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CHARACTERISTICS OF CRYSTAL-VIDEO RECEIVERS EMPLOYING R-F PREAMPLIFICATION

by
W. E. AYER

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Technical Report No. 150-3
September 20, 1956

Prepared under
Air Force Contract AF 33 (600)-27784



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SUMMARY

The operating characteristics of crystal-video receiving systems with r-f preamplification are discussed, and equations given for the maximum sensitivity ($S_{\max}$), and for the gain required in the preamplifier to realize $S_{\max}$. Use of the equations is demonstrated by means of specific examples.

An analysis of the behavior of this type of system is presented in the Appendix, the derivation of the $S_{\max}$ equation being given there.

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CHARACTERISTICS OF CRYSTAL-VIDEO RECEIVERS EMPLOYING R-F PREAMPLIFICATION

1.0 INTRODUCTION

The development, in recent years, of high-gain broadband traveling-wave tubes has greatly increased the potential usefulness of receiving systems of the crystal-video type. A very simple receiver can be realized by preceding a simple crystal-video system with a traveling-wave tube operating as an amplifier in the radio-frequency range of interest. The general arrangement of such receiving systems is illustrated in Fig. 1.

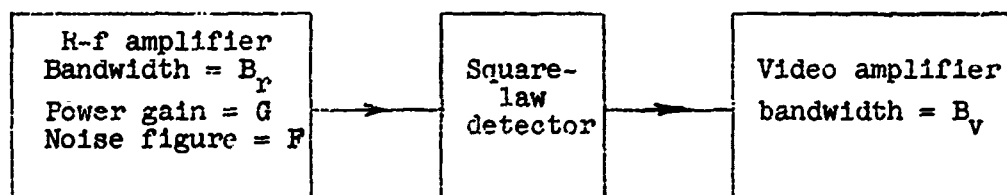


FIG. 1.--Block diagram of receiver.

Addition of the traveling-wave-tube preamplifier can result in an appreciable increase in threshold sensitivity, making such an arrangement suitable for many applications where superheterodyne receivers would otherwise be necessary.

A brief discussion of the operation of crystal-video systems without preamplification is presented in Sec. 2. Data on the threshold sensitivities obtainable with practical microwave detectors is given in graphical form.

Section 3 is devoted to consideration of the effects of various amounts of preamplification upon overall system sensitivity. The derivation of the necessary relations is indicated, and the working equations presented.

In Sec. 4 the design procedure is demonstrated by means of a practical example. Also, a circuit arrangement for indicating the presence of a c-w signal is described, and performance capabilities are calculated.

In the last section the characteristics of this general class of receivers is reviewed briefly, performance being compared with that of superheterodynes.

2.0 THE SIMPLE CRYSTAL-VIDEO RECEIVER

As the name implies, a crystal-video receiver consists of a crystal detector followed by a suitable video amplifier. The choice of video bandwidth is made in the usual way, on the basis of the type of signal to be received. Thus, if the applied signals are rectangular pulses, the bandwidth is typically made equal to $0.6/\delta$ where δ is the pulse length. R-f selectivity can be provided by means of tuned circuits ahead of the detector. It should be noted that such selectivity will not improve the sensitivity of this type of receiver, because the noise level is set by the crystal detector.

The sensitivity of crystal-video receivers is inherently low because of the low rectification efficiency of the detecting element at small signal levels. The effective noise threshold is determined by the magnitude of the video resistance of the detector, and the bandwidth of the detector--video amplifier combination. The video resistance behaves like an ordinary resistor in producing thermal noise.

A variety of silicon crystal types--1N23B, 1N26, 1N32, etc.--have been used at this laboratory in various detector mounts. The video resistance for these rectifiers generally falls in the range of 5,000 to 20,000 ohms, which is sufficiently great to override noise produced in the video amplifier if reasonable care is taken in amplifier design. A particular practical precaution worth mentioning is the use of wire-wound resistors in un-bypassed current-carrying circuits near

the front end of the amplifier. If carbon or composition resistors are used, considerable amounts of "excess" noise are produced, and overall performance will be degraded.

In Fig. 1 data on the sensitivity of crystal-video receivers is presented. These curves are based upon the performance of wideband detector mounts developed at this laboratory.^{1,2} These mounts have been designed to work from a 50-ohm source. The threshold sensitivity figure (S_x) gives the amount of pulse power which must be applied in order to produce an output just discernible in the noise on a synchronized CRT display. This measure of sensitivity corresponds roughly to pulse power equal to average noise power. The data are based upon input pulse lengths approximately equal to $0.6/B_v$ --conditions for maximum sensitivity. The "good" and "poor" lines indicate the limits of performance for crystals selected at random.

The sensitivity, as plotted in Fig. 2, varies inversely with $\sqrt{B_v}$. This characteristic results from the square-law nature of the detector. The noise output power will vary directly with the video bandwidth; the square-law action causes the output signal amplitude to increase as the square of the input signal. Thus a doubling of the video bandwidth will cause a 3 db increase in output noise, while a similar increase in output signal will be realized by a 1.5 db increase in applied signal.

¹D. J. Grace, "Analysis of two broadband untuned crystal detector mounts," TR No. 14, (Nonr 25132), Electronics Research Laboratory, Stanford University, 10 June 1952.

²D. J. Grace, "Analysis of a broadband untuned crystal mount for X-band operation," TR No. 7, (Nonr 22510), Electronics Research Laboratory, Stanford University, 10 March 1953.

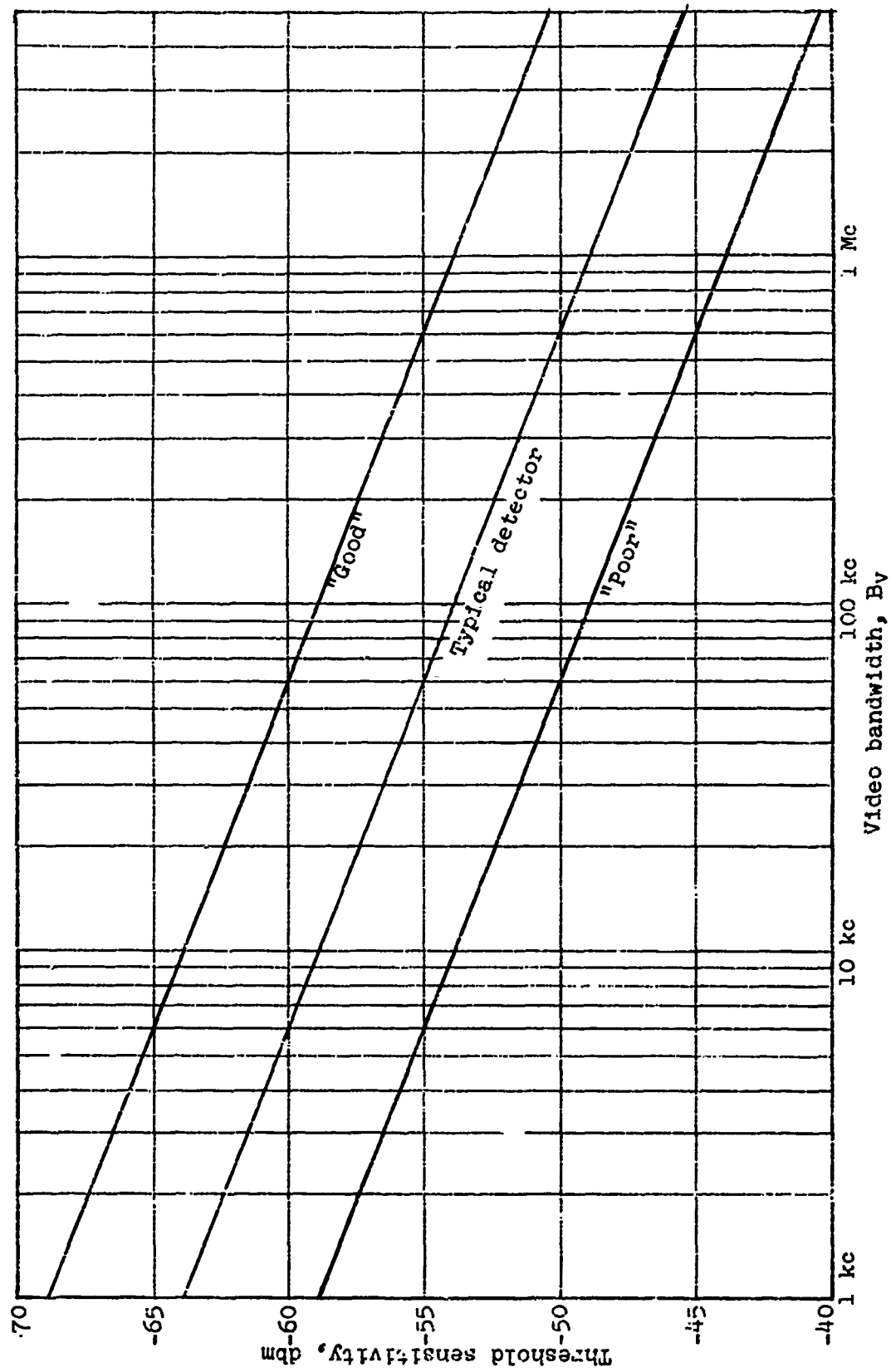


FIG. 2.--Threshold sensitivity (S_x) of crystal - video receivers as a function of bandwidth (B_v).

3.0 EFFECTS OF PREAMPLIFICATION

A qualitative picture of the effect of r-f amplification on system sensitivity can be obtained by considering progressively greater amounts of gain ahead of the crystal detector. For unity gain in the preamplifier the sensitivity will be the same as for a simple crystal-video system, since the noise at the output of the system will be due only to the crystal detector. As the r-f gain is increased, there will generally be a considerable region in which the system sensitivity increases linearly with r-f gain. For sufficiently large gains, the output noise due to the preamplifier will override that due to the detector. Further increase in gain will no longer increase sensitivity, once the threshold is set by the r-f amplifier. The behavior described is sketched in Fig. 3.

3.1 DETERMINATION OF MAXIMUM SYSTEM SENSITIVITY, $S_{\max}$

An analysis of system performance has been made for the maximum-sensitivity condition, corresponding to predominance

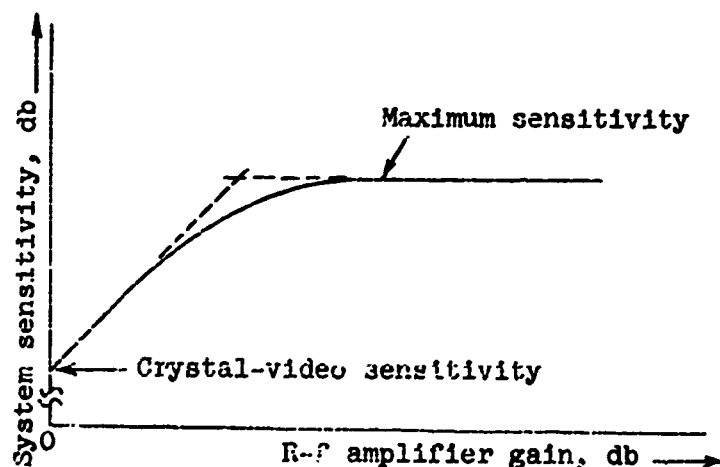


FIG. 3.--Variation of sensitivity with r-f gain.

of r-f amplifier noise at the output. This analysis is presented in the Appendix. The maximum sensitivity is given by:

$$S_{\max} = -114 \text{ dbm} + F + 10 \log_{10} [B_e] \quad (1)$$

where -114 dbm is the available thermal noise power per megacycle at the input of the preamplifier, F is the noise figure of the preamplifier in db, and B_e is the effective bandwidth of the system in megacycles. The effective bandwidth is given by:

$$B_e = [2B_r B_v - B_v^2]^{\frac{1}{2}} \quad (2)$$

where B_r and B_v are the preamplifier and video bandwidths, respectively, in megacycles. When the r-f bandwidth is at least 10 times the video bandwidth, B_e is given quite accurately by:

$$B_e = [2B_r B_v]^{\frac{1}{2}} \quad (3)$$

3.2 PREAMPLIFIER GAIN REQUIRED TO REALIZE $S_{\max}$

The gain requirement for realization of maximum system sensitivity can be deduced from a plot of the type shown in Fig. 3. With the sensitivity of the crystal-video portion of the system known, the sloping line corresponding to small amounts of preamplifier gain is established quantitatively. The horizontal line, corresponding to maximum possible system sensitivity, is found from Eqs. (1) and (2) or (1) and (3). The intersection of these two straight lines gives the preamplifier gain required for the output noise due to the preamplifier to equal that due to the detector. This condition corresponds to an output signal/noise ratio which is 3 db worse than that which will be obtained when there is sufficient r-f gain to completely override crystal noise. Since the

detector action is square-law, a 1.5 db increase in input signal will bring the output signal/noise ratio up by 3 db, so that, for this particular amount of preamplifier gain, the system sensitivity will be 1.5 db below $S_{\max}$.

A plot of the variation of sensitivity with r-f gain in the region of $G = |S_{\max} - S_x|$ is given in Fig. 4. When the gain is 3 db greater than $|S_{\max} - S_x|$, the sensitivity is only 0.5 db less than $S_{\max}$. Accordingly, a reasonable practical rule for determining gain is:

$$G \geq |S_{\max} - S_x| + 3 \quad (4)$$

where all quantities are in terms of decibels.

4.0 PRACTICAL EXAMPLES

Calculation of the performance characteristics of preamplifier--crystal--video combinations is a relatively straight-forward procedure. In order to illustrate the calculations and, as well, to point out certain practical precautions, two examples will be considered.

4.1 MICROWAVE PULSE RECEIVER

Consider the following system characteristics:

$$S_x = -52 \text{ dbm}$$

$$B_v = 0.6 \text{ Mc}$$

$$B_r = 20 \text{ Mc}$$

$$F = 20 \text{ db}$$

These numbers are consistent with pulse receiving applications in the kMc range, where a T-W tube followed by a tuned cavity is utilized as the preamplifier. (Note that the cavity must follow the TWT if high sensitivity is to be realized--otherwise

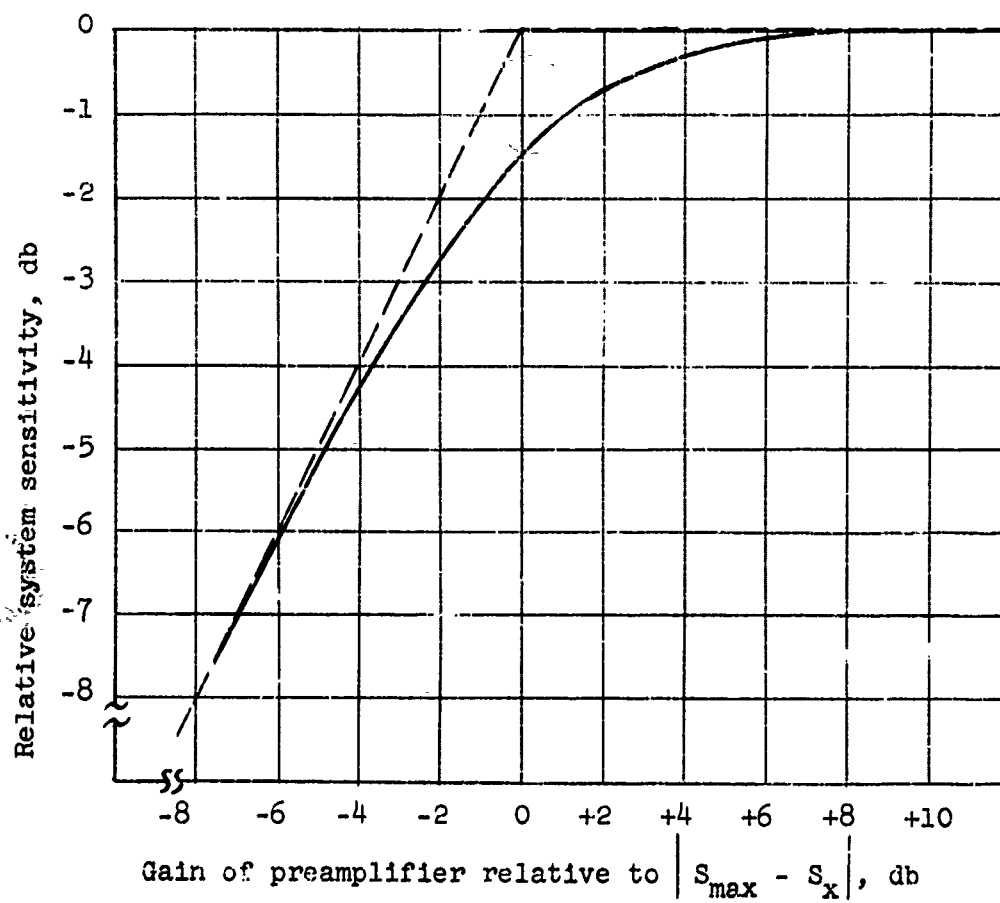


FIG. 4.--Variation of system sensitivity with preamplifier gain.

all of the TWT noise will be applied to the crystal. In some applications an additional cavity ahead of the tube might be needed to prevent overloading). From Eq. (3),

$$B_e = [2 \times 20 \times .6]^{\frac{1}{2}} = 4.9 \text{ Mc}$$

$$\begin{aligned} \text{Then } S_{\max} &= -114 \text{ dbm} + 20 \text{ db} + 10 \log_{10}(4.9) \\ &= -114 + 20 + 7 = \underline{-87 \text{ dbm}} \end{aligned}$$

The minimum preamplifier gain is then, from Eq. (4):

$$G_{\min} = |-87 + 52| + 3 = \underline{38 \text{ db}}$$

4.2 C-W DETECTION SYSTEM

An arrangement for determining the presence of a c-w signal is illustrated in Fig. 5. The purpose of the modulation of the r-f input is to produce a video component in the envelope of the signal which, when detected, will pass through

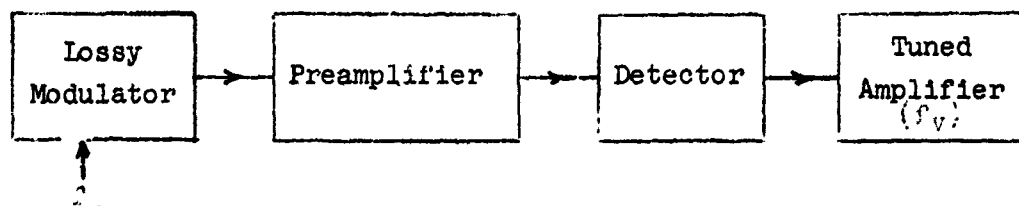


FIG 5.--C-w detection receiver.

the tuned video amplifier. The actual modulator could be a ferrite device, or perhaps a transmission-line structure with semi-conductor diodes whose characteristics are changed by the modulating voltage at the frequency f_v .

For this sort of application, where it is desired to close a relay or perform some other simple function when a continuous

signal is received, a very narrow video bandwidth may be employed.

Assuming, for sake of simplicity, that the modulator goes from a "full-on" (zero loss) to a "full-off" (infinite loss) condition in a square-wave fashion at a fundamental frequency f_v , the maximum system sensitivity may be calculated in much the same manner as was used in the preceding example. On the basis of a 1 kc video bandwidth, the crystal-video sensitivity for a "typical detector" is found from Fig. 2 to be -63 dbm. Assuming an r-f bandwidth B_r of 20 Mc and a pre-amplifier noise figure of 20 db, Eqs. (3) and (1), respectively, yield an equivalent bandwidth of 0.45 Mc, and an S_{max} of -97 dbm. From Eq. (4), the required preamplifier gain is found to be 37 db.

There are two points regarding the performance of such a device which should be discussed. First, one might wonder why a modulator is needed at all: that is, why not use a d-c amplifier to provide "direct detection" of the c-w signal? The answer lies in the fact that there is a large component of "noise" at d-c at the output of the detector which would make the system sensitivity extremely low. This is shown in the Appendix.

A second question is: why not introduce the modulation by appropriate variation of the voltage on a control element in the preamplifier? The trouble with this technique is that the entire noise output of the preamplifier becomes in effect a "carrier" for the modulation, and the sensitivity is again drastically reduced.

5.0 CONCLUSIONS

If it can be assumed that sufficient r-f selectivity is obtainable to limit B_r to the actual value required for the intended application, then the sensitivity of the type of receiver considered here can be made essentially equal to that

realizable by superheterodyne techniques. For such cases the simplicity of the preamplifier crystal-video combination may well indicate its use in preference to a superheterodyne.

Again, in many applications the simpler system will not provide the ultimate in sensitivity, but its performance may be entirely adequate for the specific problem at hand.

APPENDIX: DERIVATION OF MAXIMUM SENSITIVITY OF CRYSTAL-VIDEO
RECEIVER WITH R-F PREAMPLIFICATION

In order to simplify the calculation of system performance, an idealized noise spectrum will be assumed at the input to the detector. The noise, which in reality is continuously distributed in frequency, will be considered as a discrete line spectrum. The components will be arbitrarily assumed to be spaced uniformly at 1 cycle intervals across the r-f bandwidth B_r , each amplitude corresponding to the thermal noise in 1 cycle of bandwidth. The phase of each such "equivalent noise signals" will be considered to be random with respect to all the other components. This equivalent noise spectrum will appear as shown in Fig. A.1.

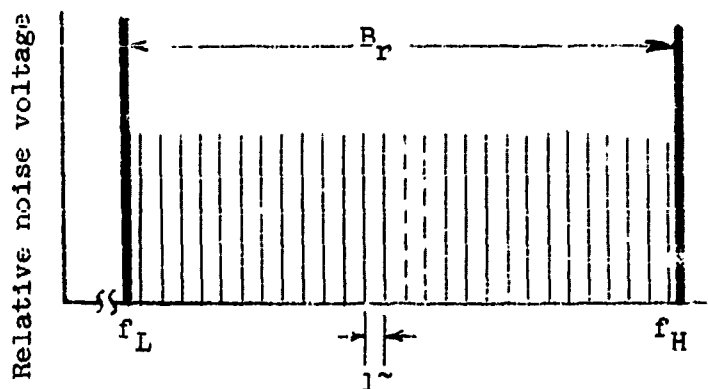


FIG. A.1.--Model of noise spectrum.

The detector will be considered to operate in its square-law region, as given by:

$$e_o = K_x e_1^2 \quad (A-1)$$

where e_1 is the instantaneous voltage at the input to the detector, and e_o is the corresponding output voltage. K_x accounts for the overall efficiency of detector mount and crystal.

Calculation of the noise at the output of the detector is accomplished by substituting the expression for the model of the input noise spectrum into the relation for the detector characteristic:

$$e_o = K_x [V_n \sin(\omega_1 t + \phi_1) + V_n \sin(\omega_2 t + \phi_2) + \dots + V_n \sin \omega_n t + \phi_n]^2 \quad (A-2)$$

where V_n is the peak value of the applied noise voltage per cycle. If the r-f bandwidth B_r is expressed in cycles/sec, there will be a total number of components in the noise spectrum model equal to $|B_r|$.

For convenience in manipulation, the expressions for $\sin(\omega_1 t + \phi_1)$, $\sin(\omega_2 t + \phi_2)$, etc., will be represented by a_1 , a_2 , etc. Taking the common amplitude term outside of the brackets and substituting rms for peak voltage (v_n for V_n), the expression is:

$$e_o = 2K_x v_n^2 [a_1 + a_2 + \dots + a_{B_r}]^2 \quad (A-3)$$

Expanding, the output voltage is:

$$e_o = 2K_x v_n^2 \left\{ a_1^2 + a_2^2 + a_3^2 + \dots + 2a_1 a_2 + 2a_2 a_3 + \dots + 2a_1 a_3 + 2a_2 a_4 + \dots + 2a_1 a_4 + 2a_2 a_5 + \dots \right\} \quad (A-4)$$

Remembering that the various coefficients a_1 , a_2 , etc., represent sine waves, the squared terms reduce to d-c and second harmonic components, while the product terms reduce to sum- and difference-frequency components. Restricting the analysis to cases where the video bandwidth B_v is equal to or less than the r-f bandwidth B_r , only the d-c and difference-frequency components need be considered.

There will be $|B_r|$ d-c components, each of amplitude $1/2$. The difference frequency terms at 1 cycle/sec result from the products of adjacent components $2a_1a_2$, $2a_2a_3$, etc. There will be a total of $|B_r| - 1$ such components, each of unit amplitude. Similarly, at m cycles per second there will be $|B_r| - |m|$ components, each of unit amplitude.

Because of the random phase of the components of the original r-f spectrum model, the difference-frequency components occurring at each cycle in the video band must be added power-wise. The expression for the video output is thus:

$$e_o = 2K_x v_n^2 \left\{ \frac{|B_r|}{2} + [|B_r| - 1]^{\frac{1}{2}} \cos(2\pi t + \phi_a) + [|B_r| - 2]^{\frac{1}{2}} \cos(4\pi t + \phi_b) + [|B_r| - 3]^{\frac{1}{2}} \cos(6\pi t + \phi_c) + \dots \right\} \quad (A-5)$$

The output noise spectrum, in terms of the squares of the rms values of each component, is sketched in Fig. A.2. To find the total noise voltage output within a video bandwidth B_v , the spectrum is integrated over B_v . This must be done power-wise, and then the square root taken. Assuming that the video amplifier response approaches, but does not include the d-c term, the expression is:

$$v_{no} = K_x v_n^2 \left[\int_0^{B_v} 2B_r \left[1 - \frac{f}{B_r} \right] df \right]^{\frac{1}{2}} \quad (A-6)$$

Integrating, the output noise voltage is found to be:

$$v_{no} = K_x v_n^2 [2B_r B_v - B_v^2]^{\frac{1}{2}} \quad (A-7)$$

The threshold sensitivity of the system corresponds to the condition of the signal voltage at the output of the

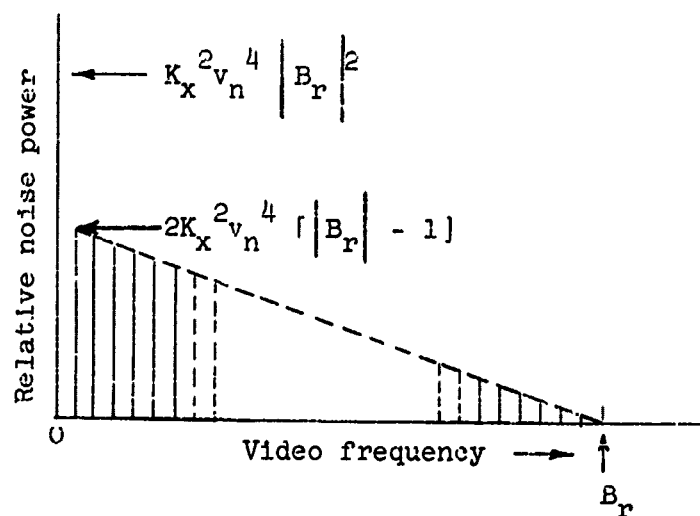


FIG. A.2.--Idealized noise output spectrum.

detector (v_{so}) being equal to the above determined noise voltage. (It is assumed here that the noise due to the crystal itself is negligible: This is necessary for the realization of maximum system sensitivity).

The signal output voltage of the detector will be:

$$e_{so} = K_x [V_s \sin \omega_s t]^2 \quad (A-8)$$

where V_s is the peak value of the signal voltage applied to the detector. The peak output voltage for a c-w input, or a pulse which is sufficiently wide to pass through the video amplifier, will be given by the d-c term obtained when the squaring is performed. Thus:

$$v_{so} = \frac{K_x V_s^2}{2} = K_x v_s^2 \quad \text{where} \quad (A-9)$$

v_s is the rms value of the input signal. Equating signal and noise output voltages,

$$v_s^2 = v_n^2 [2B_r B_v - B_v^2]^{\frac{1}{2}} \quad (A-10)$$

where v_n is the thermal noise voltage per cycle of r-f bandwidth, as previously defined. This may be rewritten in terms of available powers at the input to the detector:

$$P_s = P_n [2B_r B_v - B_v^2]^{\frac{1}{2}} \quad (A-11)$$

Putting noise power and bandwidths on a megacycle basis, and converting to decibel measure:

$$P_{s_{\text{dbm}}} = -114 \text{ dbm} + 10 \log_{10} [2B_r B_v - B_v^2]^{\frac{1}{2}} \quad (A-12)$$

The above relation applies at the detector input. This is readily translated to the input of the preamplifier by adding in the effect of the excess noisiness of the preamplifier. The resulting relation for the maximum sensitivity of the system is:

$$S_{\text{max}_{\text{dbm}}} = -114 + F + 10 \log_{10} [B_e] \quad (A-13)$$

where F is the preamplifier noise figure in db and B_e is the effective system bandwidth:

$$B_e = [2B_r B_v - B_v^2]^{\frac{1}{2}} \quad (A-14)$$

When B_r is at least 10 times B_v , B_e is given with good accuracy by:

$$B_e = [2B_r B_v]^{1/2} \quad (A-15)$$

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