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ON THE PERFORMANCE OF FM COMMUNICATIONS IN THE PRESENCE OF RF NOISE

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ABSTRACT

A critical view is taken of some common notions of input signal-to-noise ratio "thresholds" below which frequency-modulation radio links become inoperative but above which highly satisfactory communications result.

Experimentally derived curves are shown giving output vs. input signal-to-noise ratios for three FM receiver bandwidths and a signal employing sine wave modulation. When the experimental FM curves are compared with theoretical curves for AM, DSB, and SSB, it becomes clear that the "threshold" concept is extremely misleading. FM systems can enjoy a competitive output signal-to-noise ratio for low input S/N against uniform RF noise, while against narrow-band RF noise, wide-band FM is superior to the other systems for practical output S/N.

1. INTRODUCTION

This technical note is intended to help clear up some popular confusion with regard to the noise performance of frequency-modulation communication receivers. The notion of an input signal-to-noise ratio "threshold" has been propagated in the belief that below this threshold FM reception is hopelessly lost in the noise whereas above the threshold all reception is "hi-fi" and clear (Ref. 5, p. 279, and Ref. 8). Of course, no such threshold exists in fact; the FM output S/N is smoothly related to the input S/N in spite of the nonlinearity of the receiver, and in the case of a low input S/N the output S/N may be not only quite useful but larger than the input S/N.

Perhaps the phenomenon known as the "capture effect" has caused some of the confusion. In the first place, so-called capture results not from the receiver limiters or frequency detector, but rather from the definition of frequency measurement itself which the receiver merely tries to carry out. Secondly, the capture effect refers to the specific case of two constant-amplitude input signals, of which the desired FM signal is one. In this case the average output frequency equals the average frequency of the larger amplitude signal (Ref. 6). If the deviation ratio[1] is large, then the FM receiver output indicates the (slowly changing) frequency modulation of the larger amplitude signal while showing evidence of the smaller amplitude signal only during those instants in time when the difference between the instantaneous frequencies of the two signals is less than the receiver audio bandwidth. Finally, if either near-unity deviation ratios or amplitude-modulated signals are being considered, it is best to abandon notions of the capture effect and take a fresh look at the specific situation.

Bandlimited Gaussian noise is not a constant-amplitude signal. Because of the instantaneous amplitude fluctuations of the noise, capture of the FM carrier could be considered to take place only during the occurrence of noise peaks exceeding the FM carrier amplitude. In such a situation the RF noise would always produce some peaks large enough to produce interference and yet, because the noise envelope also goes to zero occasionally, the noise does not cause capture all the time. The percentage of time that the noise peaks exceed the FM carrier amplitude is a smooth function of the signal-to-noise ratio, the func-

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[1] The deviation ratio shall be considered to be one-half the ratio of the FM receiver IF to audio bandwidths.

tion possessing nonlinearities but not abrupt thresholds. Thus it is a nonlinear relationship between the output and input signal-to-noise ratios which is of interest and which will be experimentally determined. The experimental results will be noted and compared with the theoretical predictions and results of others.

2. EXPERIMENTAL PROCEDURE

The experimental test equipment consisted simply of an FM signal source, a radio-frequency noise source, a good quality FM receiver, a wideband voltmeter, and a narrowband selective voltmeter. The input signal and noise levels were set separately by obtaining equal rms voltages at the output of the 455-kc fixed gain IF amplifier of the receiver; then calibrated attenuators were used to obtain the desired input ratio. The output noise voltage was measured in the absence of signal modulation (for convenience[2]), while the output signal was measured by a selective voltmeter (HP 300A wave analyzer). Figure 1 shows a

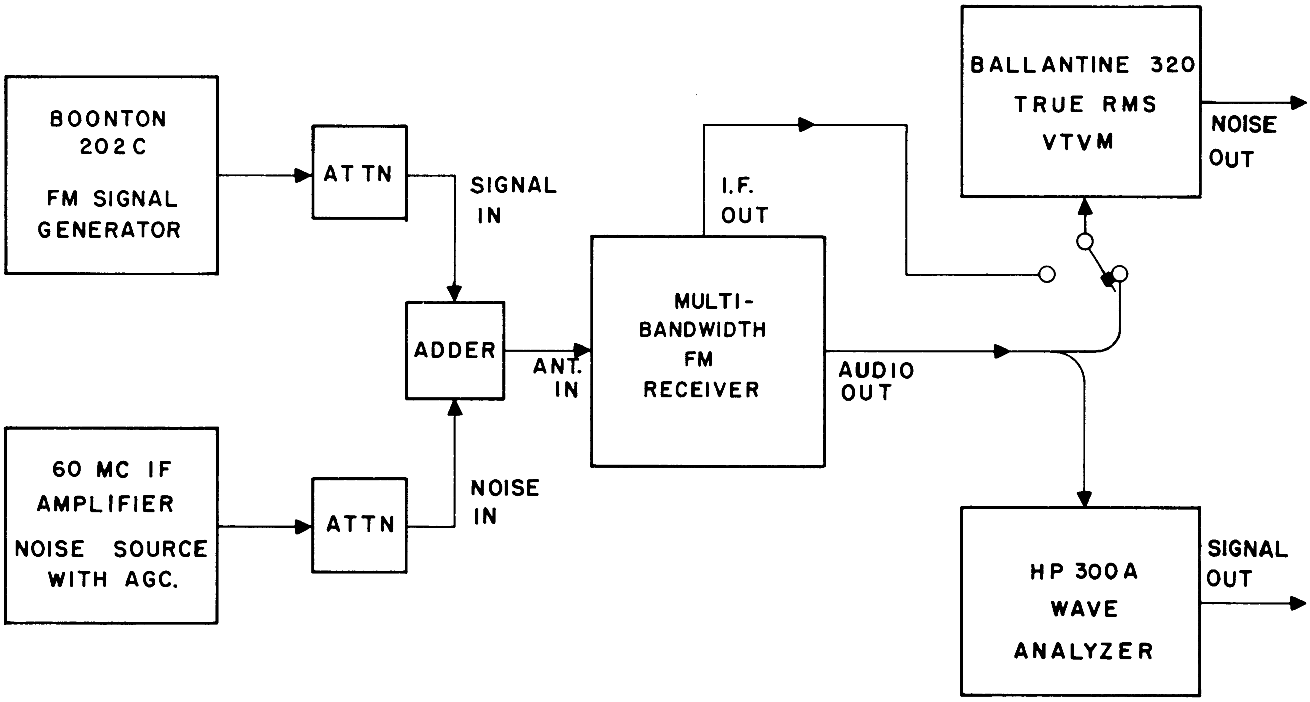

Fig. 1. Block diagram of experimental test system.

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[2] The change in output noise when the signal modulation is removed is small and not important to these measurements.

block diagram of the test system.

These tests all involve (1) 1-kc sine-wave signal modulation, (2) near maximum modulation depth, (3) audio bandwidth of 3.4 kc (100 cps to 3.5 kc), and (4) white Gaussian radio-frequency noise interference, linearly added to the receiver input. For frequency-modulation signals, maximum modulation depth is assumed to be a peak deviation equal to one half the receiver bandwidth. However, when the input noise level is high, the maximum audio output signal is normally obtained with the input deviation reduced to about 70 or 80 percent of maximum. This results from the slight attenuation occurring at the band edges of the IF amplifier frequency response. If less than maximum signal deviation is normally used, the output signal level is decreased, and thus the output S/N is decreased. The use of any sine wave frequency within the 3.4 kc audio bandwidth would yield the same results; 1 kc was arbitrarily chosen. The use of other audio bandwidths affects the results since this changes the deviation ratio. The output noise spectrum is approximately uniform for low input S/N and approximately proportional to frequency for large input S/N (Refs. 3, 4, and 7).

3. BASIC EXPERIMENTAL RESULTS

Figure 2 shows both the output signal and the output noise as functions of the input S/N for the three IF bandwidth positions of the FM receiver. The interfering noise signal is assumed to have a wide bandwidth and uniform distribution, while noise power included in the S/N ratio is only that noise in a fixed 6.8-kc bandwidth. This method of S/N measurement is conventional and is used in all the discussions in the references. The method meaningfully relates to the communication range problem in which the interfering signal is uniform wideband atmospheric or receiver noise.

At high input S/N, the receiver output signal is a maximum corresponding to the actual deviation of the input carrier. The noise is reduced by only a certain amount, as indicated by the theoretically derived asymptote shown in Fig. 2 in accord with the observations of Crosby and others (Refs. 1, 2, 5, and 9). The asymptote has unity slope so that at high input S/N the output S/N is proportional to the input S/N and the deviation ratio. At low input S/N, the receiver output noise reaches its maximum value, a function of the receiver IF and audio bandwidths, while the signal modulation is suppressed. Theoretical calculations show that the audio output signal should be reduced linearly with the amplitude of the RF input

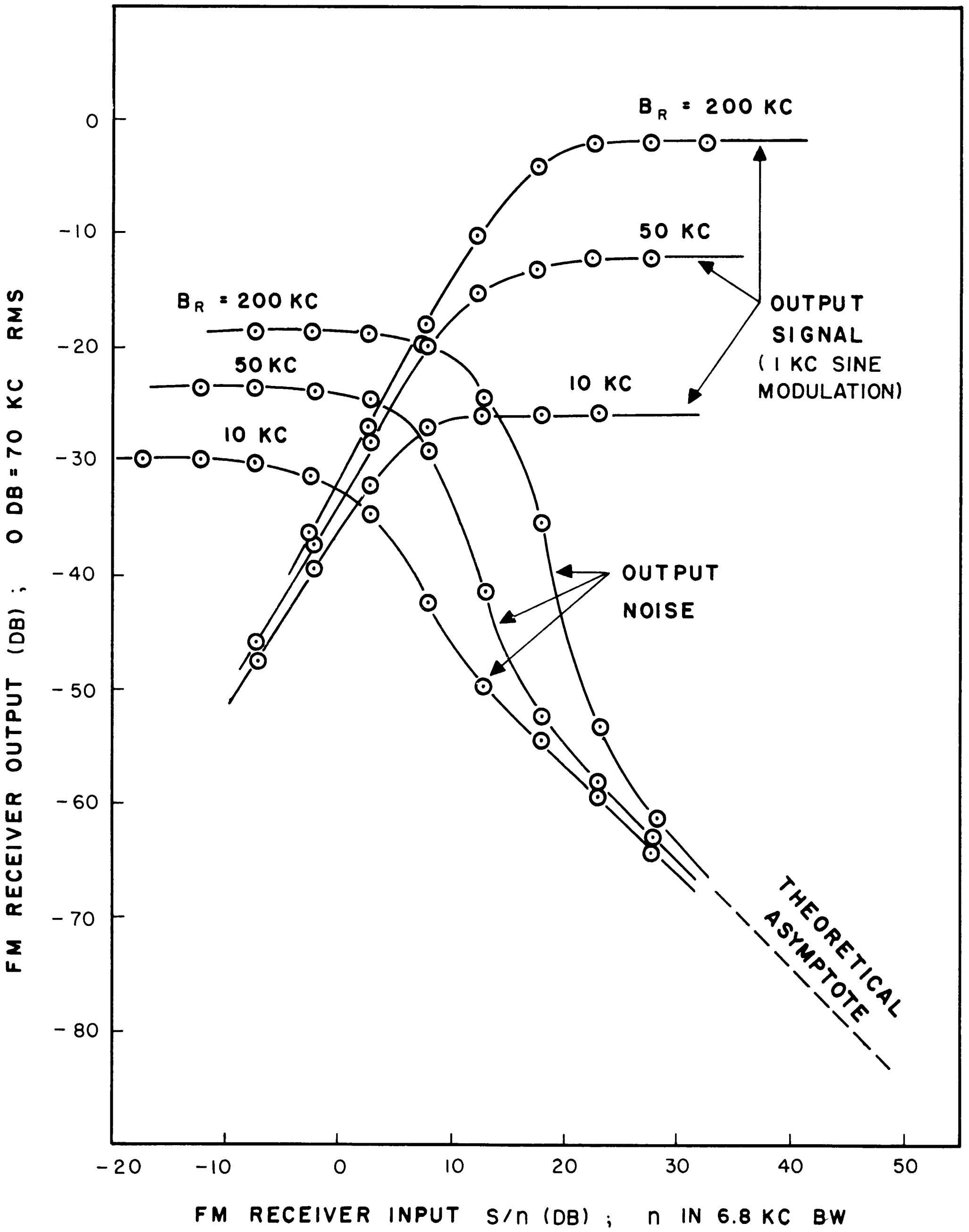

Fig. 2. FM receiver output signal and noise vs. input FM carrier-to-noise power ratio, the noise power taken in a fixed 6.8 kc bandwidth.

signal for a given (large) amount of input noise (Ref. 7). However, the experimental evidence of Fig. 2 points more toward a square-law effect; that is, the level of the signal component of the output will change as the square of the input carrier voltage.

The experimental results of Fig. 2 also show an interesting phenomenon in that the maximum obtainable output signal is nearly independent of the receiver bandwidth with high-level, uniform input noise. That is, at low input S/N ratios there is an input signal deviation (normally about 70 percent of the receiver half-bandwidth) yielding a maximum output signal whose magnitude is about the same for the three bandwidths shown. This result has not been predicted by theory.

4. INPUT VS. OUTPUT S/N

4.1 Broad-Band Noise Performance

If the decibel differences between the respective signal and noise curves of Fig. 2 are plotted against input S/N, one obtains the curves of Fig. 3, relating the input and output signal-to-noise ratios. In addition to the experimentally obtained FM curves, there are curves representing AM, SSB, and DSB systems where average power values are considered (for the AM input signal power just the carrier power is measured). The SSB and DSB curves are theoretical but easily obtained by ordinary receivers. The AM curve, experimentally obtained on a good quality AM receiver, matches the theoretical curve quite closely. It must be noted that the AM receiver's departure from linearity at less than 0 db S/N is the fault of the envelope detector and is not a necessary evil when using AM transmissions. The AM signal may be demodulated in the same manner as a DSB signal without the low S/N degradation.

It should be remembered that the input noise power parameter of Fig. 3 (and Fig. 2) is really noise power per 6.8 kc of bandwidth regardless of the operating bandwidth of the receiver. With the curves plotted in this manner, the classical observations may be made: FM is better only at high input S/N, and the wider the FM bandwidth the better. FM is much poorer at low input S/N, and the wider the FM bandwidth the poorer the output S/N. This "improvement threshold" that is often mentioned for FM is located at the S/N where the FM output S/N reaches its highest value above AM. These "thresholds" are observed from Fig. 3 to be at input S/N of about 10 db for 10-kc FM, 18 db for 50-kc FM, and 27 db for 200-kc FM. Clearly, the FM output is usable at input S/N below these values if AM, DSB, or SSB are similarly usable at relatively low output S/N. Thus, in order to compare the efficiencies of the various systems, one must suggest a minimum output S/N ratio at which the required input S/N ratios are to be compared.

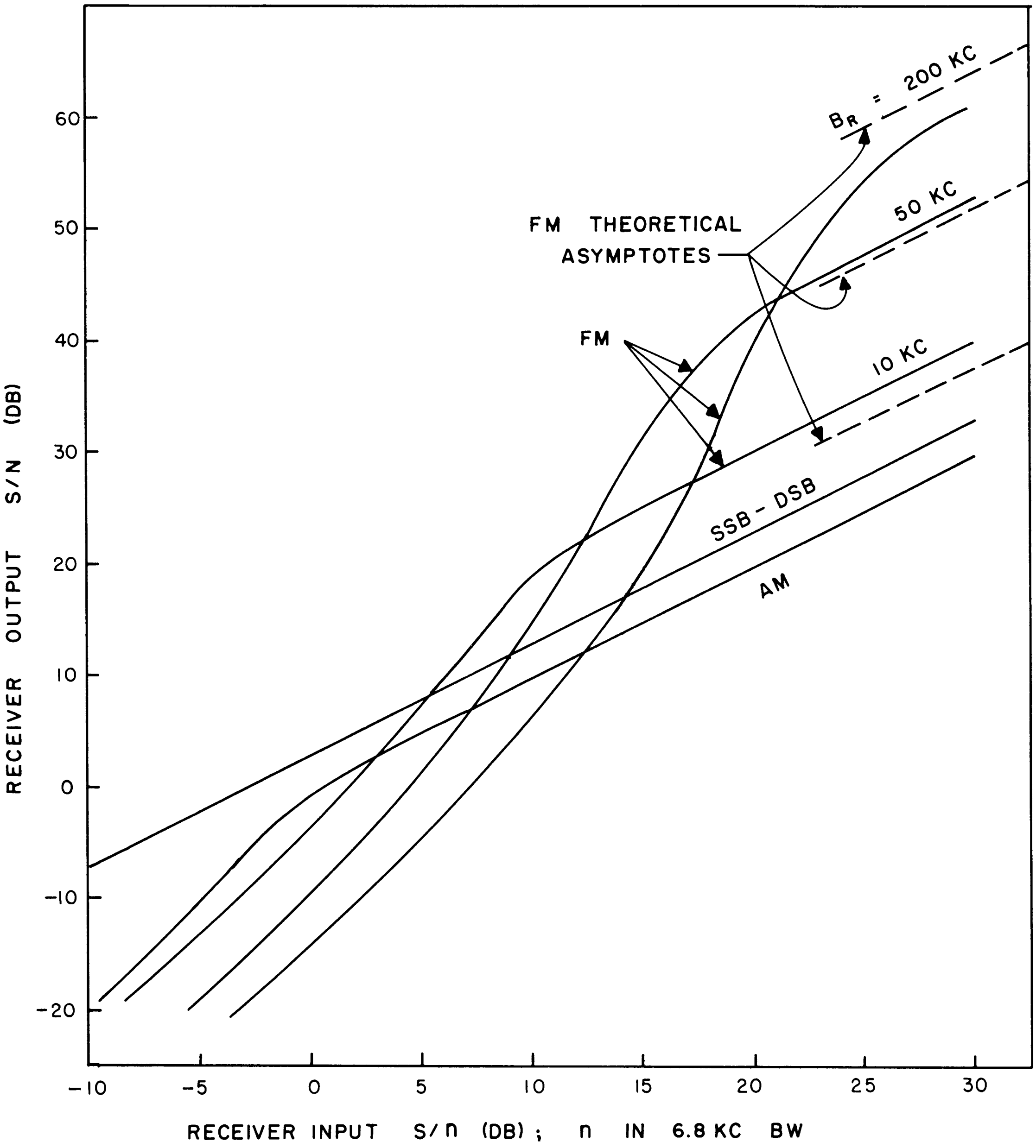

Fig. 3. Receiver output vs. input signal-to-noise ratios. The input noise power is taken in a fixed 6.8 kc bandwidth.

4.2 Performance Against Intentional Narrow-Band Noise

The use of input noise-power-per-unit-bandwidth is valid for studying receiver operation against either broad-band interference or atmospheric and receiver noise. However, if one is to study receiver effectiveness in the presence of intentional narrow-band interference, he must reshuffle the curves of Fig. 3 so that the input noise parameter represents the total noise power entering the receiver within its bandwidth. In addition, let us change the input signal power from average to peak envelope power, another reasonable

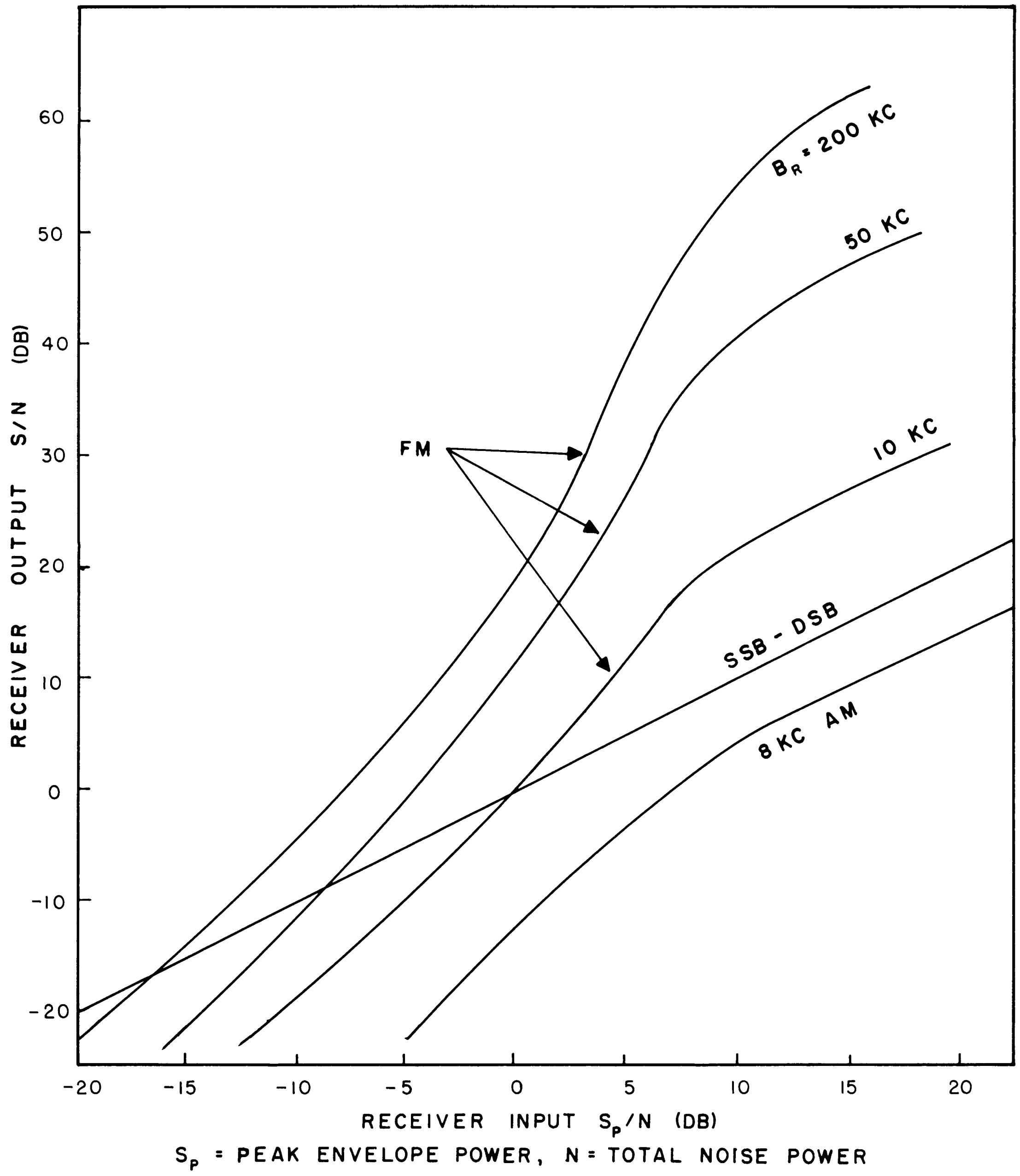

Fig. 4. Receiver output vs. input signal-to-noise ratios. The input noise power is the total power entering the receiver; the input signal power is the peak envelope power.

measurement in a practical situation with peak power limited transmitters. The result is Fig. 4, where a completely different set of conclusions must be drawn as to relative resistance to narrow-band, radio frequency noise interference.

It is now seen that FM is always superior to AM, and wideband 200-kc FM is better than even SSB for output S/N above about -15 db (a practical lower limit for voice communications if one must assign limits). At the point where the 200-kc FM curve and the

SSB-DSB curves intersect, the FM signal is some 28 db below the so-called threshold and yet still as good as SSB. These results for the spot-interference case show FM communications to be quite useful in spite of the contrary feelings of many, who believe (Ref. 8) that within a few but unspecified number of decibels of the "improvement threshold" reception is reduced to a very low but unspecified level of usefulness.

It should be emphasized that these tests were made using sine-wave modulation of the desired signal. Care should be exercised in extrapolating the test results to include other modulation waveforms such as pulse or speech signals. In general, the main concern is over the peak-to-average power ratio of the modulation wave since the modulation systems are by nature peak limited, whereas the output signal average power is of interest. Unclipped speech signals possess very high peak-to-average power ratios, thus resulting in a low average signal power. Extrapolating these results to include interference signals other than RF noise should not be attempted. One should consider, however, that although other jamming signals may be 5 to 10 db better against an ordinary receiver, counter-countermeasures often may be employed to reduce the effectiveness of even the best, most sophisticated interference signal to that of RF noise.

5. CONCLUSIONS

In conclusion, these simple laboratory experiments have shown that FM "thresholds" should be treated as what they are: namely, an arbitrary point on a smooth curve above or below which the curve exists and may be used, depending on the situation. In addition, the curves indicate that FM transmission, both narrow-band and wide-band, possesses competitive performance capabilities for military voice communications use, especially considering some of the practical advantages of building and powering FM transmitters.

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