Low-Resolution TV: Subjective Effects of Noise Added to a Signal

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(Manuscript received September 19, 1966)

The visibility of noise in a television presentation is related to the spatial-frequency and flicker-frequency components of the noise display. The visibility of sine wave interference, which generates a sine wave grating on a TV screen, demonstrates remarkable linearity by giving a good approximation to the visibility function measured with narrow bands of noise.

A difference in visibility between moving and stationary gratings produces a difference between noise visibility in TV and photographs. This fact is important in evaluating the computer simulation of a system by calculations for a single TV frame. The variation of visibility with motion predicts increased visibility for additive noise in a television frame repeating system. Applications to predistortion and reconstruction filters for transmission of analog and digital TV signals are discussed.

I. INTRODUCTION

For the design of a television communication channel it is desirable to have a figure of merit for comparison of channels. As our sophistication in the design of communication channels increases, so we must also increase our sophistication in defining and measuring a suitable figure of merit. As a measure of merit we may use the power spectrum $N(\omega)$ of the error, or noise, added in the channel which can be measured for all frequencies, ω, in a given transmission system. However, the ultimate receiver is a person viewing the picture, and his sensitivity to noise superimposed on the picture depends upon the distribution with frequency of that noise. This dependence of the viewer's sensitivity to noise can be considered equivalent to a linear filter and a linear detector. We will call this sensitivity function a subjective noise-weighting function, $W(\omega)$, defined on the video bandwidth, 0 to Ω.[1,2,3,4] This subjective noise-weighting function gives the value at each frequency of the relative contribution of noise to an overall figure of merit. We define this figure of merit as $1/P$, where

$$P \equiv \int_0^\Omega N(\omega)W(\omega)\, d\omega, \tag{1}$$

and P the weighted noise.

The subjective noise-weighting function is the transfer function of the system consisting of the television kinescope and human visual system specified as a function of the electrical video-signal frequencies. The input is an electrical signal; the output is the response of the viewer. It is convenient for discussion to divide this function into three parts.

The first portion of this function, which we call T_a, is the transfer function of the kinescope. It is a mapping of a 1-dimensional electrical signal to a 2-dimensional picture. The second part of the function, T_b, is the modulation transfer function of human vision. This function, which has been called the sine-wave response, is the transmission from object to interpreted image in the brain. The third part, T_c, is the translation from the image in the brain to a verbal response. The weighting function is the product of these 3 functions:

$$W = T_a T_b T_c, \tag{2}$$

where

T_a = transfer function of kinescope,
T_b = transfer function of vision,
T_c = translation to words.

Measurements are made of the complete transfer function $W(\omega)$ and are accomplished by comparing the viewer's subjective response to noise bands having different frequency components. If two noise bands with power spectral densities N_1 and N_2 are found to be subjectively equivalent, then and only then, we have

$$\int_0^\Omega W(\omega)N_1(\omega)\, d\omega = \int_0^\Omega W(\omega)N_2(\omega)\, d\omega. \tag{3}$$

By using a sufficient set of noise bands we can calculate $W(\omega)$ to any desired accuracy.[2]

By making subjective comparisons between the interfering effects of sine waves and white noise of various power levels, we would expect to be able to evaluate the subjective noise-weighting function most easily. Results with sine wave interference have been obtained by others.[5] The weighting function as determined by using sine waves exhibits rather extensive structure related to horizontal-line and frame or field-rate multiples.

It is possible to subjectively compare the interfering effect of wide bands of noise to that of flat noise. By this procedure we smooth out all the fine structure. Results of such experiments have been published.[2,3,4] This smoothed version of the weighting function shows a reduced visibility for high video frequencies.

The purpose of this paper is to clarify the effect of random noise on a video presentation by examining in more detail the subjective effects of noise added to a video signal. In particular, it is desired to determine the fine structure and microstructure of the subjective noise-weighting function related to multiples of the horizontal line rate and the frame rate, respectively. This requires measurements with noises whose bandwidths are small compared to the horizontal line rate but wide enough to appear as noise. Noises of bandwidths which are small compared to the frame rate are also required. These are effectively sine waves

Applying measurements of sine wave visibility to the noise-weighting function requires an approximate linearity of the system. The question of linearity is considered through all the following discussion.

II. NONLINEARITY

The use of the noise-weighting function in (1) implies linearity of the system. There is a problem because, in fact, the system is not linear; the translation from electrical signal voltage to luminance in the kinescope is nonlinear, and vision is not linearly sensitive to luminance. This fact disavows the linear superposition of noise power in (1). However, for a reasonable transmission system the signal-to-noise ratio must be sufficiently large, say 30 to 40 dB, that this nonlinearity will not be significant in regard to luminance variation due to the noise. This approximation is justified by the consistency of the results. It must be remembered that the kinescope nonlinearity results in a dependence of the transmission factor for small signal variations superimposed on the average luminance level. These nonlinearities give the well-known result that a small signal is most visible when superimposed on a dark gray area of a kinescope presentation.

The translation of a scene into a verbal response is obviously a nonlinear function. By proper choice of test procedure the effect of this nonlinearity can be made small.

III. T_a, TRANSFER FUNCTION OF KINESCOPE DISPLAY SYSTEM

3.1 *Spatial Noise*

In a television receiver the scanning procedure generates a picture with 2 spatial dimensions and 1 time dimension from a video signal with 1 voltage and 1 time dimension. The noise superimposed on the video signal is also mapped onto the picture with 2 spatial dimensions and 1 time dimension.

In order to relate spatial frequencies to video frequencies, we can refer to Mertz and Gray[6] or to Huang[7] where a complete theoretical description of the scanning process is given. Although we will later use some of their results we will here consider a different viewpoint that will, we hope, aid our understanding of noise in a television system.

The reconstruction of the 2-dimensional picture from a video signal involves aligning successive segments of the signal (translated to brightness values) below one another to form a raster on the kinescope. For convenience we consider a square raster; results are easily extended to a rectangular raster. This square raster is shown in Fig. 1. The segments of the signal appear as gently sloping lines almost parallel to the horizontal or x direction. For the square picture, the picture height equal to the picture width is taken as the unit of linear measure. Let L be the number of lines in a complete picture. It must be recalled that in a real system a portion of the picture is blanked for retrace.

For a single frame, consider a narrow strip along a scan line. This strip is merely a segment of the video signal. Therefore, there is a linear relation between video frequencies, f, and spatial frequencies along the raster line designated r. This is written

$$\frac{f}{f_h} = r \tag{4}$$

for spatial frequencies measured in cycles per picture width, where f_h is the horizontal line scanning frequency.

Now consider a narrow vertical strip of the frame. Successive points down this strip represent samples of the original signal spaced at $1/f_h$ intervals. Sampling and modulation principles can be used to derive information about the presentation in the vertical direction as a function of the original signal.

The original video signal may contain time-varying components from very low frequencies to several hundred times f_h. In the sampled signal appropriate sidebands at each sampling frequency multiple will contain components that fall in the frequency band between 0 and $(\frac{1}{2})f_h$. To understand this, consider the triangular-shaped power spectrum of a video signal shown in Fig. 2 (a). This signal is centered on the fourth harmonic of f_h. With a sampling frequency of f_h, the sampled version contains this triangular shaped power spectrum centered at each multiple of f_h as shown in Fig. 2 (b). Since the original band of

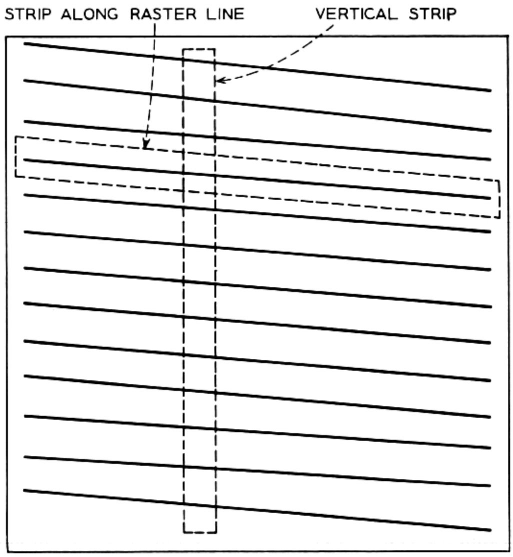

Fig. 1 — Diagram of television raster presentation.

signal could have occurred anywhere in the range 0 to Ω we see that each input frequency of the video signal will generate a component that falls in the band between 0 and $(\frac{1}{2})f_h$ as well as in every band between pf_h and $(p \pm \frac{1}{2})f_h$, for any integer p.

If we consider only the points in the vertical strip, there is a linear relation between the sampled-signal frequencies f_s and spatial frequencies in the vertical direction n,

$$f_s = f_v n \ , \tag{5}$$

where f_v is the frame frequency. The appropriate scale for spatial frequency is shown in Fig. 2 (b) with the sampled spectrum. From this we see that a low frequency, $f_s \ll f_h/2$, is presented in the vertical strip as a low spatial frequency, i.e., a gradual change of brightness down the slice. A frequency f_s near $f_h/2$ will be presented in the vertical strip as a high spatial frequency in the sense that it is presented as alternate light and dark spots down the slice. In the vertical strip we see mainly those spatial components corresponding to frequencies between 0 and $f_h/2$, since higher spatial frequencies are generally beyond the visual acuity limit and/or the cutoff frequency of the low-pass spatial-filtering action of the kinescope beam.

In reference to Fig. 2, we see that a video frequency near any multiple

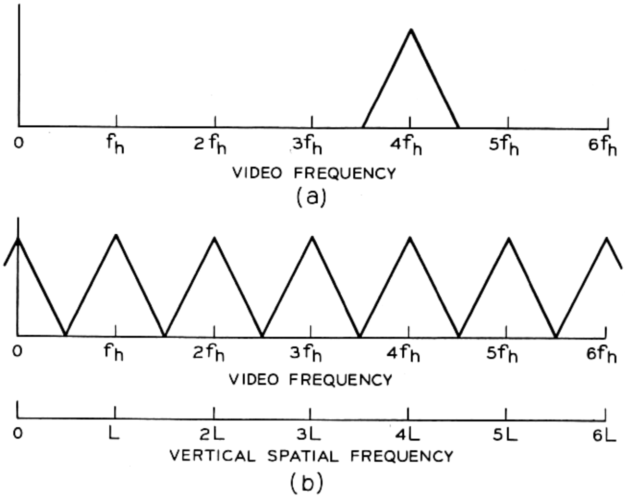

Fig. 2 — (a) Triangular spectrum of input video signal; (b) sampled spectrum of (a) as function of video frequency and vertical spatial frequency.

of f_h, at the peak of the triangle, will appear as a low spatial frequency. A video frequency near $(p \pm \frac{1}{2})f_h$, at a bottom corner of the triangle, will appear as a high spatial frequency. All other components will appear as appropriate intermediate spatial frequencies.

For a general relationship between video frequencies, f, and spatial frequencies for a stationary picture we have, as derived by Mertz and Gray,[6]

$$f = f_h m + f_v n, \tag{6}$$

where m is the spatial frequency in the horizontal direction. Since the scan lines are not quite horizontal m is not equal to r except when n equals zero. In this case of a stationary picture, m and n are integers, and f is restricted to multiples of f_v. Each pair (m,n) corresponds to a stationary grating in the presentation. Each frequency, f, generates a sequence of pairs (m,n) and corresponding gratings. This set of gratings is exactly equivalent to the set of spatial frequencies described as generated by the sampling process. Again we see principally those gratings for which m and n are less than $L/2$. Motion in the presentation can be considered as a modulation on the values of m and n or as an additional term in (6). Conversely, a frequency that is not a multiple of f_v produces a moving grating in the reproduced scene. For our purposes, given any input frequency, f, we want to select that value of m such that $n < L/2$. If we choose m such that

$$m - \tfrac{1}{2} \leqq f/f_h \leqq m + \tfrac{1}{2}, \tag{7}$$

then (6) gives the desired value of n such that $n < L/2$.

3.2 *Application to Measurements*

Given as the input to the video presentation a narrow band of noise with a flat power spectrum between pf_h and $(p \pm \frac{1}{2})f_h$ for any integer p, that is, flat noise replacing one-half the triangle spectrum of Fig. 2(a), then in a strip along y this would appear in the same way as a band of noise extending from 0 to $(\frac{1}{2})f_h$, that is, a flat band of spatial frequencies between 0 and $L/2$ cycles per picture height, abbreviated *c/ph*. For an input noise signal flat over a bandwidth a few times f_h, we can assume the spatial noise as it appears in the vertical strip to be nearly flat over its entire range, since the effects of the edges of the input would be small. For an input noise of sufficient bandwidth, the vertical spatial-noise spectrum is nearly independent of the center frequency and bandwidth of the input noise. Therefore, the gross character of the noise-weighting function measured with wide bands of noise depends almost entirely on the horizontal spatial frequencies.

To examine the procedure for measuring the fine structure, consider an input noise with bandwidth narrow compared to f_h. If the center of the band is near pf_h, for integer p, the vertical spatial-noise spectrum consists of low spatial frequencies only. But if the center of the band is at $(p \pm \frac{1}{2})f_h$, then the vertical spatial-noise spectrum consists of high spatial frequencies. For variations in the center frequency between pf_h and $(p \pm \frac{1}{2})f_h$, the horizontal spatial-power spectrum would have a relatively small change, while in the vertical direction the change is from one extreme to the other; from low spatial frequencies to high spatial frequencies. The above should hold true regardless of the value of p. Therefore, the fine structure of the noise-weighting function depends on vertical spatial frequencies.

It is of interest to note that with an input noise bandwidth of f_h we should expect to find almost no variation in subjective response for a center frequency variation from pf_h to $(p + \frac{1}{2})f_h$, since in all cases the vertical spatial-noise spectrum would be flat over its entire range and the change in the horizontal direction would be small.

To predict the weighting-function variations between multiples of the horizontal-line frequency, we have to resort to the constituent gratings described above. For the grating where the horizontal frequency is m and the vertical frequency is n, then the spacing between bars, λ, is given by

$$\lambda = \frac{1}{\sqrt{m^2 + n^2}}. \tag{8}$$

Consider the video frequency range from f_h to 1.5 f_h. At f_h, $m = 1$ and $n = 0$ gives $\lambda = 1$. At 1.5 f_h, $m = 1$, and $n = L/2$ gives $\lambda \approx 2/L$ (since $L \gg 1$). For a similar frequency range at the top of the band between $Lf_h/2$ and $(L + 1)f_h/2$, at $Lf_h/2$ then $m = L/2$ and $n = 0$ gives $\lambda = 2/L$, and at $(L + 1)f_h/2$ then $m = L/2$ and $n = L/2$ gives $\lambda = \sqrt{2}/L$.

From these numbers, we predict that for low m the variation of W with n, the fine structure, will be large and roughly equivalent to the variation over the complete range of m. For large m, the variation of W with n should be rather small.

3.3 *Flicker Noise*

Consider a succession of frames, again assuming that there is no interlace. Each frame constitutes a sample of the input noise. Any single point in the picture represents a time sample of the noise voltage translated to a luminance value spaced $1/f_v$ in time where f_v is the frame or vertical frequency. Sidebands at multiples of the sampling frequency f_v contain components that appear as flicker frequencies between zero and $(\frac{1}{2})f_v$. For any integer p, input frequencies near pf_v appear as low flicker frequencies and frequencies near $(p \pm \frac{1}{2})f_v$ appear as flicker frequencies near $(\frac{1}{2})f_v$. For these flicker frequencies varying from zero to $(\frac{1}{2})f_v$ we should expect a subjective variation in visibility. The higher frequencies of the sampled function we expect to be insignificant due to the sharp cutoff of human vision. Because of this variation we expect a microstructure to be imposed on the noise-weighting function. By measurements with sine wave interference, one can determine this microstructure, whereas with relatively wide bands of noise greater than f_v, the effect of this microstructure is smoothed out.

3.4 *Small-Signal Transfer Function of Kinescope*

We can now give a general discussion of the operation in the kinescope at the system receiver considering only the principal gratings seen. For any sine wave component of the input video signal a sine wave grating is presented on the kinescope screen. The grating has horizontal and vertical spatial-frequency components m and n given by (6) and (7). The spacing between grating bars λ is given by (8).

The grating has an apparent movement in a direction perpendicular to the bars of the grating. This apparent motion can be described as a traveling wave. The luminance is given by

$$I = A + B \sin 2\pi(Ft + x/\lambda). \tag{9}$$

The constants A and B depend on the average luminance and modulation amplitude. The variable x is along the direction of apparent motion. The frequency F is given in terms of the input video frequency f by

$$F = f - pf_v , \tag{10}$$

where p is an integer such that $|F| < f_v/2$.

The velocity of the grating v is given by

$$v = F\lambda \tag{11}$$

in picture heights per second. For small changes in f, F can be made to vary from 0 to $F_v/2$. Since λ is almost unchanged, then v varies over a large range.

Since the translation from input voltage to kinescope luminance is nonlinear, for a given small superimposed input signal voltage variation the transmission to luminance depends on the average signal level, or luminance level, in the area under consideration.

IV. T_b, MODULATION TRANSFER FUNCTION OF VISION

The response of the visual system to sine wave gratings is called the modulation transfer function. This function is a subjective effect and can only be determined by subjective measurements. The general subject of visual response is of interest to many people and extensive data on this function have been published, some of which is described below.

The visual response as a function of spatial frequency has a peak at an intermediate spatial frequency. The psychophysical phenomenon that leads to this response has been described[8] as a negative contribution to the response corresponding to a point on the retina due to luminance values at surrounding points. The visual effect is apparent as overshoot at luminance edges and is called Mach bands after Mach who first described it.

Lowry and DePalma[9,10] have measured T_b for step-function and sine wave inputs. Their measurements, at an average luminance of 68 cd/m², show a peak in visual response at about 15 c/mm measured on the retina. This is not what might at first be expected from consideration of the smoothed form of the noise-weighting function where the response has been shown to decrease with frequency. This has led to published discussions[11,12] concerning this difference.

We find from data presented by Schade[13] and by Schober and Hilz[14] that the location of the response peak is a function of average luminance. Schade's measurements were made with a television system, but, unfortunately, his data are normalized and the curves at different luminance levels cannot be compared.

For moving gratings Fowler[15] has reported measurements at one luminance level and one spatial frequency. His results show a peak in the visibility of a moving grating on a TV screen with motion corresponding to a frequency of luminance change at one point in the scene of 5 to 7 Hz. Davson[16] has reported Strughold's measurements that show an increase in acuity of the visual system when the target is illuminated by a source flickering at 5 Hz. This increase in response to a frequency of 5 Hz can be attributed to a negative after-image at a delay of 0.1 second as reported by Bryngdahl.[17]

Measurements at zero spatial frequency, when the entire field flickers, show a peak in response at a flicker frequency of 10 to 15 Hz.[18] The response to flicker at zero spatial frequency is dependent on the angle subtended by the flickering field and on the average luminance of the area surrounding this field.[18]

The effect of orientation of a grating on visual acuity has been reported by Higgins and Stultz.[19] They find equal acuity for horizontal and vertical orientation, but a 12 percent reduction in acuity for a grating oriented at 45° to horizontal or vertical.

The modulation level of experiments must be considered. Measurements of the modulation transfer function have been made at threshold and suprathreshold levels. Some measurements over a very wide modulation range[8] show some variation with the magnitude of modulation. We are here considering only very low modulation levels where we expect visual response to vary linearly with input modulation.

Adding two spatial frequencies not harmonically related offers no problem of linearity due to relative phase. However, adding of harmonic spatial frequencies which can form sharp edges in a picture may well be a function of relative phase. Campbell and Robson[20] find that harmonically related spatial frequencies are detected independently.

It is apparent that the visibility of a grating depends on many variables. For a complete understanding of the modulation transfer function, we require knowledge of the variation of visibility with each of these independent variables.

V. T_c, TRANSLATION TO WORDS

In the design of communication channels, the prime consideration is for best communication in spite of degrading noise. The weighting function should be a measure of the degradation or annoyance of the superimposed noise. In actual measurements, the viewer is instructed to make his decisions by considering his ability to see the picture information in the presence of the noise. Since it is readily apparent that the noise is the variable, this noise becomes of major interest to the viewer. Hence, his decision tends to be based on visibility of the noise. For this reason, measurements are reported as a measure of visibility of noise. In the application of the subjective noise-weighting function it must be assumed that a linear relation exists between visibility and annoyance.

Absolute value judgments of a viewer are not very reliable, though they can be improved by comparisons to a set of standards. When noise power can be easily changed as in the work reported here, it is useful to make direct comparisons of noise bands; one noise band is attenuated until equally visible to another. One noise band, say flat noise, can be used as a standard in all measurements. An easily measurable level of visibility is the threshold of visibility. Both these latter procedures use an easily identified visual response that minimizes the effect of translation to words.

VI. NOISE-WEIGHTING FUNCTION MEASUREMENT

6.1 *Procedure*

The video system used presents a square picture with 160 lines and a video bandwidth to correspond to 160 samples per line. Approximately 10 percent of each line and frame time is blanked for retrace. Sixty frames per second are presented with no interlace. The horizontal line frequency f_h is 9.6 kHz. Synchronization of the monitor was accomplished by a sync signal separate from the video signal. The picture transmitted was obtained from a slide of "checkered lady." This presentation is shown in Fig. 3. Viewing was from a distance of 8 times the 4.5-inch picture height. Room illumination was about 400 lux and picture highlight luminance about 170 cd/m^2. The test was to determine the relative visibility of the noise in the presence of this still picture.

Fig. 4 shows a block diagram of the equipment assembled for this experiment. The output of a white-noise generator was passed through

Fig. 3 — Picture used as presentation for noise measurements.

a low-pass filter. This noise was modulated by means of a modulator balanced for carrier suppression. The output was then further filtered to remove baseband and harmonic components to give the desired double-sideband suppressed-carrier signal. The noise bandwidth for any carrier frequency was determined by the single low-pass filter. This band of noise was added to the video signal and displayed.

Since the double-sideband noise signal is not Gaussian it was intercompared with single-sideband noise and noise passed through a band-pass filter. The noise bandwidth in each case was about 2 kHz. The noise band was centered in each case at 1.5 f_h, or 14.4 kHz. For the same power level, these three noise signals were found equally visible.

Referring to Fig. 4, the output of the white noise generator was used as a standard for comparison. The narrow band of noise of 2 or 9.6-kHz bandwidth had an rms level of 1 volt before attenuation. The reference white noise had an rms level 37.4 dB below 1 volt rms. The noise in either case was added to a 1-volt peak-to-peak picture signal.

The viewer could switch back and forth between the two presentations—the picture "Checkered Lady" with either the reference noise or narrow band of noise added. The variable attenuator was adjusted by the viewer until he found the noises in the two presentations equally visible. The attenuation value of the narrow-band noise is taken as the measure of visibility.

6.2 *Results*

Using the noise bandwidth 9.6 kHz, visibility measurements were made with the center frequency at 2.5 and 3 times f_h. The difference in attenuation for equal visibility was 1.0 dB.

Measurements of the smoothed version of the noise-weighting function were made using the 9.6-kHz band of noise. The band was always centered on a harmonic of f_h. the average results are given in Table I and shown graphically connected by a solid line in Fig. 5.

Measurements of the fine structure of the weighting function were made using the 2-kHz bands of noise centered at harmonics of f_h and midway between harmonics of f_h. The average results of these measurements are also given in Table I. These data are plotted in Fig. 5. The dashed lines connecting the data points represent the envelope of the fine structure of the noise-weighting function.

6.3 *Discussion*

The 9.6-kHz band of noise used in the experimental measurements almost smooths out the fine structure of the noise-weighting function. That it does not is to be expected since the noise generator is not

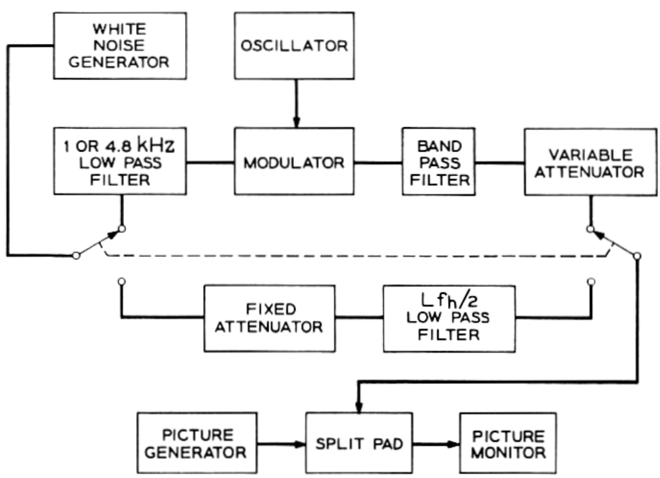

Fig. 4 — Block diagram of apparatus for noise-weighting function measurement by comparison with white noise standard.

TABLE I — COMPARISON OF NARROW-BAND NOISES TO WHITE NOISE STANDARD

Noise bandwidth 9.6 kHz			Noise bandwidth 2 kHz		
Center frequency		Attenuation for equal visibility	Center frequency		Attenuation for equal visibility
kHz	f_h harmonic	dB	kHz	f_h harmonic	dB
0	0	43.8	19.2	2	49.6
19.2	2	43.7	24.0	2.5	38.2
48.0	5	44.7	48.0	5	48.6
96.0	10	42.3	52.8	5.5	36.8
192	20	40.7	96.0	10	48.2
384	40	39.2	100.8	10.5	38.4
768	80	36.3	192.0	20	47.7
			196.8	20.5	38.8
			384.0	40	44.6
			388.8	40.5	37.7
			768.0	80	40.8

exactly flat due to flicker noise, the low-frequency cutoff of the noise amplifier, and the low-pass filter to bandlimit the noise to 4.8 kHz.

The experimental results agree qualitatively with the noise-weighting function expected by treating the noise as a sampled function. That is, spatial noise in the horizontal direction can be related to the overall frequency characteristic of the noise-weighting function, and spatial noise in the vertical direction can be related to the fine structure of the weighting function with a period equal to the horizontal frequency. From Fig. 5 we see that the fine structure of the noise-weighting function measured with 2-kHz bands of noise for low

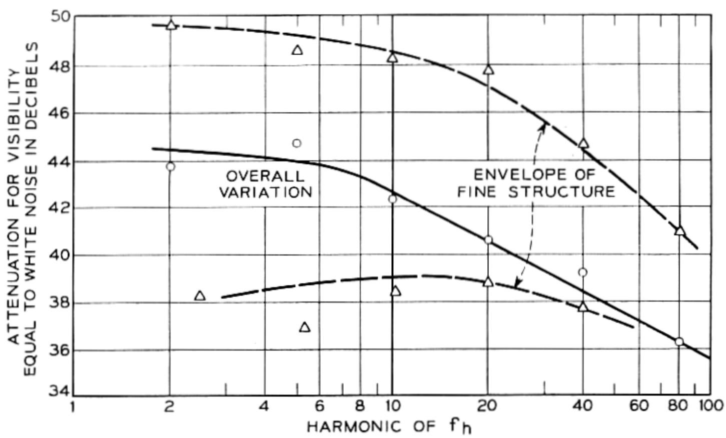

Fig. 5 — Noise-weighting function.

harmonics of f_h has a variation about equal to its overall change across the band, about 12 dB in either case. For the higher harmonics, the variation is roughly as expected from the calculated grating spacings involved.

VII. VISIBILITY OF SINE WAVE INTERFERENCE

7.1 *Experimental Procedures*

For these measurements, the same system was utilized as for measuring noise weighting, the reduced-resolution TV system which has 160 lines per frame and 60 frames per second with no interlace. The viewer sat 8 times picture height from the 4.5-inch TV presentation. The gratings were presented on the TV screen with no additional picture signal present. The input frequencies for generating the desired gratings were obtained by counting down from a common high frequency oscillator from which the horizontal and vertical drive rates were determined. In this manner, any one of a set of gratings could be reproduced precisely as desired. The input frequencies used in these measurements were all below one half the horizontal line rate. Thus, all gratings used had a horizontal spatial frequency m equal to zero and vertical spatial frequency n corresponding to the input-signal frequency,

$$f = f_v n.$$

The threshold of visibility was used as a convenient measure for the visibility function. Since the noise levels of interest for the weighting function are very low, the threshold of visibility is a reasonable measure.

The tests were conducted by having the viewers, knowledgeable colleagues, attenuate the grating signal by means of a step attenuator until the grating was just invisible; the attenuator gave calibrated one dB attenuation steps. The data taken for each grating were averaged over all viewers.

The measurements made were of $T_a T_b T_c$, as for the noise measurements; the complete transfer function was measured. We call this sine-wave visibility function V to distinguish it from the noise visibility function W.

7.2 *Motion*

To measure the dependence of V with motion, a set of measurements was made at an average screen luminance of 15 cd/m^2. Four

TABLE II — DIFFERENCE FREQUENCY AND ATTENUATION FOR THRESHOLD VISIBILITY OF MOVING SINE WAVE GRATINGS

Video frequency 2.4 kHz		1.2 kHz		480 Hz		120 Hz	
F	dB	*F*	dB	*F*	dB	*F*	dB
0	65.00	0	72.14	0	71.00	0	58.14
1.88	65.85	0.94	73.57	0.95	75.57	0.49	62.42
3.75	67.57	1.88	73.57	2.05	76.00	1.01	66.14
5.62	67.71	2.81	74.57	2.99	78.28	1.41	67.00
9.34	67.42	5.60	74.42	5.05	78.14	2.00	69.71
16.76	61.85	10.2	73.28	10.0	76.57	3.00	70.28
29.63	47.71	16.65	67.00	15.0	71.71	5.00	72.28
		29.27	56.71	22.0	64.71	10.0	70.85
				30.0	57.71	15.0	65.85
						23.0	61.14
						29.4	55.16

input frequency ranges were selected: 2, 4, 10, and 20 times the frame rate of 60 Hz producing gratings with spatial frequencies of 2, 4, 10, and 20 cycles per picture height. A set of frequencies near each of the selected frequencies was used to present the desired moving gratings on the screen. Room lighting was adjusted only to reduce reflections from the TV screen.

The average of the data for all viewers is given in Table II and is shown in Fig. 6. In Fig. 6, we see that for any spatial frequency there is an increase in V with motion for difference frequencies F less than 5 or 6 Hz.

From these measurements above and the measurements of Fowler[16] it appears that this peak at $F = 5$ to 6 cycles per second is independent of the spatial frequency and the average luminance.

For $F = 0$, or stationary gratings, we see that there is a peak in transmission vs. spatial frequency as found by Lowry and DePalma.[9, 10] The peak as shown in Fig. 7 occurs at a lower spatial frequency corresponding to the lower luminance level, at about 15 cycles per picture height. For moving gratings with luminance changes at 5 Hz, the peak in transmission with spatial frequency is shifted to lower spatial frequency, at about 8 or less cycles per picture height. This is also shown in Fig. 7. Integrating over frequencies F from $(p - \frac{1}{2})f_v$ to $(p + \frac{1}{2})f_v$, as would be done for random noise inputs according to (1), it is evident from Fig. 7 that the peak for W, if it exists, would be shifted to much lower frequencies than is evident from stationary grating measurements.

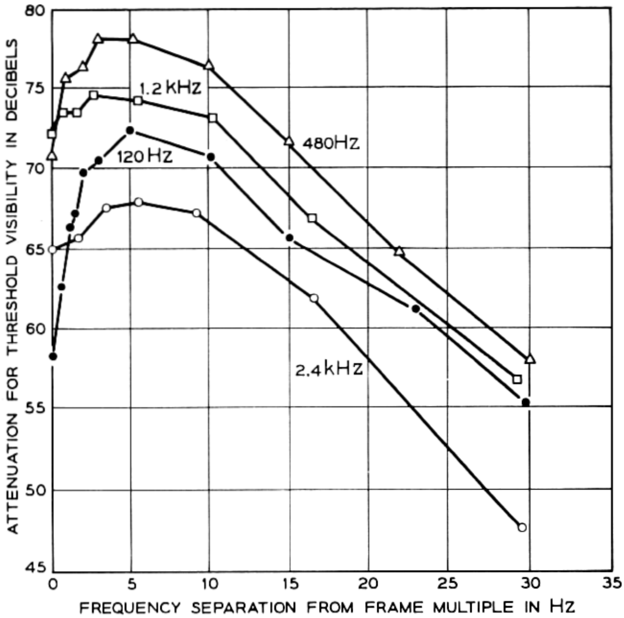

Fig. 6 — Threshold visibility of sine wave grating with motion.

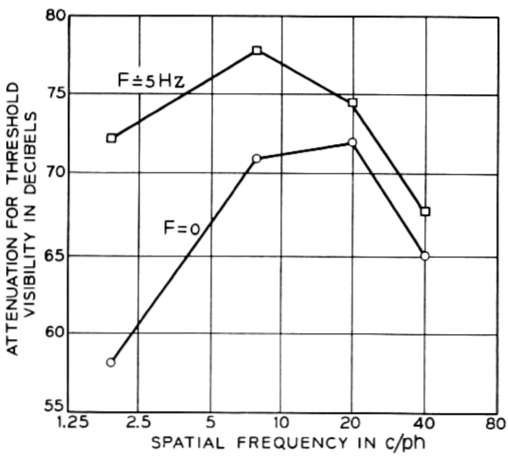

Fig. 7 — Threshold visibility of sine wave grating vs spatial frequency for $F = 0$ and 5 Hz.

7.3 *Average Luminance*

Assuming that the peak with motion occurs at 5 Hz independent of the average luminance, a series of measurements was undertaken using in all cases $F = 5$ Hz. Measurements were made at average luminance values of 0.86, 3.4, 15, and 51 cd/m². Room lighting was reduced and arranged such that the low reflection kinescope screen gave a luminance by reflection of room lighting of 0.086 cd/m².

The results of these measurements are given in Table III and shown in Fig. 8. As in Schade's results,[13] the peak in visibility with spatial frequency at any one luminance value moves to lower spatial frequencies as the average luminance is decreased. There is a peak in visibility as a function of luminance. This peak occurs at a luminance value of about 3.4 cd/m² independent of spatial frequency.

7.4 *Orientation*

We consider the dependence of the acuity of vision on the angle of a test chart. Threshold measurements by Higgins and Stultz[19] show that a 12 percent increase in grating spacing or decrease in spatial frequency is required for a grating oriented at 45° to the horizontal to appear equivalent (just visible) to a grating oriented either horizontally or vertically. If we assume that for the particular circumstances of measurements reported above there is a similar variation of visibility with angle, that is, a 12 percent decrease in spatial frequency for 45° orientation to appear equivalent to horizontal or vertical orientation, than we can estimate the effects on the weighting function.

We need to know the maximum change in the measured weighting function for a 12 percent change in spatial frequency for a given orien-

Table III — Attenuation for Threshold Visibility of Sine Wave Gratings

Average luminance	51	15.4	3.4	0.86 cd/m²
Spatial frequency (c/ph)	(dB)	(dB)	(dB)	(dB)
80	49.6	56.0	59.0	56.4
40	66.2	68.6	73.4	70.4
20	75.2	77.0	80.2	78.0
8	73.4	79.8	84.8	83.6
2	63.2	70.4	79.8	78.6

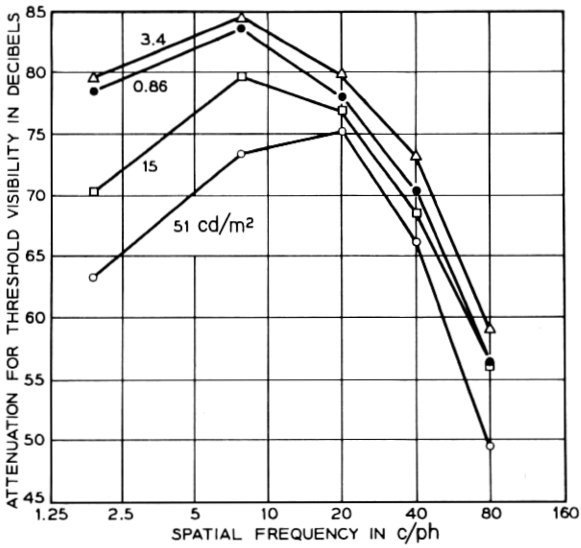

Fig. 8 — Threshold visibility of sine wave grating vs spatial frequency for $F = 5$ Hz and various average luminance values.

tation of grating. This will give us the maximum effect on the weighting function that we should expect as a result of eye anisotropy.

For narrow band noise located at harmonics of f_h for relatively large harmonics, these noise bands produce mainly gratings with vertical bars, i.e., large m and small n. From (6), with small n, then m and video frequency are linearly related and hence the spatial frequency of the grating is linearly related to video frequency. From the data in Fig. 5, the maximum change of the curve through these points is about 0.6 dB for a 12 percent change in frequency. Thus, we expect this curve to reflect everywhere less than 1-dB variation due to a phenomenon related to the variation of eye acuity with orientation.

7.5 *Modulation Level*

The threshold measurements with sine waves were all made with the signal more than 45 dB below 1 volt rms at a gain setting corresponding to a 1-volt peak-to-peak video signal. The suprathreshold noise measurements were all made with noise-power levels below 35 dB below 1 volt rms for a 1-volt peak-to-peak video signal. We do not believe that this difference would be significant in regard to the transfer function on a relative basis. A constant ratio should exist between the two curves.

VIII. RELATION BETWEEN V AND W

It has been considered by many that the modulation transfer function as measured with sine waves and bands of random noise were quite incommensurate. With all the known nonlinearities involved, (1) certainly cannot give an accurate statement of the noise-weighting function from measurements made with sine-wave interference.

However, the data on sine waves presented here indicate that a very reasonable estimate of the noise-weighting function can be obtained. Ignoring grating orientation and modulation level we are considering visibility in a 4-dimensional space. The visibility V of each video frequency component of the interference has been discussed as a function of the corresponding spatial frequency $1/\lambda$ and motion v of that component and the average luminance $\boldsymbol{l}$ at which it is viewed. This is written as

$$V = V(\lambda, v, \boldsymbol{l}).$$

Many values of V for particular values of the parameters have been measured which indicate the form of the function. Through our knowledge of the scanning procedure we can transform $V(\lambda, v, \boldsymbol{l})$ to a function of video frequency f and $\boldsymbol{l}$, $V(f, \boldsymbol{l})$.

For normal television viewing, the noise signal is superimposed on a picture such that the noise is seen at a continuum of brightness levels in the various parts of the TV screen. Thus, for V to correspond to noise-weighting we require an integration over the range of average luminance. Measurements of amplitude statistics on the electrical video signal voltage indicate a rather flat density function. This is equivalent to saying that the area in the picture from a small signal voltage range is independent of the voltage. We expect from this that an integration of V should be performed over luminance levels specified as video signal voltage levels. This problem is easily solved by the measurement of visibility of sine waves superimposed on a TV picture.

The resulting function $V(f)$, after smoothing average luminance effects, contains all the structure of the noise-weighting function. The microstructure stems from the motion of gratings and the overall function and fine structure are due to the constituent gratings as described in Section III. W and V are qualitatively alike.

The fine structure of W measured with narrow bands of noise discussed in Section VI stems from smoothing the variations at multiples of the frame rate. There is also a partial smoothing of the fine structure due to the actual bandwidth of noise, 2 kHz, which is not small compared to the period of this structure occurring at multiples of 9.6 kHz. The corresponding version of V is obtained from the sine wave data by first integrating with respect to v, or equivalently F, since the microstructure stems from this variation. This involves integration over the curves displayed in Fig. 6. The curves have a logarithmic scale. Since these curves are all similar but displaced vertically the integral would be approximately a constant times the peak value. This constant is applied to the average curve of visibility with spatial frequency as in Fig. 8.

The average of the curves of Fig. 8 should approximately represent the first portion of the fine structure of the weighting function, that is, for $m = 0$ and n varying from 2 to 80 c/ph.

For the smoothing due to the 2-kHz noise bandwidth, we consider the curves of Fig. 8. The data points between 0 and 10 c/ph and between 60 and 80 c/ph can be "visually averaged." The difference between these two average values indicates less than a 17-dB variation for the fine structure of the weighting function. This is 4 dB larger than the 13-dB measurement of W. Considering that there were two "integrations" performed over average luminance and motion and not all luminance values are considered, this difference should be expected.

There is a peak in visibility in the "average" of the curves of Fig. 8 at about 4 c/ph or less. A rather narrow band of noise, 60 Hz, would be required to verify the existence of this peak in the fine structure of W.

The overall weighting function is obtained by smoothing out the fine structure. There is a substantial difference in the fine structure of the weighting function across the band. The fine structure at the low end of the band corresponds to gratings of spatial frequencies varying from 1 to 80 c/ph. At the high end of the band there are spatial frequencies varying from 80 to 80 $\sqrt{2}$ c/ph. We do not expect the integration to lead to a constant times the peak of the fine structure.

The peaks of the fine structure measured with 2-kHz bands of noise as shown in Fig. 5 give only a 10-dB variation for m varying from 2 to 80 compared to the 12 to 14-dB variations measured for the equivalent change in n. For complete smoothing of the fine structure, Fig. 5 shows that only an 8 or 9-dB variation was obtained for m varying from 2 to 80.

IX. APPLICATIONS AND IMPLICATIONS

9.1 *Noise Weighting for Photographs and TV*

The data of Section 7.2 show a significant difference in the noise-weighting function depending on the presence or absence of motion. Huang's measurements[11] with still pictures verifies this difference. His weighting function has peaks at spatial frequencies that correspond approximately with those measured for stationary gratings.

Signal processing of a single TV frame can be conveniently accomplished on a multipurpose computer to quickly examine some of the many possible processing procedures. It must be remembered that the resultant noise viewed on the single output picture has a different noise weighting than the completed system processing a sequence of TV frames to be viewed.

9.2 *TV Frame Storage and Repetition*

Consider a frame-repeated television presentation[21] where one frame of a television signal is stored in a memory such that it can be repetitively flasked k times on the kinescope, then another frame is accepted, stored and repetitively shown, etc. Examine any one point on the kinescope presentation, as in Section 3.3. For human vision, which does not see the 60-cycle flicker, there is presented a luminance value which is held constant for k frames, then a new luminance value is presented. As a sampling function this represents one sample for every k frames of the original TV signal without frame repeating.

We wish to examine the visibility of noise for TV frame repetition. All frequencies of the video input have been shown to contribute to the flicker at a point in the frequency band from 0 to 30 Hz for the nonrepetitive ($k = 1$) TV presentation. Each frequency also contributes to each 30-Hz wide band above 30 Hz but vision filters out almost all contributions above 30 Hz.

The frame repetition procedure samples the video signal at each point on the screen at $60/k$ Hz. Each input video frequency contributes to flicker in a band from 0 to $60/2k$ Hz. The repetition of frames, in effect, holds this sampled value for k frame times. This filter action reduces flicker frequencies above $60/2k$ Hz; the 60-Hz frame frequency is filtered by the visual process. Considered as a true sample and hold filter the response would be $(\sin x)/x$ where $x = \pi kF/60$. The first zero would be at $F = 60/k$.

The net effect of frame repetition is to fold noise from the 0 to 30-Hz band into the 0 to $30/k$-Hz band. From Fig. 6 it is evident that for

$k = 2$ the flicker noise is in a frequency region, $0 - 15$ Hz, where on the average it is more visible. For $k = 4$, the noise is in the band $0 - 7.5$ Hz where it may be somewhat more visible than for $k = 2$. For $k > 4$, the data of Fig. 7 indicates that the noise limited to a band < 7.5 Hz will be less visible than for $k \leqq 4$.

9.3 *W and Average Luminance*

The data for the sine wave interference visibility at various values of average luminance show a substantial variation. However, the noise-weighting function is to be used as a relative measure. Since the curves of Fig. 8 are all similar except at very low spatial frequencies, it appears that W measured at any one luminance value is reasonable.

9.4 *W Applied to TV Transmission System*

Two examples are given below of the application of the noise-weighting function as a figure of merit for television systems.

9.4.1 *Analog Transmission*

Thermal noise, assumed flat over the video bandwidth, is added to the signal in the analog channel. A TV signal has extensive structure in its power spectrum.[6] The power is densely packed at harmonics of frame and horizontal line rates and predominately at low frequencies. Most of the frequency band has very low signal power.

It is possible to increase the signal-to-noise ratio by linear pre-emphasis of the signal before transmission with the inverse reconstruction operation at the receiver.[22] The pre-emphasis filter increases the signal power where it is very low with a corresponding reduction in power where the original signal power was high to maintain the transmitted power constant. The reconstruction filter performs the inverse action on the signal plus noise. Thus, where the original signal was of low power the noise is substantially reduced, whereas, where the original signal was of high power the noise is increased. Since the usual TV transmission channel is actually peak-power limited, the expected improvement is further limited by this constraint.

However, if we consider the signal-to-weighted-noise ratio as a criterion[23] a quite different result is obtained. Wherever the TV signal power is high, at harmonics of f_h and f_v and at low frequencies, the noise-weighting function is also high. The filtering procedure above increases the noise power where it is most visible. Even with the optimum filter pair[23] designed for maximum signal-to-weighted-noise ratio there is very little improvement possible.

9.4.2 *Bandwidth Reduction for PCM-TV*

Noise in a pulse code modulation (PCM) system is principally due to amplitude quantization. It is possible to shape the power spectrum of this noise. This fact is utilized in differential PCM[24] and error-feedback coding.[25,26] The combination of pre-emphasis and reconstruction filters with noise-power-spectrum shaping has proved effective when using horizontal picture correlation which corresponds to the smoothed power spectrum of the video signal.[22,26]

The pre-emphasis and reconstruction filters are employed as in the analog transmission system of Section 9.4.1 to boost signal where it was originally low keeping total power constant. Noise-spectrum shaping is used to reduce the noise at frequencies where the original video-signal power was high. This noise filtering is accomplished by a feedback loop around a quantizer and gives an increase in total quantization noise power.

A differential system incorporates the signal pre-emphasis and quantizing-noise shaping in the one filtering path of the quantizer feedback loop. O'Neal[27] has calculated the signal-to-noise ratio for some differential systems. He considers operation on the overall signal-power spectrum and on the power peaks at horizontal line harmonics both separately and combined. He finds that either operation separately gives a substantial increase in signal-to-noise ratio, but that the combined operation does not give any additional improvement.

Since this combined operation redistributes the noise power to regions where it is less visible we expect that the signal-to-weighted-noise ratio should be increased for the combined filtering operations over that obtained for either filter operation separately.

9.5 *Measurement of Smoothed W*

Previous measurements of W have been with relatively wide bands of noise.[2,3,4] The bands of noise chosen for these measurements have not always been the best. With noise bands selected on an octave basis[2] there is a confounding of the results by the fine structure at the low frequency end of the band. With an input noise bandwidth of exactly f_h the spatial-noise power spectrum along y would be flat, independent of the center frequency of the input noise band. Using these relatively narrow bands of noise we expect to smooth out the fine structure of the noise-weighting function and make a more precise measurement of the gross noise-weighting function than with wider bands of noise.

9.6 *Disproving an Hypothesis*

The hypothesis[28] has been suggested that anisotropy of the noise is important in visual response. We take as a definition of anisotropy that the spatial power spectra in orthogonal directions are not the same. The hypothesis states that the more anisotropic a noise is the more objectionable it is. However, judging from our results, this cannot be true. If we examine our experimental results for frequencies about 1.5 f_h and 2 f_h, then we have low horizontal spatial frequencies. Near 2 f_h the narrow band of noise is folded to appear as low vertical spatial frequencies. The result for this noise, which is fairly isotropic, is that it is annoying. Near 1.5 f_h the narrow band of noise is folded to appear as high vertical spatial frequencies. Our result for this anisotropic noise is that it is less annoying than the isotropic noise. This is in contradiction to the hypothesis under consideration.[28]

X. CONCLUSION

The subjective noise-weighting function consists of the transfer functions of the kinescope and the visual process. The scanning procedure of the kinescope produces a complicated variation in the spatial and flicker frequencies of the display as a function of the input video frequency. A rather extensive discussion has been given for the scanning process for a square picture. These results are applicable to any rectangular picture also. A change in the picture height control to form a rectangular picture requires only that a constant factor be applied to all vertical spatial frequencies. The modulation transfer function of vision is strongly dependent on spatial and flicker frequencies. The resultant weighting function has a fine structure related to scan-line-frequency harmonics and a microstructure related to frame-frequency harmonics.

Subjective measurements were made to determine the fine structure and microstructure of the noise-weighting function. Noise near a multiple of the horizontal line frequency is much more visible than similar noise between multiples of the horizontal line frequency. Sine waves differing by 5 Hz from a multiple of the frame frequency are much more visible than sine waves midway between multiples of the frame frequency and, particularly for low spatial frequencies, are much more visible than sine waves at multiples of the frame frequency.

The measured visibility of noise and sine-wave interference in television is in good agreement with that expected from considering the TV presentation due to scanning. This indicates a quite linear system for the small additive interferences. This linearity leads to rejection of a hypotheses that visibility of noise in TV may be a function of anisotropy of the spatial noise power spectrum.

The subjective noise-weighting function is valuable in determining a figure of merit in many applications. When considering the results of calculations on only one frame of a television sequence, as is done in computer simulations, one can be lead to erroneous results of visibility of noise due to a significant difference in visibility between stationary and moving patterns in a TV presentation. The variation in visibility with motion leads to conclusions about the visibility of noise with television frame repeating which have been tentatively verified by others.[21] A variation in visibility with average luminance must be considered for noise-weighting function measurements on a flat screen at only one average luminance level.

The use of weighted noise as a measure of merit for television transmission, as an analog or PCM signal, leads to a significantly different result in either case from published results considering only the noise as a measure of merit.

XI. ACKNOWLEDGMENT

Thanks are due to my colleagues, C. J. Candy, L. H. Enloe, B. Prasada, and W. T. Wintringham for their helpful discussions and constructive criticisms and to E. S. Bednar for his efforts in the subjective measurements reported.

TABLE OF SYMBOLS

c/ph	cycles per picture height
f	video frequency
f_h	horizontal-line scanning frequency
f_v	frame scanning frequency
f_s	frequency components of sampled video signal
F	frequency associated with moving grating patterns
l	luminance
L	number of lines in picture
m	horizontal spatial frequency
n	vertical spatial frequency
N	noise power spectrum
P	weighted noise power
r	spatial frequency in direction parallel to horizontal-scan lines

T_a transfer function of kinescope
T_b transfer function of vision
T_c translation to words
v velocity of moving grating patterns
V sine wave visibility function
W subjective noise-weighting function
λ spatial wavelength of grating patterns

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