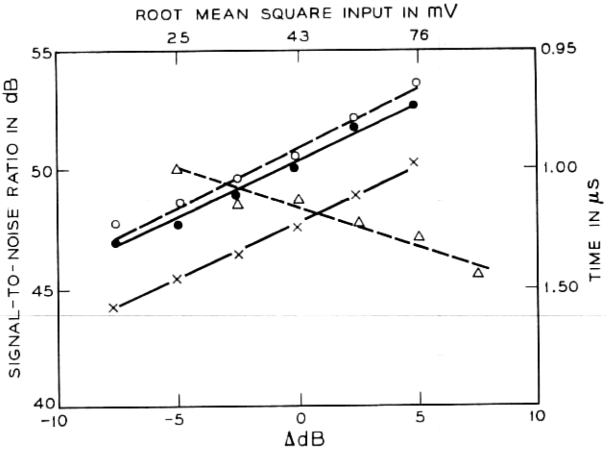


Fig. 12 — Measurements of signal-to-noise ratio and slope-overload as a function of input signal level for the sliding-scale coder.

noise occurring at or near the sampling rate. Since the gaussian noise occupied the full band, some subjective weighting was necessary. The uncoded picture with added noise was passed through the same low-pass filters as the coded picture. The two pictures with equalized contrast were alternately switched onto the monitor and the added noise adjusted until they were judged subjectively equal. The signal-to-noise was measured in terms of peak-to-peak signal to root mean square noise on the uncoded picture with added noise. The results are shown in Fig. 12. The equivalent signal-to-noise of the two test pictures was substantially the same, ranging from 47 dB to 54 dB over an input signal range of 10 dB. With the input signal level optimized (0 dB) the equivalent signal-to-noise was 50 dB. The signal-to-noise of a companded 3-bit differential pulse code modulation coder, using the same measuring technique, was 45 dB. When the picture sweep rates and the digital processig rates were unlocked, the signal-to-noise was decreased by 3 dB. This decrease in signal-to-noise is caused by sampling position differences from frame to frame at the smaller brightness boundaries.

VII. CONCLUSIONS

This experiment, with the sliding-scale coder, demonstrated that 15 "effective" levels are sufficient to produce a high quality television

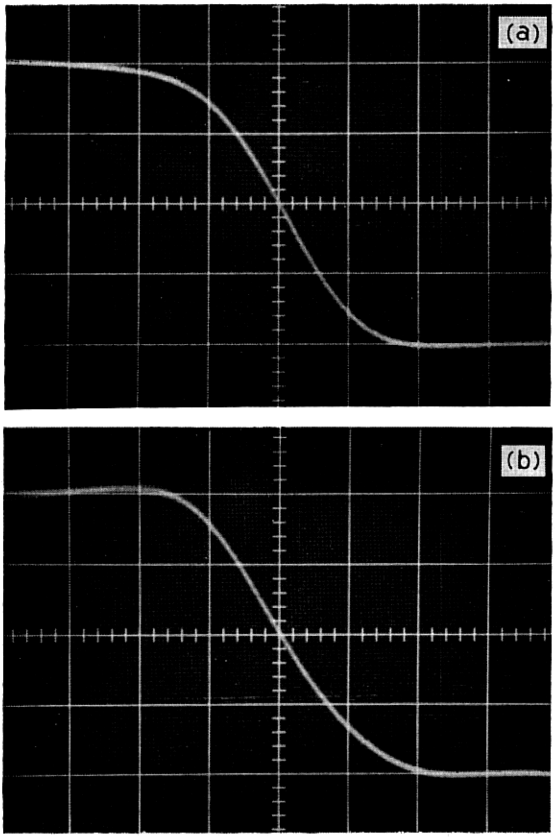


Fig. 13 — Waveform response to a 75 percent change in brightness level when bandlimited to 1.0 MHz: (a) analog response; (b) response of sliding-scale coder.

picture with a small increase in circuit cost and complexity. The increase in circuit cost and complexity is offset by the double processing technique which reduces the requirements on the number of threshold and quantizing circuits.

The most significant improvement offered by the sliding-scale coder is in the rendition of the subjectively critical large brightness changes. The coder performance approaches that of a seven-bit PCM system.

A reduction in the sampling rate of about five percent permits the sliding-scale coder to nearly triple the number of quantizer levels without an increase in channel bit rate.

VIII. ACKNOWLEDGMENTS

Discussions with J. C. Candy, C. C. Cutler, H. Kogelnik, and J. O. Limb were most helpful. Mr. R. K. Jackson assembled the coder.

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