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**Publisher's version / Version de l'éditeur:**
https://doi.org/10.4224/21273434
*Report (National Research Council of Canada. Radio and Electrical Engineering Division : ERA); no. ERA-326, 1957*

ERA-326

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NATIONAL RESEARCH COUNCIL OF CANADA
RADIO AND ELECTRICAL ENGINEERING DIVISION

# THE JAMMING OF "DICKE FIX" RADAR RECEIVERS

S. G. JONES AND T. H. SHEPERTYCKI



OTTAWA
AUGUST 1957 NRC# 35410

## ABSTRACT

The "Dicke Fix" type of radar receiver as a countermeasure to FM-by-noise barrage jamming is investigated. Characteristics of carcinotron-generated jamming signals and design and operation of receivers are discussed. Laboratory test results showing the effect of varying jammer and receiver parameters on the ratio of jamming to signal power required to mask radar signals on both A-scan and PPI displays are presented. Performance in the presence of multiple jammers is examined, and an attempt is made to assess the usefulness and limitations of the "Dicke Fix" technique as an anti-jamming measure.

# CONTENTS

## TEXT



## FIGURES

## PLATES

V. (a) - (d) Increase in Number of Jamming Impulses due to Additional Noise Jammer

(e) - (f) Effect of Optimizing Clip Level in the Presence of C-W and Noise Jamming

# THE JAMMING OF "DICKE FIX" RADAR RECEIVERS

- S.G. Jones and T.H. Shepertycki -

## INTRODUCTION

The advent of the type "M" carcinotron has made possible the development of very effective barrage jammers. It appears practical for a modern bomber to self-screen itself — that is, to deny range information — from the present search and GCI radars operating in a frequency band 200 to 300 mc/s wide by the use of a single carcinotron, frequency modulated by video noise. An effect similar to a large increase in the thermal noise level of the receiver is observed when the main lobe (and the side lobes if the jamming is sufficiently strong) of the radar antenna pattern pass through the azimuth of the jammer. However, the signal radiated by the jammer is not white Gaussian noise, and anti-jamming receivers may be developed which exploit the peculiarities of the jamming signal to advantage.

If the jamming signal is a carrier swept randomly and rapidly within a frequency band which is large compared with the bandwidth of a single radar receiver, and if the time for the carrier to cross the receiver passband is short compared with the reciprocal of the bandwidth, the energy accepted by the radar receiver is in the form of impulses separated by relatively long time periods. It is to be expected, therefore, that methods which earlier had been used in the communications field to alleviate impulse interference should be considered as radar anti-jamming measures. In one type of receiver, a wide band input section to minimize the time duration of the impulse response is followed by an amplitude limiter and a filter of normal bandwidth. In 1940, this technique was described by Wald [1] for use in the VHF frequency range. Previously, in 1936, a similar approach was employed by J.J. Lamb in his i-f noise silencing circuits [2], but a scheme of gating off the noise bursts rather than limiting was used, probably because of the difficulties associated with having many signals within the wide bandwidth simultaneously, which could scarcely be avoided in the broadcast and short-wave bands. An unwanted signal large enough to exceed the limit level would cause a smaller, wanted signal to be suppressed. On this continent, when applied to radar, the method is conveniently referred to as the "Dicke Fix", following an appendix to the report of Project Lamp Light [3] entitled "The Dicke Fix to the Carcinotron" which credited the suggestion to Dr. R.H. Dicke of Harvard University. It is understood that the method was suggested independently by several persons in the United Kingdom, and that the technique for use in radar has been investigated there.

In Canada, an experimental receiver employing the technique was fitted in an AN/MPS-501B radar by the Defence I Section of the Radio and Electrical Engineering Division of the National Research Council in September 1955. Considerable success was achieved in tests conducted during Operation "Bracket" against the

S-band experimental carcinotron barrage jammer developed in the United Kingdom at the Royal Aircraft Establishment. At that time, laboratory facilities for determining the characteristics of carcinotrons and for measuring the susceptibility of receivers to jamming were nearing completion in the Defence II Section, and an experimental investigation to determine the usefulness and limitations of the "Dicke Fix" was added to the program of the jamming studies project in which the authors were engaged. While the inquiry was oriented toward the requirement for jamming such receivers, close liaison was maintained with the radar counter-countermeasures group (Defence I Section). This cooperation in the design and testing of prototype receivers has helped to speed the process which has resulted in the successful testing of pre-production models in operational radar equipments of the Canadian armed forces.

The work to be described is part of a continuing study of radar jamming problems, the purpose and orientation of which was dealt with in some detail in the initial report [4]. Briefly, the study is concerned with the properties, capabilities, and limitations of the more promising generators of jamming signals, and the manner in which jamming signals affect jammed systems, so that the feasibility of jamming can be predicted with confidence. One of the most useful quantities which requires evaluation is the " camouflage factor", which for a given jamming signal - receiving system combination is the ratio of jamming signal power to the minimum useful level of signal power at the receiver. This quantity will be represented hereinafter by the symbol (J/S), and will, in general, vary with jamming signal power level as well as other jammer and jammed system parameters. A previous report [5] explored the way in which (J/S) varied when FM-by-noise barrage jamming was used against ordinary radar receivers employing A-scan and PPI displays. The present report extends that investigation to the "Dicke Fix" or wide-band-limiter type of receiver.

Receivers without r-f preselection were considered normal, so that both images contribute to the i-f output. Therefore, in this report, the symbol J will stand for the sum of the powers in a 0.7 mc/s r-f frequency band at each image, which is equal to the power in a 1.4 mc/s band if the spectrum is uniform and covers both images. For receivers with r-f preselection and with a uniform jamming spectrum, J will be equal to twice the power in a 0.7 mc/s frequency band at the sensitive image. In this way a value of J has been made to correspond to a given jamming power density regardless of whether or not r-f preselection is employed. The symbol S stands for the minimum detectable r-f peak signal power under the conditions of jamming prevailing at the time of measurement. The ratio (J/S) is the camouflage factor mentioned above. Low (J/S) values correspond to more effective jamming, whereas high (J/S) values indicate less effective jamming or more effective anti-jamming performance. The symbol W represents the width of the jamming barrage, $B_n$ the bandwidth of the video noise used to frequency modulate the jammer carrier, $B_1$ the bandwidth of the wide band input section of the receiver, and $B_2$ the bandwidth of the narrow band, post-limiter section of the receiver.

## CHARACTERISTICS OF THE NOISE JAMMING SIGNALS

A brief description of the jamming signals used in the experiments would perhaps be of interest to those not familiar with the techniques of FM-by-noise barrage jamming. The generator of jamming signals is a backward-wave oscillator, in which a one-to-one relationship, almost linear, exists between the output frequency and the voltage applied to one of the electrodes. The voltage which is used to vary the frequency of the oscillator is video noise with an approximately uniform spectrum over the frequency range 0.1 to 6 mc/s, and having a nearly uniform probability distribution of amplitude. Thus, the frequency of the oscillator will vary randomly and rapidly in accordance with the noise amplitude variations. The probability distribution of output frequency will be nearly uniform since it corresponds to the amplitude distribution of the noise. The peak-to-peak noise amplitude is sufficient to cause the output frequency to vary over a 300-mc/s band centered at about 2850 mc/s.

The characteristics of the noise can only be described statistically, but one or two points should be emphasized. The noise voltage, which is obtained by suitably clipping and compressing Gaussian noise, appears to cross levels near the middle of the waveform more often than it crosses levels toward the extremes. Evidently the near uniformity in amplitude distribution is achieved because the voltage levels toward the edges are crossed relatively less often but more slowly than levels in the middle of the waveform. Also, there is less uniformity in the time between crossings at levels near the extremes, there being a tendency for the crossings to appear in closely spaced pairs separated by longer periods. If a radar receiver is tuned to a frequency corresponding to a voltage level near the edge of the noise waveform, it will be excited by frequency sweeps which tend to be slower, fewer, and to appear in pairs, than if the receiver were tuned to the center of the barrage.

The effect on the radar receiver of a swept-frequency signal crossing its pass band depends on the sweep rate relative to the natural response time (which is approximately equal to the reciprocal of the bandwidth) of the receiver. With a very slow sweep rate, the output of the receiver would build up slowly and decay as the signal frequency is swept across its pass band, and the response would have the same shape as the receiver pass band. However, as the sweep rate is increased it will eventually reach a critical region where the time taken to sweep across the pass band is of the same order as the response time of the receiver. With further increases in sweep rate, the width of the response will not change appreciably, but the amplitude will diminish, and the shape of the response will be that of the characteristic response of the receiver to an impulse. This implies [6, 7] that if the time duration of the impulsive excitation is short compared with the reciprocal of the bandwidth, the shape of the output response will depend only on the shape of the receiver response curve, and not on the bandwidth or the waveform of the impulse. Of course, for the same pass band shape, the bandwidth and time of response bear a reciprocal relationship to one another, and as the time scale shrinks with widening of the bandwidth the output voltage scale expands proportionately keeping the time integral of the output independent of the bandwidth.

If the bandwidth of the video noise voltage used to frequency modulate the carrier is less than the receiver bandwidth, successive responses of the receiver will not overlap, but as these bandwidths become equal, overlapping will commence and when the video noise bandwidth reaches about twice the receiver bandwidth, the output of the receiver cannot be distinguished from the normal receiver noise.

## RECEIVER DESIGN CONSIDERATIONS

### Basic Configuration

Except for the i-f amplifier, the receivers are similar in design to the usual radar superheterodyne receivers. In these, the microwave circuits and crystal mixer are capable of operating over a band of frequencies corresponding to the tuning range of a tunable magnetron. It will be shown later that tunable r-f preselection of the proper bandwidth can be employed to advantage in such a system. The second detector and video system can be the same as in conventional radar receiving systems.

The i-f amplifier is composed of three parts: an input section with low-noise input stage, a bandwidth several times as wide as that normally employed, and sufficient gain to increase the thermal noise level to a few volts (rms); an amplitude limiter with good limiting characteristics; and a narrow band section of normal radar bandwidth.

### Input Section Bandwidth

The input section bandwidth must be a compromise between two conflicting requirements. It should be as wide as possible to minimize the duration of the impulse response, but not so wide that the time taken for the signal to sweep across the pass band is, on the average, longer than the impulse response duration.

In what follows, frequencies and bandwidths will be measured in megacycles per second and time in microseconds. Let W be the peak-to-peak frequency deviation of the jammer output, and $B_n$ the bandwidth of the video noise modulation signal. Let $T_1$ be the average time interval for the carrier to sweep across the input bandwidth $B_1$, the definition of which will be discussed below.

$$T_1 = \frac{B_1}{(\overline{dF/dt})},$$

where $(\overline{dF/dt})$ is the average rate of change of jammer frequency. An approximate value for $(\overline{dF/dt})$ can be obtained by considering the output frequency function F to vary sinusoidally with amplitude W/2 and frequency $\frac{B_n}{2}$. Then

$$F = F_0 + \frac{W}{2} \sin (2\pi \frac{B_n}{2} t) \cdot$$

$$dF/ft = 2\pi \frac{B_n}{2} . \frac{W}{2} . \cos (2\pi \frac{B_n}{2} t),$$

$$(\overline{dF/dt}) = 2\pi \frac{B_n}{2} . \frac{W}{2} . \frac{2}{\pi} = W.B_n,$$

and $$T_1 = \frac{B_1}{W.Bn} .$$

The total time, T, of the disturbance at the input to the limiter will be approximately $T = T_1 + T_2$ where $T_2$ is the duration of the impulse response of the receiver input section, which will be assumed to be equal to a constant K divided by the input section bandwidth $B_1$.

$$T = T_1 + T_2 = \frac{B_1}{W.Bn} + \frac{K}{B_1} .$$

The minimum value of T will be obtained for the optimum value of $B_1$, $B_1$ opt. Setting the derivative of T with respect to $B_1$ to zero, gives

$$dT/dB_1 = \left( \frac{1}{W.Bn} - \frac{K}{{B_1}^2} \right) = 0,$$

from which $B_1$ opt. $= (K.W.B_n)^{\frac{1}{2}}$.

That is, the optimum bandwidth, $B_1$ opt., is that for which $T_1 = T_2$.

Since the expected number of crossings [8] of the mid-barrage frequency is $1.155\ B_n$, the interfering duty cycle, D, at the center of the barrage is given by

$$D = 1.155\ B_n T = 1.155 \left( \frac{B_1}{W} + \frac{KB_n}{B_1} \right)$$ if r-f preselection is used,

and twice this quantity if the receiver is sensitive at both images. When $B_1 = B_1$ opt. this gives $D = 2.31 \left( \frac{K.B_n}{W} \right)^{\frac{1}{2}}$. This is a measure of the fraction of the time during which the receiver, because of the jamming, cannot pass signal information.

Before hastening to calculate values for optimum $B_1$ and for D, using typical values for W, $B_n$, and K, some discussion of the above results may be profitable. The relations derived indicate the approximate manner in which $B_1$ and D vary with W, $B_n$, and K for some fixed ratio of peak jamming impulse amplitude at the input to the limiter, to the limit level. The value of this ratio for which it applies depends not only on the criterion by which we measure $B_1$, but also on the shape of the bandpass. It is not difficult to see that $T_1$ and $T_2$, and hence T and D, increase with increased jamming level, and yet this quantity does not appear in the expressions derived. It might be suggested that this be accommodated in the definition for $B_1$, but this puts the impossible requirement on $B_1$ that it be an increasing function of the jamming level in $T_1$, and a decreasing function of jamming level in $T_2$. Of course, if the bandpass had extremely steep skirts, $T_1$ would be independent of the jamming level, but in that event, $T_2$ would be increased since circuit configurations having steep skirts also have prolonged impulse response time. This would seem to imply that preferred bandpass shapes exist, but discussion of this will be deferred to a later section. It suffices to say here that it is difficult to define the bandwidth in a satisfactory way if different bandpass shapes are to be accommodated. One tends to feel that the effect of bandpass shape is to some extent self-compensating in that shapes which increase $T_1$ decrease $T_2$ and vice versa.

Despite the fact that there are doubts about obtaining an adequate definition for the bandwidth of the input section of the receiver, let us assume that the usual 3-db bandwidth is satisfactory and calculate a value for the optimum bandwidth on that basis, using typical values for W, K and $B_n$.

In the S-band, tunable magnetrons for radars are capable of tuning over a range of about 200 mc/s. Therefore let us assume that W is 250 mc/s. $B_n$ equals 5 mc/s, is a good compromise between jamming performance and jammer modulator weight and cost. K = 2 was observed to be a satisfactory value.

$$B_1 \text{ opt.} = (250 \times 5 \times 2)^{\frac{1}{2}} = 50 \text{ mc/s.}$$

Such a bandwidth coupled with the approximately 100-db gain which is required to provide good limiting at low jamming levels is not easily obtained in a practical i-f amplifier. Perhaps r-f amplification using travelling wave devices to obtain a large portion of the required gain would provide the answer. In any event, the receivers used in these experiments contained from 12 to 14 tubes, each having a figure of merit in excess of 100 mc/s. The 3-db bandwidths obtained were about 14 mc/s for the stagger-tuned receiver and about 6 mc/s for the synchronous-tuned receiver. These bandwidths are considerably less than the optimum calculated, so that operation is in the region where $T_2$ is greater than $T_1$. This implies that for this receiver an effort should be made to obtain minimum impulse response in the amplifier rather than steep skirts on the pass band, and that the interference duty cycle D is approximately proportional to $B_n$ rather than to the square root of $B_n$.

Stagger-tuned or Synchronous-tuned Receiver?

When wide-band i-f amplifiers are required the practice of using stagger-tuned pairs, triples, etc., in cascade to decrease the loss in gain-bandwidth product over that which would be realized if synchronous-tuned stages were cascaded has become widespread. When the poles and zeros of the receiver transfer function are positioned in the usual Butterworth or maximally-flat configuration, more uniform gain over a large part of the wider (3 db) bandwidth and faster pulse rise time are obtained than if the same number of tubes giving the same mid-band gain are used in a synchronous-tuned receiver. All this is obtained at the expense of a moderate amount of overshoot which in many cases is not objectionable. In the present application, however, where minimum length of impulse response time above some critical level is desirable, the fast rise time implies a short primary lobe in the impulse response, but the overshoot undulations indicate the additional lobes which extend the length of the response. The desirable features, such as lack of overshoot, in the transient response of Gaussian-shaped bandpass filters, to which a cascaded synchronous-tuned amplifier is a close approximation, invite the question as to which of these two amplifier types, the stagger-tuned or the synchronous-tuned is to be preferred.

Formally, at least, the transfer function of each type of receiver which will provide the same gain and use the same number of tubes need only be written down, and the inverse Laplace (or Fourier) transform calculated, since the system function and its impulse response are transform pairs. However, for a large number of stages in the receiver such calculations are lengthy and time-consuming. Moreover, they do not easily lend themselves to an assessment of the variations to be expected from inexact values of parameters due to normal circuit tolerances, though perhaps a carefully constructed low-frequency analog would. While a complete study of the questions has not been made, some preliminary calculations, and observations on a six-stage analog, point out two somewhat different requirements. For best performance at low jamming levels, the width of the impulse response a few db below the peak should be kept as short as possible. This is best met by stagger-tuned amplifiers in which the primary lobe of the response is shortened due to interference effects between the natural modes. At high jamming levels, however, it is the width of the response many db below the peak which is important. To keep this as short as possible requires employment of large damping factors for all stages, and the synchronous-tuned receiver would be preferred. A good compromise might be a receiver composed of staggered pairs, since the primary lobe is short due to interference between the natural modes, and yet the damping is greater than for other stagger-tuned arrangements, and only slightly less than that for the synchronous-tuned receiver.

Operation of the Limiter

A detailed analysis of the interaction of thermal noise, radar echoes, and jamming signals in the limiter is complex and difficult, and is beyond the scope of this report. However, useful insight into the operation can be obtained from experimental observations and the published studies of special cases.

It has been found that the performance at low jamming levels improves as the gain prior to limiting is increased, at least until the rms level of receiver noise approaches the fixed limit levels. H. Pettigrew [9] has calculated that in the absence of jamming the minimum detectable signal increases by two db as the degree of limiting of the wideband thermal noise increases from zero to a very heavy value. K. Amo [10] has studied the effect of applying the sum of a large and a small sinusoidal signal of different frequencies to an amplitude limiter. He shows that the small signal output is suppressed relative to that of the large signal at all values of input sufficient to produce clipping, and approaches 6 db as the input is increased without limit.

In the absence of jamming, therefore, we can expect at most a 2 db decrease in receiver sensitivity due to interaction of the signal and receiver noise in the limiter. The presence of a large interfering signal will cause the output amplitude of the smaller desired signal to be decreased by from once to twice the ratio of the interfering signal amplitude to the limit level. To a first approximation, then, the wanted signal is gated off for the period during which the response of the wide-band (pre-limiter) portion of the receiver is greater than the wanted signal. Similarly, jamming is suppressed for the period during which the signal exceeds the jamming, so that a capture or thresholding effect similar to that present in FM reception is in evidence. To be detectable, the radar signal must have sufficient amplitude to suppress the jamming for such a fraction of the pulse length that its contribution causes the output of the narrow-band section of the receiver to be noticeably different from what is obtained when it is absent. It is not difficult to see that for the same received jamming power, the larger the peak-to-average amplitude ratio of the jamming signal at the limiter input, the smaller will be its effectiveness. Impulsive interference consisting of large amplitude signals of short duration separated by relatively long periods should cause little interference, whereas a c-w signal can produce complete suppression. Suppression by a c-w signal is equivalent to a reduction in overall receiver gain, and can be compensated for by an increase in post-limiter gain.

## Description of Experimental Receivers

The test results presented in this report were obtained with a stagger-tuned receiver constructed for the tests from a basic design by Mr. R.S. Richards of this Division, and a synchronous-tuned receiver borrowed for a short period from Mr. Richards. Two different limiters were used with the stagger-tuned receiver. Initially, a circuit using a type-6BN6 gated-beam tube was employed, but this was replaced by a saturated pentode circuit with more desirable characteristics. For convenience, the receivers will be referred to hereafter as follows:

Receiver No. 1 — stagger-tuned with type-6BN6 limiter
Receiver No. 2 — stagger-tuned with pentode limiter
Receiver No. 3 — synchronous-tuned with pentode limiter

Since details of the design and characteristics of the receivers have been published [11], only a brief summary will be included here.

All receivers had similar low-noise cascode input circuits, using a pair of W.E. type-417-A triodes. In Receivers No. 1 and No. 2 this was followed by three maximally-flat triples and one extra stage tuned to the center frequency. Receiver No. 3 had eleven synchronous-tuned stages following the low-noise input stage. In all cases, type-E88CC (Phillips) tubes connected in a cascode circuit were employed. The 3-db bandwidth of Receivers No. 1 and No. 2 was about 14 mc/s, while that of Receiver No. 3 was about 6 mc/s. Voltage gains of the order of $10^5$ were obtained, providing a receiver noise output to the limiter of one or two volts rms. Normally, in the absence of signals, receiver noise was limited to about the unclipped rms level.

## INSTRUMENTATION AND EXPERIMENTAL PROCEDURE

### Description of Test Bench

Fig. 1 is a block diagram of the experimental setup used to evaluate various "Dicke Fix" type receivers against FM-by-noise barrage jamming. The jammer consists of a low-power backward-wave oscillator frequency-modulated by noise. The following three jammer parameters can be varied independently: (a) jammer modulation bandwidth, $B_n$, (b) output spectrum width, W, and (c) center frequency of the jammer spectrum, $f_{jo}$. The noise generator has a nearly flat output spectrum over the frequency range from 0.1 to 6 mc/s, and the jammer modulation bandwidth can be varied by inserting one of several low-pass filters between the noise generator and the modulator. The width, W, of the jammer output spectrum is determined by the setting of $AT_3$, which controls the noise input voltage to the modulator. Spectrum widths up to 300 mc/s can be obtained. The center frequency of the jammer spectrum, $f_{jo}$, is fixed by the d-c voltages applied to the tube electrodes.

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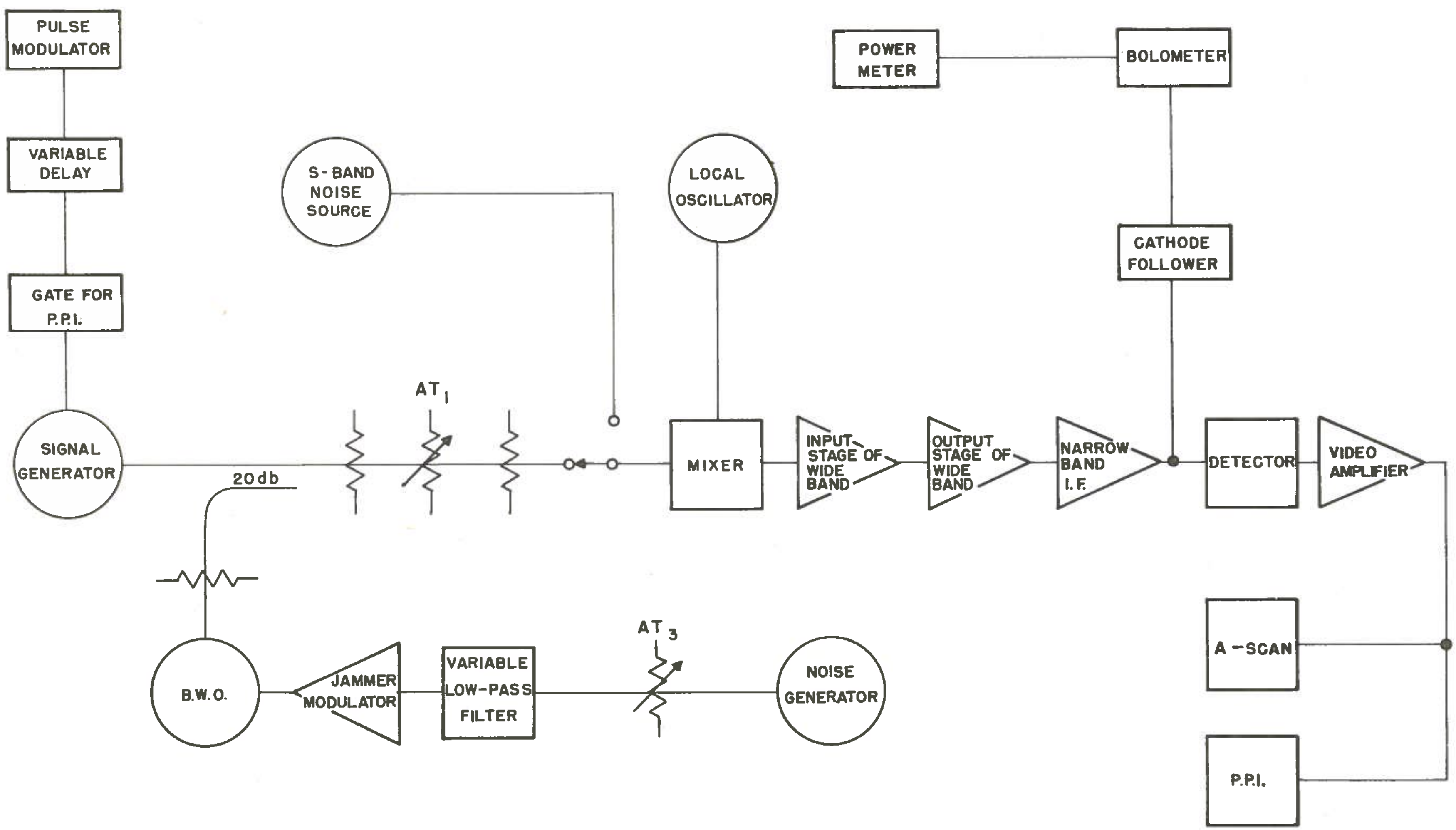


FIG. 1. BLOCK DIAGRAM OF TEST BENCH

A pulsed signal generator was used to simulate a radar echo. The signal generator output could be gated to give a more realistic PPI display. The radar and jamming signals were combined in a directional coupler, the output of which was fed into a variable attenuator and then into the particular receiver to be tested. The function of this attenuator will be described below, as will that of the cathode-follower-bolometer arrangement which is very useful in helping to obtain J/S values. The receivers have been described previously.

Calibration and Measurement Procedure

Since one of the objects of this report was to present J/S values for various receiver-jammer-indicator combinations, a description of the method and procedure used to measure J/S will be outlined below.

The system used to determine the minimum detectable signal, S, is essentially the same as the one described in Reference 5. It consists of reducing the amplitude of the signal pulse to a value well below the detection threshold for the jamming level employed, and setting the position of the signal pulse on the sweep, i.e., the range of the signal pulse, randomly to one of four or five possibilities. In this way the observer does not know at what range the signal will appear. The pulsed signal amplitude is then slowly increased until the observer detects its presence on the display and correctly indicates its range. The power level at which the signal is first correctly detected is recorded. In 90% of the measurements, this procedure was repeated with three different observers, each taking ten readings. The results were combined to give an average value of S for the particular jammer-receiver-indicator combination being used. This method has made it possible to obtain repeatable results.

The average jamming power in the narrow-bandwidth, J, was measured by means of the cathode-follower-bolometer arrangement described in Reference 5. The determination of J/S will be described in conjunction with Fig. 1.

1) The output section of the wide-band amplifier shown in Fig. 1 was replaced by variable attenuator $AT_2$. With the S-band noise source feeding the receiver, $AT_2$ was adjusted until the narrow-band i-f power, as indicated by the power meter, read about 0.5 mw. The exact power reading was recorded. With this level at the power meter, there was no danger of saturation occurring at any point between $AT_2$ and the power meter.

2) The S-band noise source was disconnected, the signal generator was switched off, and $AT_2$ was left at the value obtained in (1). The jammer was connected to the receiver and $AT_1$ was adjusted to obtain the same power reading as in (1). $AT_1$ could then be calibrated to indicate the jamming power in -dbm at the receiver input in a frequency band equal to twice the bandwidth of the narrow-band section of the receiver, since no r-f preselection was employed.

3) With $AT_1$ and $AT_2$ set at the values obtained in (1) and (2) above, the jammer connection to the directional coupler was replaced by a flat-load, and the signal generator was tuned and its c-w output adjusted to give the same power reading as in (1) and (2). The setting of the calibrated attenuator on the signal generator was then recorded, at which setting J = S, and J/S = 0 db.

4) $AT_2$ was replaced by the output section of the receiver, and the jammer and the signal generator were connected to the receiver. The signal generator was switched to pulse output and retuned, using the A-scan as a tuning indicator.

5) $AT_1$ was adjusted to give the desired level of jamming and S was obtained as previously described. The difference between the average signal generator attenuator reading corresponding to S db, and the value obtained in (3) was taken as J/S for the particular level of jamming and the particular jammer-receiver-indicator used.

Most of the results included herein were obtained using type-A display. Initially, both type-A and PPI displays were used, but it soon became apparent (see Fig. 5) that the ratio of the camouflage factors measured for the two display types was essentially constant, and therefore PPI measurements were discontinued. This proportionality has been noted previously [5] when the bandwidth of the modulating noise exceeded the receiver bandwidth, but the action of the limiter in the Dicke Fix receiver appears to reduce the degree of the peaking in the noise output so that the proportionality exists for bandwidths of modulating noise less than the receiver bandwidth.

The following is a list of the more important parameter values used in the experiments:

| | | | |
|---|---|---|---|
| a) | Pulse Signal: | Pulse Length | 3.5 microseconds |
| | | Frequency | 2830 mc/s |
| | | Repetition Rate | 360 pps. |
| b) | Receivers: | Responses at 2770 and 2830 mc/s, except where r-f preselection was used. | |
| | | Local Oscillator Frequency | 2800 mc/s |
| | | Intermediate Frequency | 30 mc/s |
| | | Wide Bandwidth — Sub-section (5) above. | |
| | | Narrow Bandwidth (post limiter) | 0.7 mc/s |
| | | A-scan Sweep Length | 100 microseconds/cm. |
| c) | Jammer: | Spectrum Width: | up to 300 mc/s, usually set at 200 mc/s |

Video Noise Bandwidth: 0.1 - 6.0 mc/s, with upper frequency reduced to 3.0, 1.0, or 0.3 mc/s, if desired, by use of low-pass filters.

## FACTORS AFFECTING THE CAMOUFLAGE FACTOR (J/S)

### Jamming Power Level

The aim of jamming with noise-like signals is to increase the detection threshold of the receiver above that which exists due to thermal noise. In the case of thermal noise, this threshold usually occurs at some fixed ratio of noise to signal power. If the jamming were as effective as thermal noise it would, in general, be considered to be ideal, and the camouflage factor for any system against which it was used would be a constant, equal to that which applies for thermal noise. On the other hand, if the receiver is completely successful in combatting the jamming, there would be no change in the minimum detectable signal as jamming is added, and the curve of (J/S) against J would rise linearly with unity slope. This would constitute an ideal anti-jam receiver, and is only possible when the characteristics of the jamming differ in some important way from those of white noise.

The above are the bounds within which the combination of a practical jammer — practical anti-jam receiver would be expected to operate. If the noise at the receiver input is different from white noise, — i.e., only partially effective — the slope of the curve of (J/S) against J would be expected to be somewhere between zero and one; the more effective the jamming, the closer to zero; the less effective, the closer to unity. Of course, because all practical receivers will be limited in the range of input powers which can be accommodated in the normal or desired mode of operation, the above conditions would be expected to exist for some limited range of jamming and signal powers above thermal noise threshold, after which the slope of the curve would tend to zero or even become negative, depending on the limiting characteristics of the receiver.

In the Dicke Fix receiver, operating against a carrier which is frequency-modulated with video noise of bandwidth $B_n$, and having a frequency deviation large compared with the input bandwidth $B_1$, a slope of the (J/S) against J curve varying from zero when $B_n$ is greater than $B_1$ to approximately unity when $B_n$ is much less than $B_1$ would be expected. Also, since the limit level is set to about the thermal noise level, this would be expected to apply over a range of jamming levels approximately equal to the ratio of the wide to narrow bandwidths ($B_1/B_2$) of the receiver above the thermal noise level. The above statements apply in the absence of r-f preselection. When r-f preselection is used the effective $B_n$ is halved, because jamming impulses at one image frequency are now rejected. In this case, therefore, the slope of the "(J/S) against J" curve should vary from zero when $\left(\frac{B_n}{2}\right)$ is greater than $B_1$, to approximately unity when $\left(\frac{B_n}{2}\right)$ is much less than $B_1$.

Fig. 2 shows a plot of (J/S) against J for a 200 mc/s barrage with various values of $B_n$ for Receiver No. 2. Fig. 3 shows a similar plot for Receiver No. 3. The curves will be seen to have the characteristics mentioned above. Comparison of Fig. 2 and Fig. 3 indicates that Receiver No. 2 gave better results than Receiver No. 3. However, only a part of the difference can be attributed to the difference in bandpass shape and bandwidth, since some of it is thought to be due to the lighter limiting in Receiver No. 3 caused by a few db deficiency in wide-band section gain. The chief advantage shown by Receiver No. 2 compared with Receiver No. 3 is in the slope of the initial portion of the curve. The slopes are in the ratio of 1.4:1 for equivalent types of jamming. Operationally, the large initial slope is probably more important than the maximum value of the curve since it denotes greater resistance to jamming at lower jamming levels — i.e., longer ranges.

Fig. 4 shows input-output curves of Receiver No.2 for the jamming signal and for a sinusoidal signal. The dynamic range for the sinusoid is about the ratio of the wide to narrow bandwidths, as would be expected. The decrease in the noise can be thought of as being due to suppression of the thermal noise because of increased limiting, or as being due to energy translated to harmonic frequencies which previously fell within the narrow bandwidth for the same reason.

<u>Video Noise Bandwidth</u>

The bandwidth of the video noise voltage used to modulate the jammer frequency determines the average number of receiver crossings per second and consequently is a very important jammer parameter.

For a jammer spectrum width of 200 mc/s, and a video noise bandwidth greater than about 0.35 mc/s, the average rate of change of frequency will be sufficiently large to initiate at each passage the impulse response of a receiver located in the center of the spectrum. The average receiver response in the wide bandwidth, i.e., at the limiter input, will have a constant width, and a height which will depend upon the sweep rate and the jamming level [12].

Curves and photographs showing the effect of the video noise bandwidth on the jamming efficiency, J/S, for Receiver No. 2 are presented in Fig. 5 and Plate I. The curves show that for a fixed jamming level, the jamming efficiency increases (J/S decreases) with increasing video noise bandwidth. These curves were obtained for a jamming level of -80 dbm, and since the minimum detectable signal of the receiver without jamming is -108 dbm, the maximum possible (J/S) value at this jamming level is -80 + 108 = 28 db. The "J/S vs. $B_n$" curve approaches this value for a video noise bandwidth of 0.1-0.3 mc/s. This video noise bandwidth results in receiver impulse responses at the limiter input which do not over-

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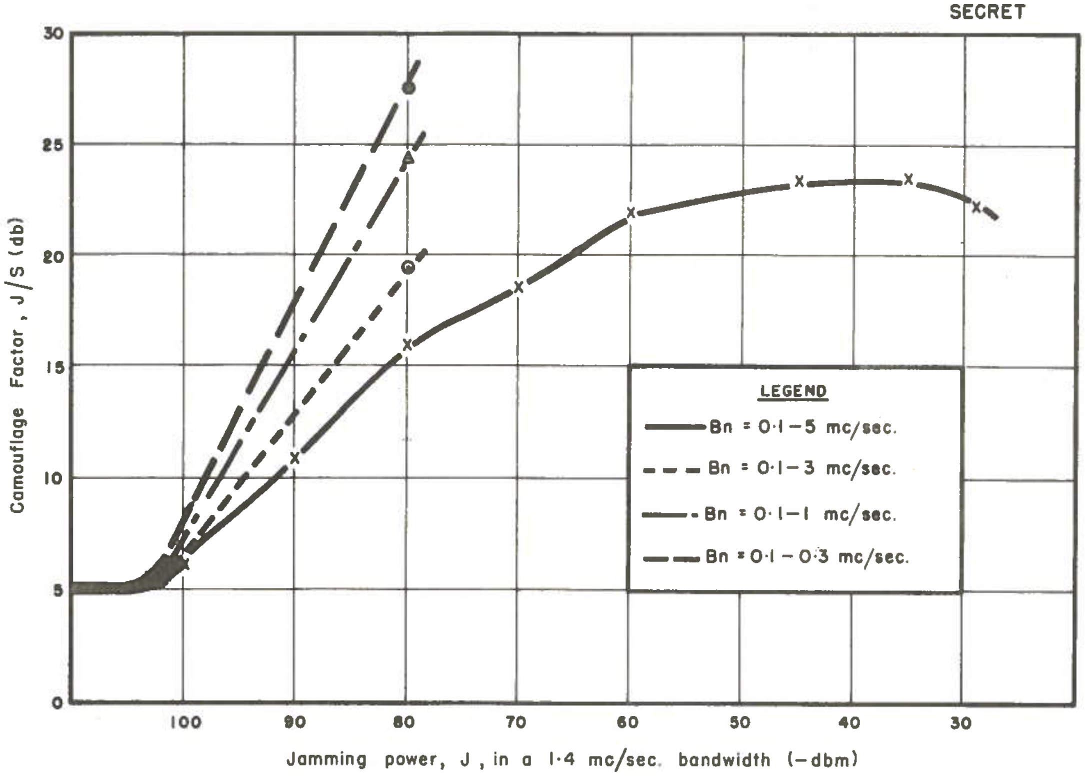


FIG. 2. EFFECT OF JAMMING LEVEL ON CAMOUFLAGE FACTOR FOR RECEIVER NO. 2 FOR VARIOUS VIDEO NOISE BANDWIDTHS

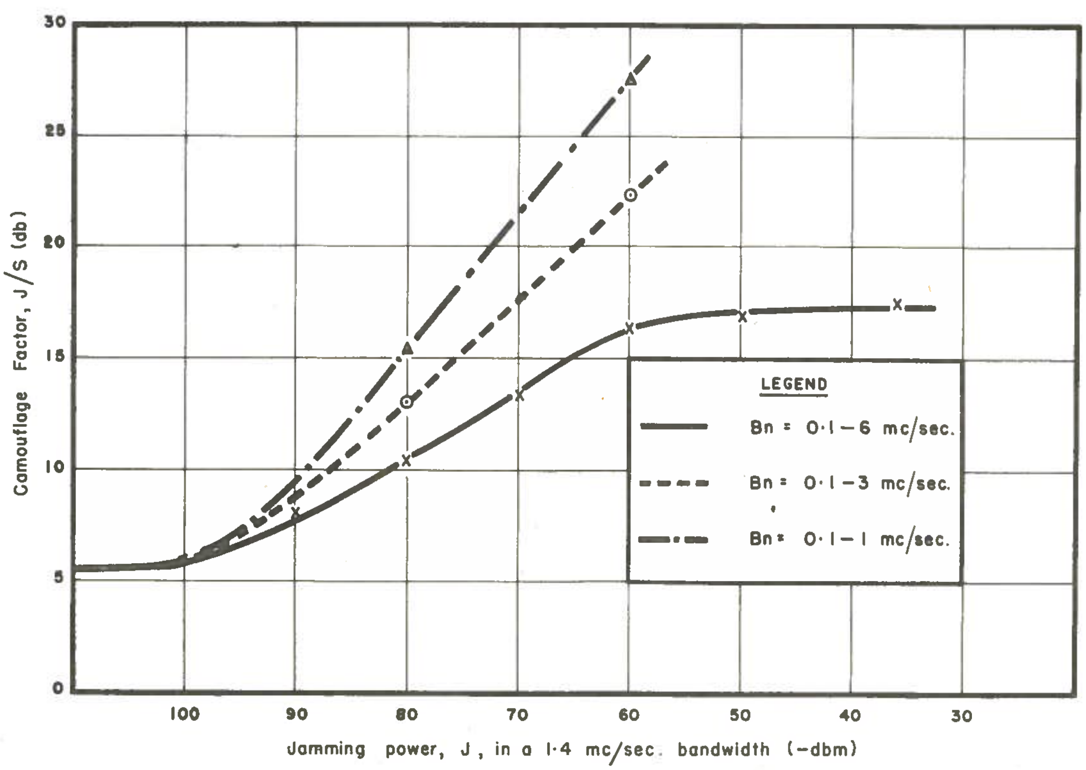


FIG. 3. EFFECT OF JAMMING LEVEL ON CAMOUFLAGE FACTOR FOR RECEIVER NO. 3 FOR VARIOUS VIDEO NOISE BANDWIDTHS

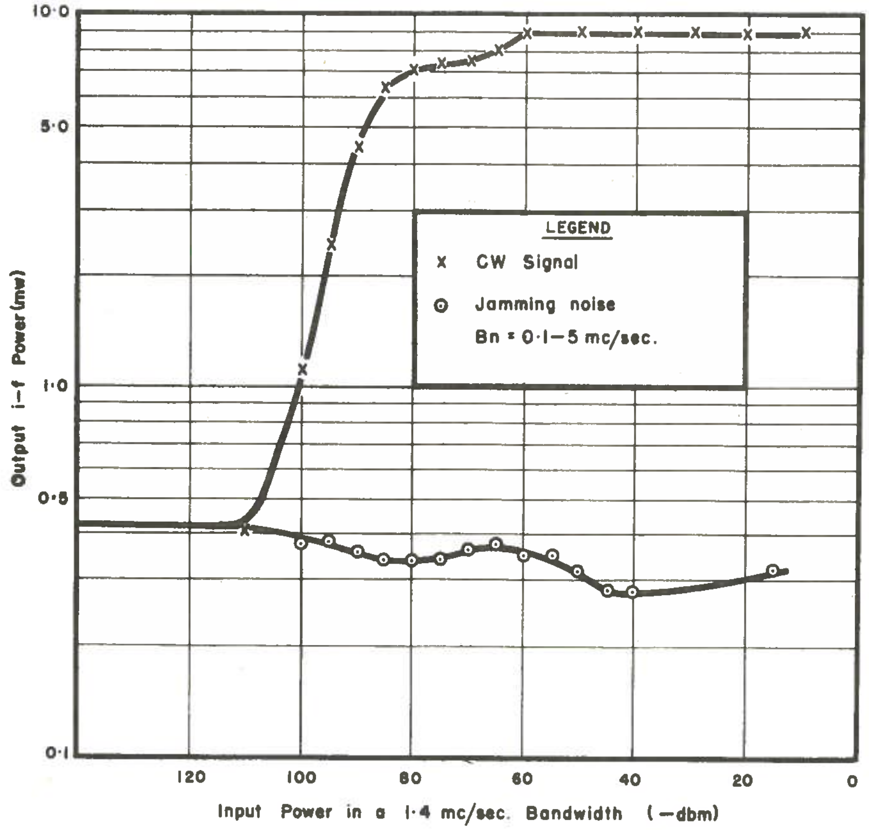


FIG. 4. INPUT–OUTPUT CHARACTERISTICS OF RECEIVER NO. 2 FOR C-W AND JAMMING SIGNALS

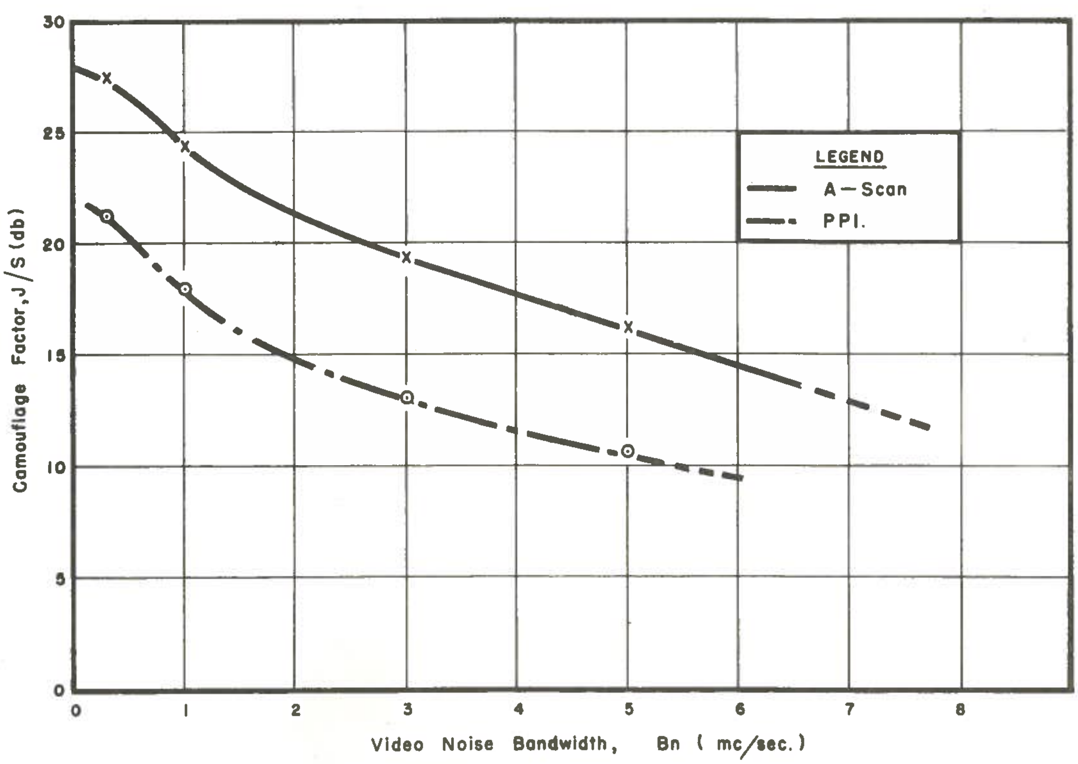


FIG. 5. EFFECT OF VIDEO NOISE BANDWIDTH ON CAMOUFLAGE FACTOR FOR RECEIVER NO. 2 FOR BOTH A-SCAN AND PPI JAMMING LEVEL = -80 dbm

lap; i.e., the jamming duty cycle is low and the probability of seeing a signal among these responses is high. As the video noise bandwidth is increased the average spacing between these responses decreases, making it more difficult to see the signal; i.e., increasing the video noise bandwidth results in decreasing J/S.

Since the phase and amplitude of one impulse response with respect to the one following or preceding is random, overlapping of impulse responses will result in either addition or subtraction, and thus put the receiver in a constant state of agitation. When this condition is reached, the jamming efficiency will become equal to that of thermal noise. Extrapolation of the A-scan curve in Fig. 5 indicates that this should occur at a video noise bandwidth of about 14 mc/s, which is the wide i-f bandwidth $B_1$ of the receiver.

Plate I shows photographs of the waveforms at the limiter input of a -60 dbm signal and impulse responses due to - 70 dbm barrage jamming of various video noise bandwidths which verify the preceding statements.

Plate I also shows photographs comparing receiver noise at the limiter input with the jamming noise due to three different video noise bandwidths; viz., 5 mc/s, 3 mc/s and 1 mc/s. As should be expected, the noise due to the 5 mc/s video noise bandwidth approximates receiver noise better than the other two video noise bandwidths. With video noise bandwidths larger than 14 mc/s, one should not be able to tell the difference between receiver noise and jamming noise.

## Limit Level of the Limiter

Variation of the limit level of the limiter, which is usually accomplished by varying the gain of the receiver prior to limiting, would be expected merely to shift the point on the input power scale at which changes in the mode of operation due to limiting occur. That this is so, is clearly shown in Fig. 6, which is a plot of (J/S) against J for Receiver No. 3 for the cases where the gain prior to the limiter was maximum and 10 db less than maximum. There appears to be little to recommend limiting more heavily than the rms level of the receiver noise, since it requires additional wide-band gain which is not easily obtained, and it degrades the unjammed sensitivity of the receiver slightly. However, if the limit level is set much above the rms level of receiver noise, the best performance at low jamming levels will not be achieved. Some special exceptions, such as combined c-w and FM-by-noise jammings, are encountered, but discussion of these will be reserved for a later section.

## Width of Jammer Output Spectrum

A receiver located in the center of a FM-by-noise barrage will experience only a decrease in the average rate at which the carrier sweeps across the pass-

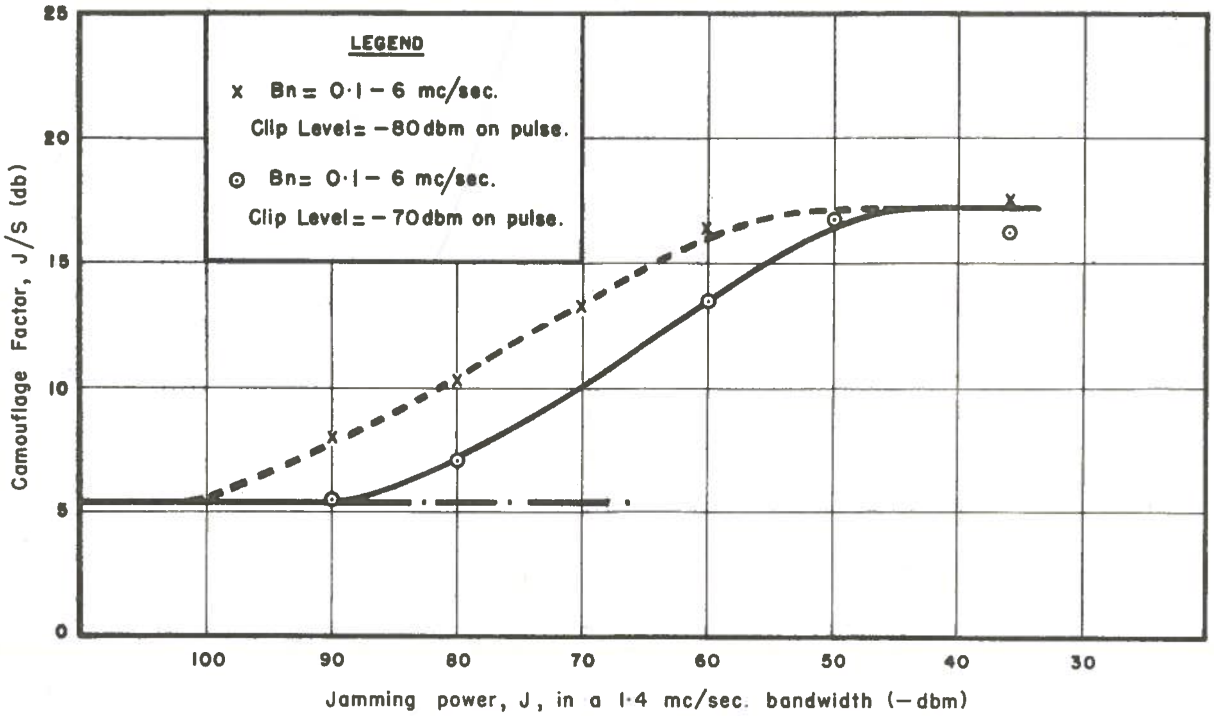


FIG. 6. EFFECT OF JAMMING LEVEL ON CAMOUFLAGE FACTOR FOR RECEIVER NO. 3, WITH TWO LIMIT LEVELS

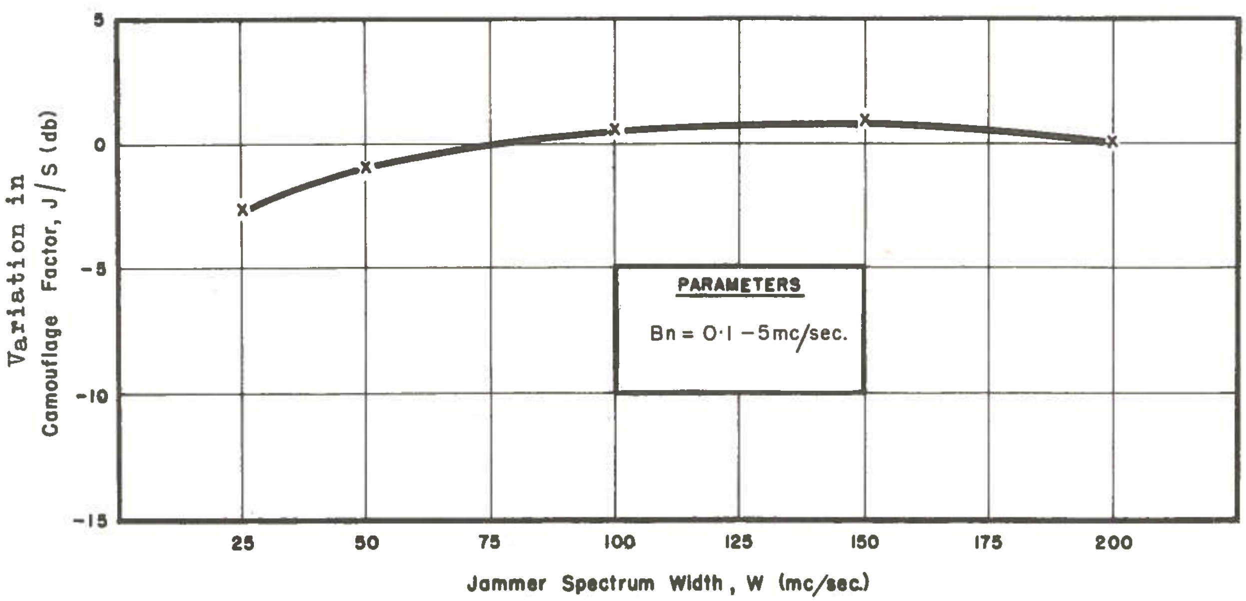


FIG. 7. EFFECT OF JAMMER SPECTRUM WIDTH ON CAMOUFLAGE FACTOR FOR RECEIVER NO. 2 (R-F PRESELECTION USED)

band as the width of the barrage is decreased. There will be no change in the average number of crossings per unit time. If, at the reduced sweep rate, the carrier is still swept across the bandpass sufficiently rapidly that it can be considered to be impulsive excitation, the only effect which would be expected is that associated with the increased power level received when the same total power is spread over a smaller frequency band. Therefore, if the total power is decreased in the same proportion as the decreased barrage width, no change in (J/S) should be observed. Fig. 7 shows that such is the case. The variations in the values of (J/S) are scarcely greater than the expected uncertainties in the measurements, except toward the very narrow barrage widths where the assumption of impulsive interference commences to be of doubtful validity.

If the receiver is not located at the center of the jamming spectrum, its position would approach closer to an edge of the barrage as the spectrum width is narrowed. In this case, therefore, we have a change in the position of the receiver relative to the barrage, which is dealt with in the following section. Suffice it to say here that, for a fixed jamming level, once the average sweep rate has exceeded the critical sweep rate of the receiver, it has no further effect on the effectiveness of the jamming provided, of course, that the number of passband crossings per unit time remains constant.

## Location of Receiver in Jammer Spectrum

In the sub-section on "Video Noise Bandwidth" the characteristics of the noise generator used to modulate the jammer frequency were outlined. It was stated there that the noise generator was adjusted for approximately uniform amplitude probability distribution so that the jammer power spectrum would also be uniform, and that the number of crossings of levels near the center of the distribution was greater than for levels toward the extremes. The only "noisy" waveforms having uniform amplitude distribution and constant number of crossings of all levels are triangular or sawtooth waves of random slope and constant amplitude. Since a reduced number of zero crossings is equivalent to decreased video noise bandwidth in the modulation, the curve of "(J/S) against location of receiver relative to jammer spectrum for constant jamming input" should be a minimum when the receiver is located at the center of the spectrum, and increase as the position moves toward either edge. That this is so is shown in Fig. 8(b). Fig. 8(a) illustrates an attempt to predict the shape of the curve of Fig. 8(b) from theory and a knowledge of the (J/S) against $B_n$ relationship.

It is assumed that by suitable amplitude compression and limiting, the Gaussian amplitude distribution from the noise source is converted to a uniform distribution. (The adjustment of the noise generator is made with this end in view, but is imperfectly achieved in practice.) This infers that

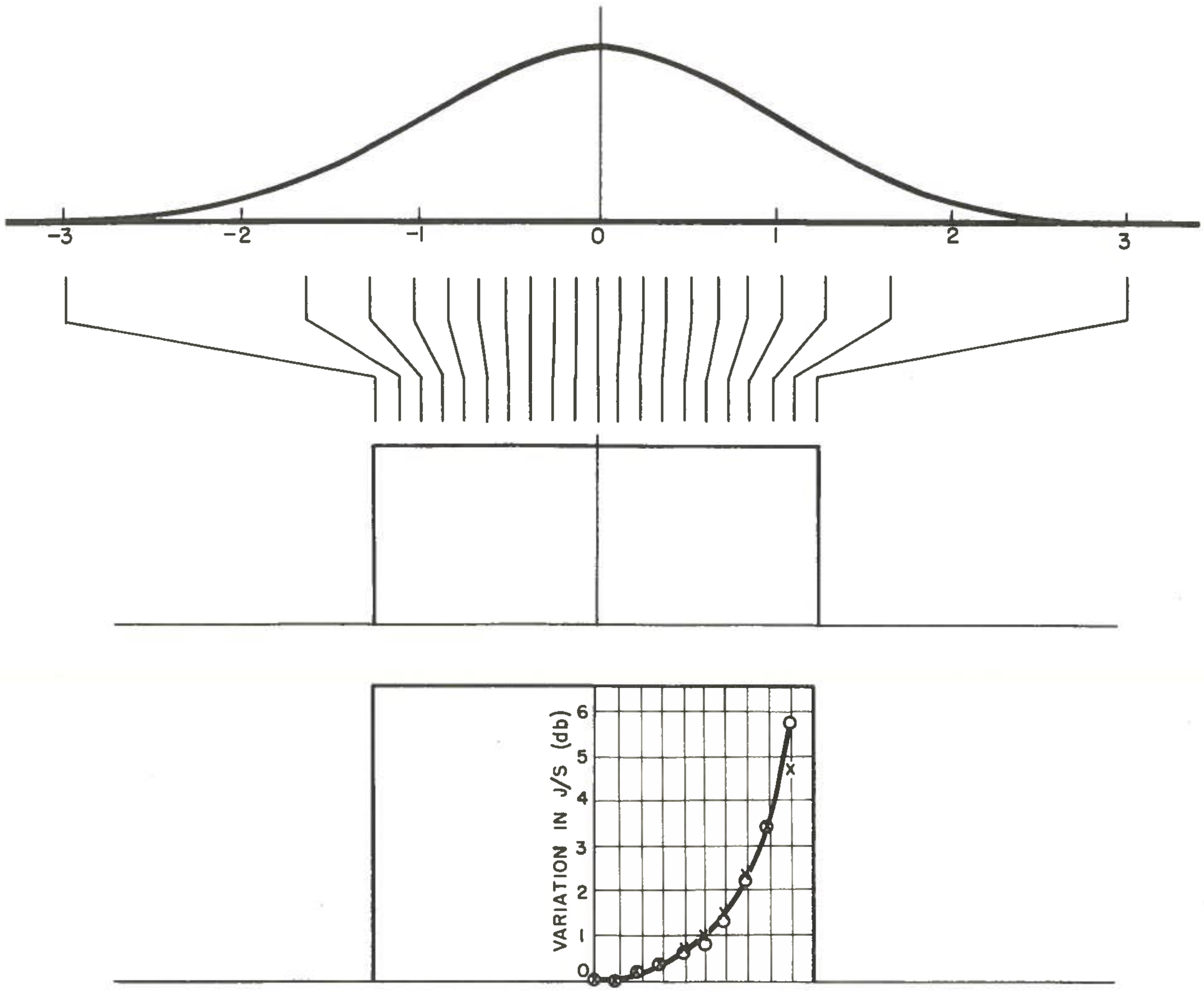


FIG. 8(a). COMPRESSION OF AMPLITUDE PROBABILITY DISTRIBUTION FROM GAUSSIAN TO UNIFORM AND RESULTING VARIATION IN CAMOUFLAGE FACTOR (o o o o calculated; ×××× measured)

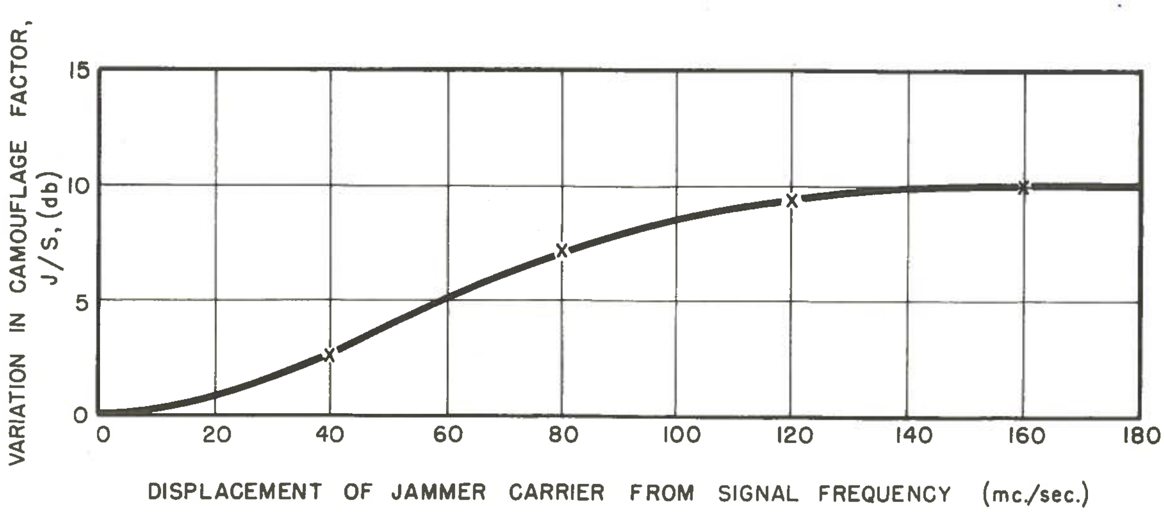


FIG. 8(b). EFFECT OF JAMMER CARRIER DISPLACEMENT FROM SIGNAL FREQUENCY ON CAMOUFLAGE FACTOR FOR RECEIVER NO. 2 (R-F PRESELECTION USED)

$$\int_0^{x_1} \epsilon^{-x^2}\,dx = \int_{x_1}^{x_2} \epsilon^{-x^2}\,dx = \text{---------} = \int_{x_9}^{\infty} \epsilon^{-x^2}\,dx = \frac{1}{10}\int_0^{\infty} \epsilon^{-x^2}\,dx.$$

That is, the range $o < x < \infty$ was divided into 10 sectors in accordance with the above relationship. Rice [8] indicates that the distribution of level crossings is also Gaussian. The relative average number of crossings is then calculated for each sector, and an equivalent modulation bandwidth established for each sector. From the measured variation of (J/S) with modulation bandwidth, relative variation of (J/S) with the location of the receiver in the jamming spectrum can be calculated. There is good agreement between the calculated and measured values except at the spectrum edge (sectors 9 and 10) where the assumption of a uniform spectrum differs most from what was actually used.

Plate II shows waveforms at the input to the limiter for various locations of the receiver with respect to the jamming spectrum. It is easily seen that the number of impulses per unit time decreases as the location of the receiver frequency is displaced from the center toward the edge of the jamming spectrum.

## Effect of r-f Preselection

Without r-f preselection, a superheterodyne receiver is sensitive to a pair of frequency bands each equal in width to the receiver bandwidth and separated by twice the intermediate frequency. Since the signal spectrum is located in only one of these bands, the other is not only unnecessary but a definite liability when operating in the presence of wide-band jamming. A bandpass filter centered on the signal frequency will eliminate the response of the receiver at the undersirable frequencies.

In the case of the wide-band FM-by-noise barrage jamming considered in this report, the receiver will be excited by an average of twice as many jamming impulses if r-f preselection is not used. Thus, the use of r-f preselection not only reduces the received jamming power by 3 db, but also reduces the equivalent bandwidth of jammer modulation by one-half, since only half the number of jamming impulses are received. Plate III shows the number of jamming impulses at the input to the limiter: (a), (b) without r-f preselection, (c), (d) with r-f preselection. Sweep lengths are 30 $\mu$sec for (a), (c) and 6 $\mu$sec for (b), (d). The overall improvement in performance can be considerably greater than 3 db. With the cooperation of the authors, the effects of r-f preselection ahead of Receiver No. 2 were investigated and reported [13] by Westby, who indicates that improvements in performance as great as 9 db at high jamming levels were obtained.

## EFFECT OF MULTIPLE JAMMERS

In order to determine the effect of multiple jammers on the same azimuth, (J/S) measurements were made for the simultaneous application of two and three jammers to a Dicke Fix receiver. The jammers are swept randomly over the same frequency band and their outputs are uncorrelated. This was accomplished by simultaneous use of up to three low-power backward-wave oscillators, each having a separate modulator and noise generator. The bandwidth of noise applied to each modulator could be varied in discrete steps by the use of low- and high-pass filters. With this arrangement, various combinations of video noise bandwidths could be used to determine the cumulative effect on a Dicke Fix receiver.

## Measurement Technique

A simplified diagram of the multiple-jammer setup is shown in Fig. 9. The jammer powers were adjusted so that each jammer delivered one-third of the total jamming power to the receiver. It should be noted that the measurements referred to in this section were taken on Receiver No. 1 which had a poor limiter, but this does not affect the validity of the results.

By the measurement technique already described, (J/S) values were obtained as a function of:

a) jamming level, J, for a single jammer with $B_n = 0.1\text{-}6$ mc/s,

b) jamming level, J, for two jammers with $B_{n1} = B_{n2} = 0.1\text{-}6$ mc/s,

c) jamming level, J, for three jammers with $B_{n1} = B_{n2} = B_{n3} = 0.1\text{-}6$ mc/s,

d) video noise bandwidth, $B_n$, for a single jammer and for multiple jammers operating with various combinations of video noise bandwidths.

The results have been plotted in Figs. 10 and 11.

## Experimental Results

It has already been shown that, for video noise bandwidths smaller than the wide bandwidth of the receiver, the jamming effectiveness increases with an increase in the average number of receiver bandpass crossings per second. When two jammers, with equal video noise bandwidths, $B_{n1}$ and $B_{n2}$, whose outputs are uncorrelated, are simultaneously applied to a Dicke Fix receiver at a jamming level, J, the jamming noise in the wide bandwidth consists of impulsive responses which, on the average, are separated by one-half the interval that would exist if only one jammer with a video noise bandwidth, $B_{n1}$, and a jamming level, J, were used; i.e., two jammers with video noise bandwidths of $B_{n1}$ and $B_{n2}$ are equivalent to one jammer with a video noise bandwidth of $B_{n1} + B_{n2}$. Photographs (a) to (d) of Plate V illustrate the increased number of impulsive responses per second due to two jammers of combined jamming level, J, over one jammer of jamming level, J. In the photograph (a) and (b) show the waveforms at the limiter input when a single jammer with $B_n = 3$ mc/s is used. The sweep lengths are 25 and 5 microseconds, respectively. (c) and (d) show corresponding waveforms when two such jammers are used.

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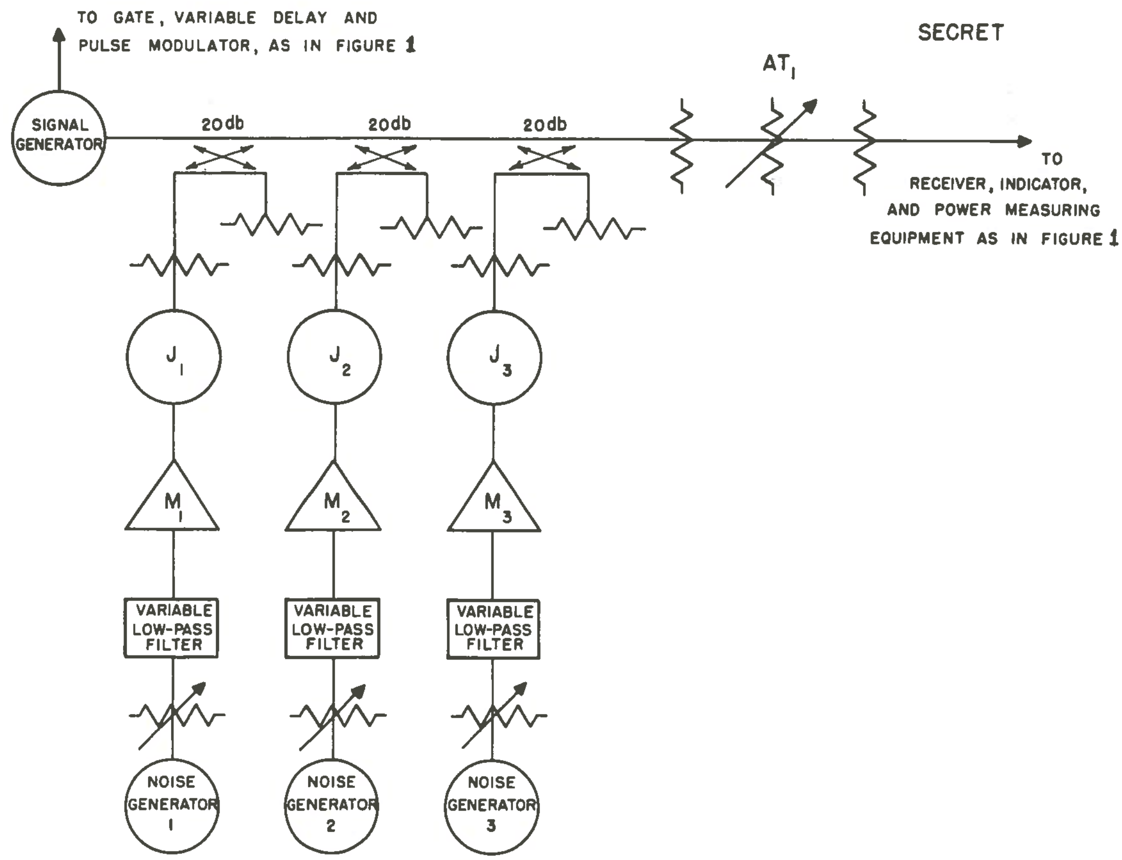


FIG. 9. SIMPLIFIED BLOCK DIAGRAM OF MULTIPLE JAMMER TEST BENCH

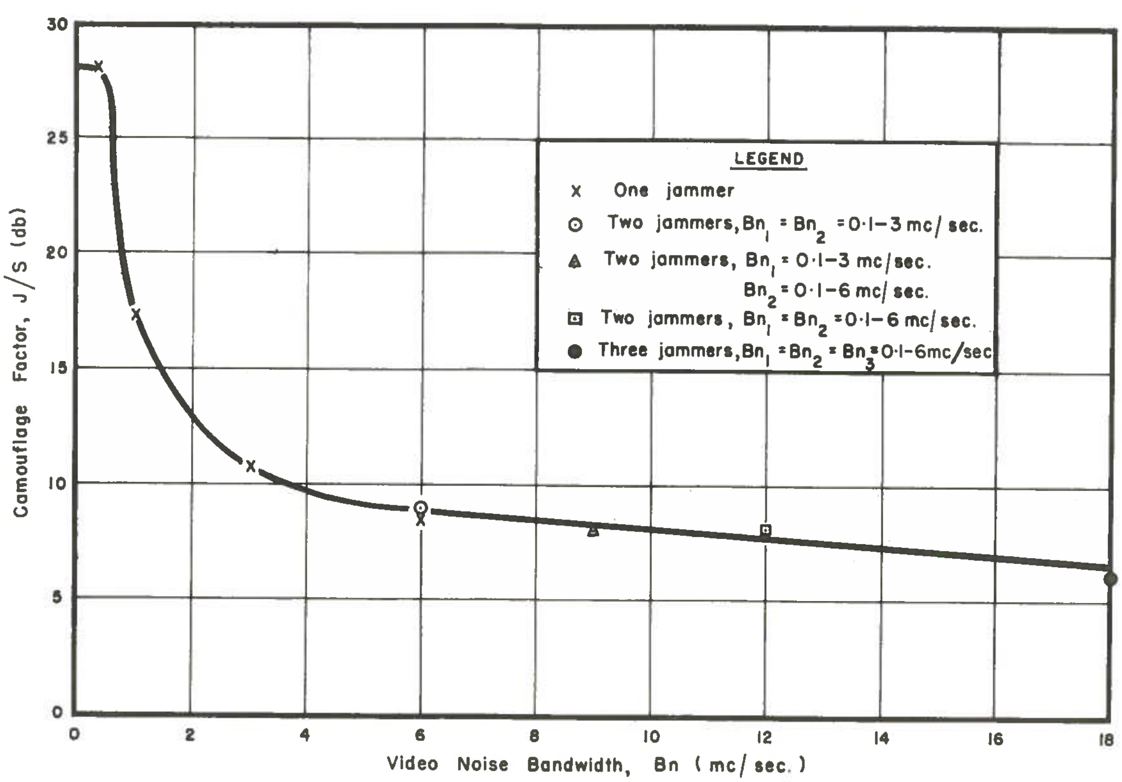


FIG. 10. EFFECT OF MULTIPLE JAMMERS ON CAMOUFLAGE FACTOR FOR RECEIVER NO. 1.
JAMMING LEVEL = -80 dbm

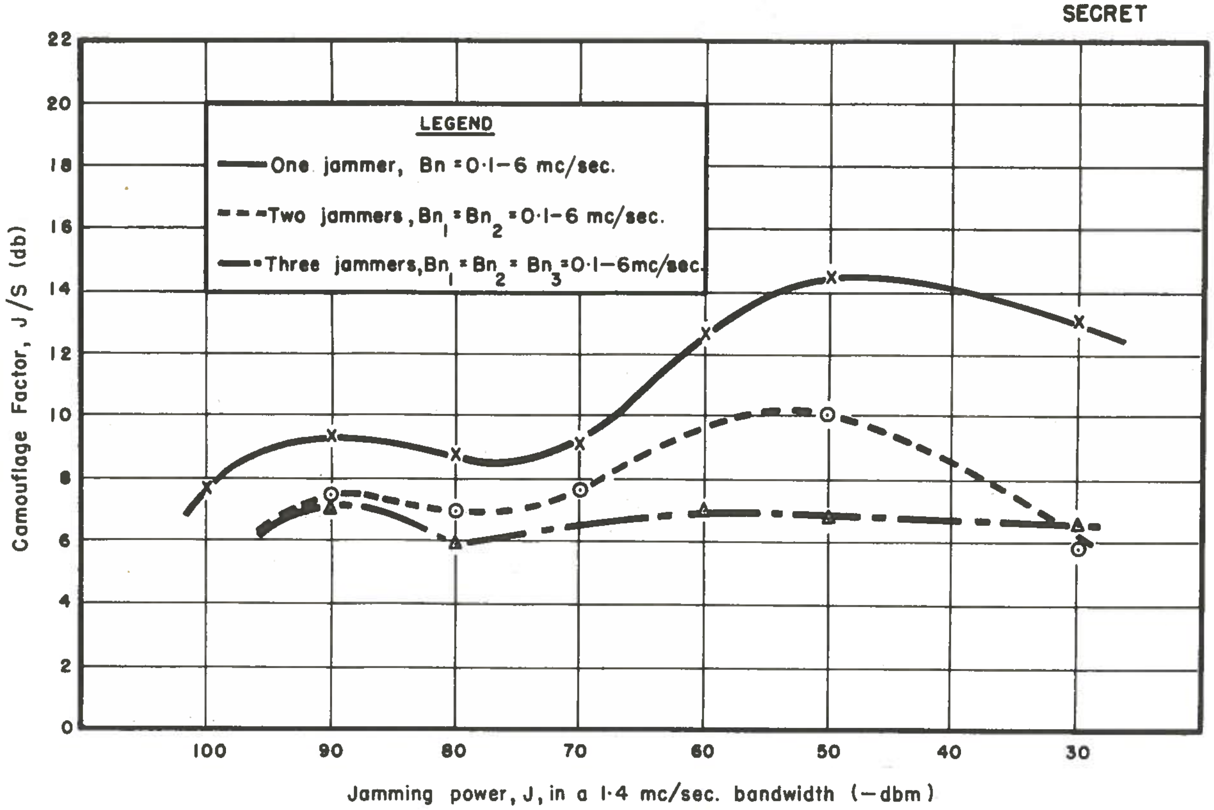


FIG. 11. EFFECT OF JAMMING LEVEL OF MULTIPLE JAMMERS ON CAMOUFLAGE FACTOR FOR RECEIVER NO. 1

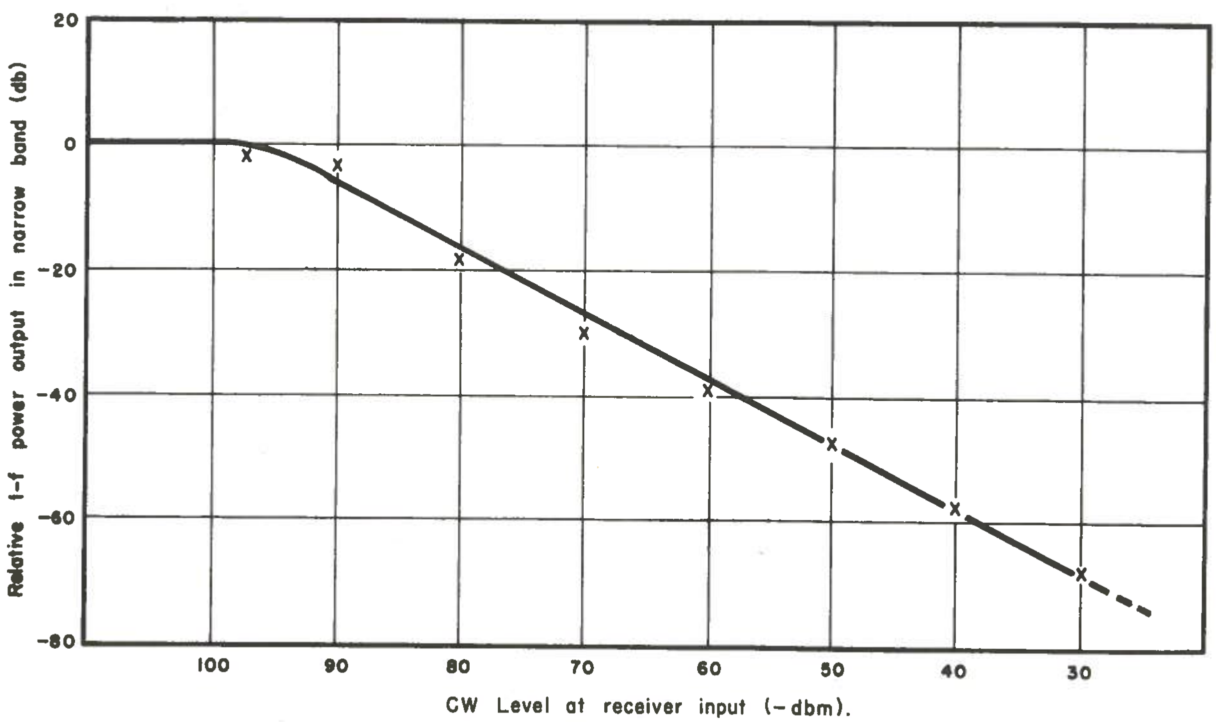


FIG. 12. SUPPRESSION OF NARROW-BAND OUTPUT DUE TO C-W CARRIER IN WIDE-BAND PORTION OF RECEIVER NO. 2

Fig. 10 shows a plot of (J/S) against $B_{n1} + B_{n2} + B_{n3}$ resulting in a fairly smooth curve. In particular, at 6 mc/s the superposition of points obtained in different ways should be noted.

Fig. 11 gives curves showing how (J/S) varies with J for

a) a single jammer with $B_{n1}$ = 0.1-6 mc/s,

b) two jammers with $B_{n1} = B_{n2}$ = 0.1-6 mc/s, and

c) three jammers with $B_{n1} = B_{n2} = B_{n3}$ = 0.1-6 mc/s.

The curve for three jammers shows a "(J/S) vs. J" curve which is essentially flat; i.e., $\frac{d(J/S)}{dJ} = 0$, which is a result similar to that obtained for receiver thermal noise. It must be concluded that the Dicke Fix technique is susceptible to multiple jammers located in the same spatial element.

## CW JAMMING

It can be shown that when two or more signals are present in the wide bandwidth of a Dicke Fix receiver and their combined amplitude is such that the limit level is exceeded, then the strongest signal present in the wide bandwidth will suppress the weaker ones in the output from the limiter. An example of this phenomena occurs when a c-w signal is allowed to fall into the wide bandwidth of the receiver, but outside the narrow bandwidth. When the c-w signal falls in the narrow bandwidth, conditions are similar to those in a narrow-band receiver which is overloaded by c-w jamming [14]. When the c-w voltage exceeds the receiver thermal noise voltage at the limiter input, the receiver noise will begin to be suppressed in the narrow bandwidth, provided the limit level is exceeded. The rms c-w voltage is equal to the thermal rms noise voltage at the limiter input when the c-w power at the receiver terminals is about -97 dbm. We should therefore expect suppression to begin at about this c-w power level. The curve in Fig. 12 begins to slope downward at a c-w power level of about -99 to -97 dbm. Further increase in the c-w signal results in a further decrease in the output i-f power in the narrow band. This relationship, as shown in Fig. 12, is linear with about unity slope; i.e., the i-f narrow band power is reduced one db for every increase of one db in c-w power. Fortunately, however, the c-w jamming signal suppresses both receiver noise and the desired signal by about the same amount and the minimum detectable signal of the receiver is maintained at its pre-jamming value, provided that enough post-limiter gain is available to compensate for the loss in gain due to suppression. This type of jamming is disastrous to a receiver which is not equipped with a post-limiter gain control of sufficient range. Any form of modulation on the c-w signal would require that the narrow-band gain be varied in synchronism if performance is to remain unimpaired. With sufficient complexity the receiver could be made to cope with c-w jamming. However, a normal radar receiver would do so more easily, and should be used in the event of c-w jamming alone.

The suppression phenomena is illustrated photographically in Plate IV. An r-f carrier, frequency-modulated by a 60-cps waveform, is allowed to sweep across the wide bandwidth of the Dicke Fix receiver. The photographs of the narrow-band detected output show suppression of the receiver noise when the level of the sweeping carrier reaching the limiter through the wideband section exceeds the limit level. A peak in the output, having the shape of the narrow passband, occurs as the carrier sweeps through frequencies to which the narrow-band receiver is sensitive. A set of these photographs was taken for various c-w levels. The additional peaks present at the higher input carrier levels; i.e., in (d), (e) and (f), occur when the difference between the signal and local oscillator frequencies is a subharmonic of the i-f frequency. These appear to be the result of beats between corresponding harmonics of the signal and local oscillator frequencies. From these photographs, a plot of suppressed bandwidth against c-w level was made, which shows the shape of the passband of the wideband section of the receiver. It appears in Fig. 13. The asymmetry in this curve is due to second and third harmonic mixing becoming important at the stronger jamming levels.

## COMBINED NOISE AND CW JAMMING

Tests were conducted to determine the effects of simultaneous application of FM-by-noise barrage jamming and a c-w carrier lying within the wideband section but not within the narrow passband to a Dicke Fix receiver. (It was assumed that it would be difficult for a jammer to maintain a carrier within the narrow passband, but that it would be practical to keep it within the wide passband.) These tests were conducted at a jamming level of -60 dbm for two different video noise bandwidths; viz., 0.1-1 mc/s and 0.1-5 mc/s. With this level of barrage jamming, (J/S) values were obtained for various levels of c-w added to the barrage jamming. In this instance, J is the jamming level due to the barrage jamming only. In the previous section it was shown that with receiver noise or r-f thermal noise jamming (as obtained from an S-band source), (J/S) is constant and independent of the level of c-w signal introduced into the receiver. With FM-by-noise barrage jamming, however, the introduction of a c-w signal reduces (J/S) in the manner shown in Fig. 14. For both 1-mc/s jamming and 5-mc/s jamming (J/S) falls to 3 or 4 db by addition of -40 to -50 dbm of c-w signal. The curve for the video noise bandwidth of 5 mc/s experiences a 2.5 db rise in (J/S) when the c-w level is increased from -50 to -40 dbm. This is due to a change in the structure of the noise as presented on the type-A display. With a c-w signal level of -40 dbm the structure of the noise is such that the signal is discernible in it as a break in the base line of the type-A display. It probably would not be detected on the PPI. Because of the higher peak-to-rms voltage ratio of the jamming at the limiter input when $B_n = 1$ mc/s relative to $B_n = 5$ mc/s, a higher c-w

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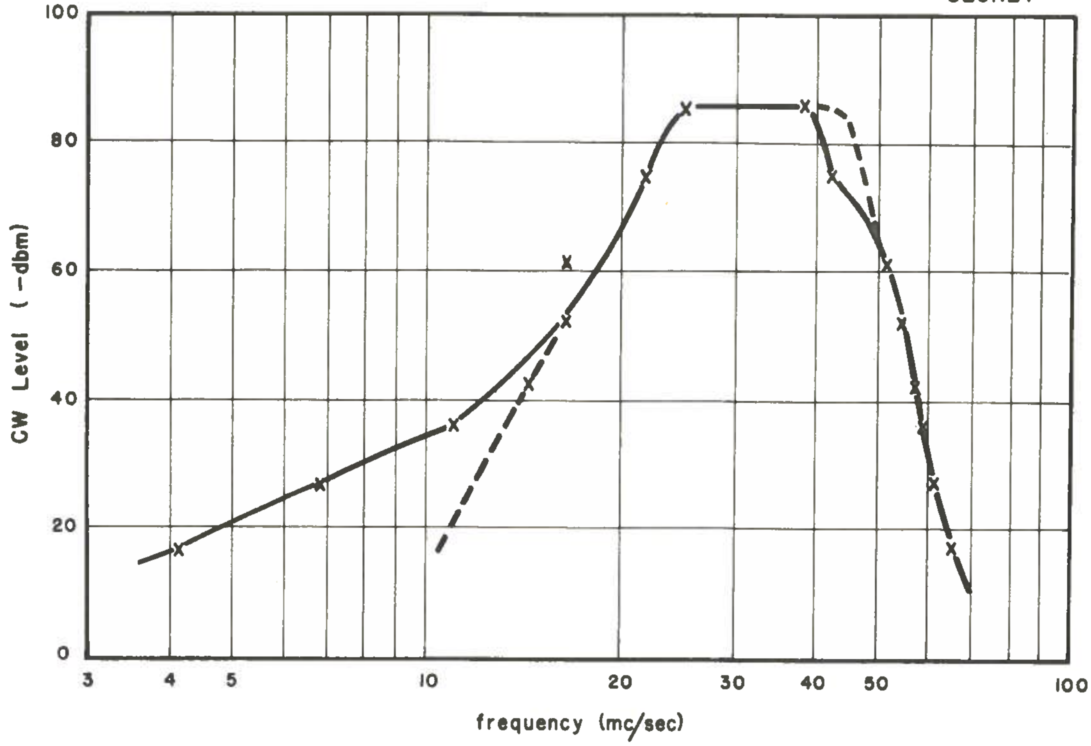


FIG. 13. SUPPRESSED BANDWIDTH OF RECEIVER NO. 2 DUE TO SLOWLY SWEEPING C-W SIGNAL

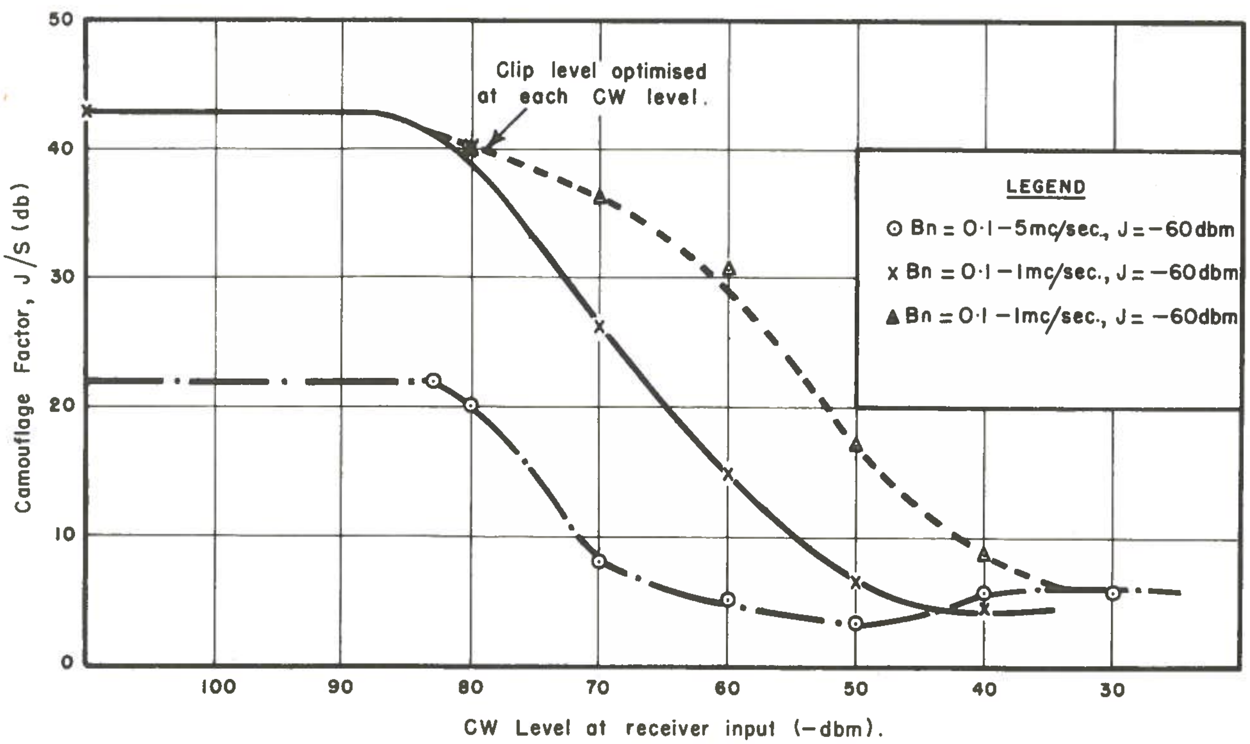


FIG. 14. EFFECT OF COMBINED C-W AND FM-BY-NOISE BARRAGE JAMMING ON CAMOUFLAGE FACTOR FOR RECEIVER NO. 2 WITH LIMITER LEVEL VARIED

signal level is required to reduce the (J/S) to the value for the thermal noise (5 db) in the case of the 1 mc/s jamming.

A limited degree of improvement can be obtained in the face of this combined jamming if the limit level is adjusted (i.e., if the proportion of overall gain provided by wide-band and narrow-band sections is adjusted) to be optimum at the c-w signal level prevailing. A curve illustrating this in the case of 1 mc/s-noise jamming is also included in Fig. 14. It will be noted that increases in (J/S) of as much as 15 db are obtained at some c-w signal levels, but if sufficient c-w power is used the receiver performance is no better than that of a normal narrow-band receiver. Photographs (e) and (f) of Plate V show the effect on the type-A display of optimizing the limit level for a particular set of jamming conditions.

The presence of a modest amount of c-w energy at points separated by 40 or 50 mc/s across the FM-by-noise barrage can wipe out any improvement in resistance to jamming which the Dicke Fix technique can provide. Such a combined jamming signal would be difficult to counter, especially if the carriers were made to wander about randomly in frequency.

## CONCLUSIONS — ESTIMATE OF USEFULNESS AND LIMITATIONS

### Expected Performance of Dicke Fix Receivers in AN/CPS-6B Radar

To obtain a quantitative estimate of the value of the Dicke Fix technique as an anti-jamming measure, and hence the extent to which it may cause increased power output or complexity to be required in jammers, the effect of its use in an AN/CPS-6B radar against wide-band FM-by-noise barrage jamming was examined.

The jamming equation [15] can be written

$$P_j G_j = \left(\frac{J}{S}\right) \cdot \frac{1}{Br} \cdot \left(\frac{P_r G_r \sigma}{4 \pi R^2}\right),$$

where $P_j$ = power per unit bandwidth of the jammer transmitter,

$G_j$ = jammer antenna gain,

(J/S) = camouflage factor, defined previously,

Br = radar receiver bandwidth for jamming signals,

Pr = radar transmitter peak power,

Gr = radar antenna gain,

$\sigma$ = radar cross section of the target,

R = distance to the target (range).

Since the camouflage factor in the Dicke Fix receiver is dependent on the jamming power at the receiver input, it is most convenient to assume values for

$P_j$ and $G_j$ as well as for the radar parameters, and calculate $\sigma_{max}$, the maximum radar target cross section which can be self-screened under the assumed jamming conditions, as a function of the range of the target at constant altitudes. Values for $\frac{Gr}{R^2}$ for the AN/CPS-6B radar for target altitudes of 10,000 feet and 40,000 feet were published [15] previously. The jamming power at the receiver input, which is required before a value can be given to the camouflage factor, (J/S), can be calculated using the formula:

$$J = P_j Br \left( \frac{G_j Gr \lambda^2}{(4\pi)^2 R^2} \right),$$

where J = jammer signal power received by the radar receiver,
λ = wavelength of the radar signal.
All other factors are as defined above.

The following values, which are thought to represent what is likely to be found in practice, were assumed for the jammer and radar parameters:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $P_j G_j$ | = | 4 watts/mc/s (over about a 250-mc/s band) | | | | | |
| Br | = | 1.3 mc/s | | | | | |
| λ | = | 10 cm | | | | | |
| Pr | = | 0.7 megawatts | | | | | |
| Gr | = | 10,000 at peak of lower beam | (elevation | 1.25 | degrees) | | |
| | | 4,800 " " " center " | ( " | 3.4 | " ) | | |
| | | 2,200 " " " upper " | ( " | 8.5 | " ) | | |

Curves of maximum radar cross section for self-screening ($\sigma_{max}$) as a function of the range of an aircraft at constant altitudes of 10,000 feet and 40,000 feet are shown in Fig. 15. For comparison, similar curves for $\sigma_{max}$ were computed for a linear radar receiver of 1.3 mc/s bandwidth, using a value of camouflage factor (J/S) = 0 db. (Experimental evidence [5] indicates this to be a good conservative value for this parameter when a PPI display is used.)

It is emphasized that the value of $\sigma_{max}$ which has been plotted is that obtained when nominal values of parameters as listed above are inserted in the given equations. This should be taken into account when the radar cross sections of particular aircraft are compared with the values on the graphs. Radar cross sections for various aircraft are often obtained by inserting nominal values of radar parameters and maximum range from operational data into the radar equation by the users of radars. Such a value would probably be most suitable for comparison purposes here. However, the primary object in presenting the curves is to show to what extent the use of the Dicke Fix technique increases the ability of the radar to resist jamming, and while high accuracy cannot be claimed for the

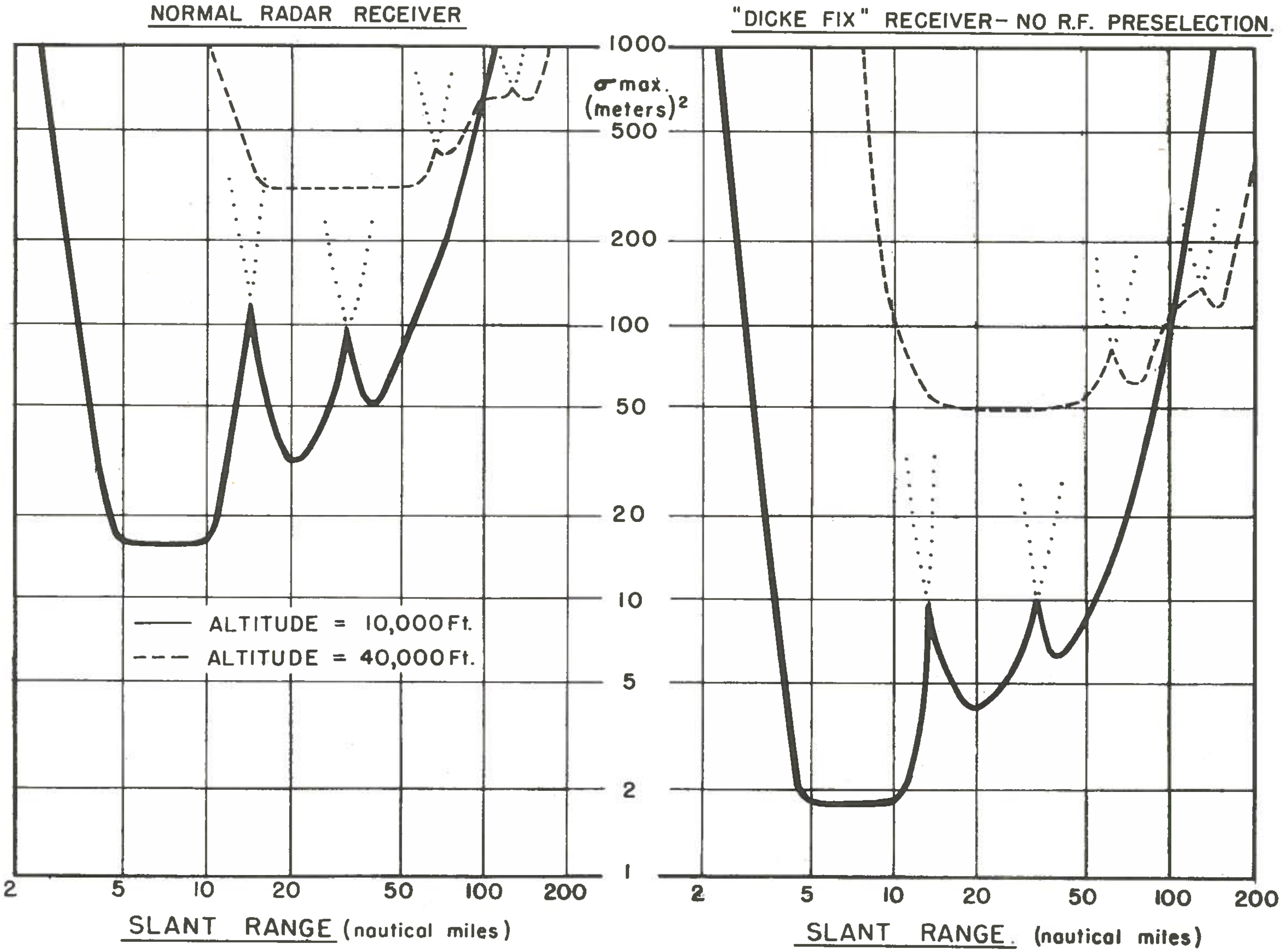


FIG. 15. MAXIMUM RADAR CROSS SECTION WHICH CAN BE SELF-SCREENED FROM AN/CPS-6B RADAR AS A FUNCTION OF SLANT RANGE (Jamming Beam Power = 4 watts/mc/s)

absolute values of $\sigma_{max}$ shown, the relative values should be reliable and provide useful comparisons.

Several important observations can be made on the basis of these curves. Except in the broadside aspect, any modern bomber carrying a single carcinotron jammer could probably self-screen itself from the AN/CPS-6B radar at all ranges when flying at 10,000 feet. At 40,000 feet about one-tenth of the assumed 4 watts/mc/s would be sufficient. The overall antenna pattern formed by the three vertical beams is an approximation to a cosecant-squared pattern. Because of this, the radar does not have a self-screening range in the usual sense, since the power required to jam the radar varies but little with the range. The curves of Fig. 15 show that it might be said to have a self-screening altitude rather than a self-screening range. While this type of antenna pattern makes efficient use of transmitted power under normal operating conditions, its use in an ECM environment cannot be justified.

If Dicke Fix receivers similar to those described in this report are used on all vertical beams of the AN/CPS-6B radar, a modern bomber carrying a single carcinotron jammer might be detected on aspects other than broadside at ranges less than 50 miles when flying at 10,000 feet altitude, but would probably escape detection completely if flying at 40,000 feet altitude. Even so, the power required to jam is six to ten times as great as would be required if the normal receivers were used. If higher antenna gain could be brought to bear at shorter ranges, (higher elevation angles) use of the Dicke Fix could force the jammer to use many times the power which would be required if normal receivers are used. Because of the nature of its antenna pattern the AN/CPS-6B is unable to take full advantage of the improvement possible with the use of the Dicke Fix technique.

It is important to realize the implications of the above. To date, all carcinotron jamming trials in Canada have been conducted at altitudes below 10,000 feet. Increasing the jammer altitude to 40,000 feet causes the jammer to be an order of magnitude relatively more effective against radars having a cosecant-squared type of antenna pattern. Counter-countermeasures which provide useful improvements against jammers flying at the lower altitude may prove to be inadequate when the jammer is operated at the higher altitude.

It is difficult to see how the use of Dicke Fix type receivers can restore usable performance to the AN/CPS-6B radar in the presence of even moderate amounts of FM-by-noise barrage jamming. This statement applies also to other radars having similar power output, antenna patterns, and gain. The chief exception to this would be if the jammer were using narrow-band noise modulation which has been shown to be very effective against PPI-equipped radars with the normal narrow-band type of radar receivers [5, 16]. In this case, the improvement due to the Dicke Fix would be much greater, and might be sufficient to warrant being included in the anti-jamming measures applied to the radar.

In the case of radars which are able to bring large antenna gains to bear on targets at short ranges (e.g., the AN/FPS-6 height finder, stacked-beam radars, etc.) the Dicke Fix should certainly find a useful place among the arsenal of anti-jamming devices with which the radars are equipped.

The effect of all this on the jammer is to force the use of higher power density and/or wider video noise modulation bandwidths. Both of these requirements lead to additional weight, volume, and primary power consumption. They may perhaps most easily be accomplished by using more jammers to cover a given frequency band. It is thought that combined noise and c-w jamming as described would keep the additional requirements to a minimum, though care must be taken to ensure that it is done correctly, and that it does not facilitate passive tracking and homing schemes which might be employed against the jamming aircraft.

## Some Limitations of the Dicke Fix Technique

For optimum performance, certain parameters, such as input bandwidth, must be adjusted in accordance with the characteristics of the jamming. The large gain and wide bandwidths required are not easily obtained, and auxiliary equipment is required if optimum performance is to be obtained under operational conditions.

Maximum discrimination against jamming is not achieved until the jamming level is considerably in excess of thermal noise level. Therefore, maximum detection range in the presence of jamming will be only a fraction of that of the unjammed radar, except when the unjammed range is horizon-limited.

If the bandwidth of the modulating video noise in the jammer is larger than the receiver input bandwidth the improvement obtained is negligible. The presence of N jammers, which cover the radar frequency, in the same azimuth-elevation solid angle sector can reduce the improvement obtained to a negligible amount if the sum of the bandwidths of the modulating video noise employed by the N jammers exceeds the receiver input bandwidth.

The presence of a carrier which is large compared with the noise level continually within the wide bandwidth of the receiver can destroy the improvement achieved against FM-by-noise barrage jamming. With sufficient flexibility in the receiver, performance can be partially restored if the added carrier is not too strong.

## Advantanges of the Dicke Fix Technique

Substantial improvement in performance over that obtained with normal receivers can be obtained in the presence of FM-by-noise barrage jamming by a single jammer per radar azimuth-elevation solid angle sector if the jammer characteristics are within the capabilities of the receiver. If the jammers are crude devices, perhaps several can be accommodated successfully.

The performance in the absence of jamming is not significantly different to that of the normal receiver. However, it is necessary also to employ a normal type of receiver since with certain types of jamming signals, it is difficult to tell from the appearance of the displays that the radar is being jammed. The desired information just fails to paint. This feature may be desirable when used with automatic data processing systems.

Even if the receiver cannot give useful performance in the presence of multiple or sophisticated jammers, its use, as is the case with many devices and techniques which provide some anti-jam capability under a limited range of conditions, helps to make certain that the enemy pays the full price for the privilege of denying detailed information concerning his position to the radar defences. It is probable that it is impossible to prevent a given radar from being jammed by a persistent intruder, but with proper planning it may be possible to cause the price in weight, size, and complexity of jammers required to meet all eventualities to be too high.

## Present and Future Designs

The receivers used in the tests reported here were not of optimum design, particularly in the width of the bandpass of the input section. This probably should have been about three times as wide for optimum performance against the jamming produced with the largest video noise bandwidths (6mc/s) employed in the tests. There is room for improvement over the results disclosed herein. The specification for an improved receiver might include:

1) R-F Preselection

The passband should be as wide as, or wider than the input i-f bandwidth. All that is required is that the undesired image be attenuated some 20 db.

2) Wide-band Input Section

a) Overall Gain: about 100 db — sufficient to cause receiver noise to be limited to below its rms voltage level by the limiter.

b) Bandwidth: about 50 mc/s, designed for minimum impulse response time, together with a bandwidth-narrowing section for use as jamming conditions warrant.

c) Gain Control: (or variable attenuator) to enable the effective limit level to be controlled.

Note: All the gain does not have to be in the i-f section. Some could be obtained with low-noise travelling-wave tube amplifiers at radio frequencies.

3) Narrow-band Post-limiter Section

a) Overall Gain: large — say 80 db, with input attenuator to reduce gain to a small value when required.

b) Bandwidth: to match radar pulse width,

$$\text{i.e.,} \quad \frac{1.2}{t} \text{ to } \frac{2}{t} \; .$$

4) Limiter— good, clean, limiting over band of frequencies passed by input stage.

5) Auxiliary Apparatus : to enable the adjustment of receiver parameters to optimum under jamming conditions encountered. This might take the form of a pulsed signal generator coupled to the receiver input which could put a pulse of controlled amplitude on a type-A display at the end of the scan. Controls would be adjusted so that the smallest possible pulse amplitude could be seen.

## ACKNOWLEDGMENT

The authors are indebted to Mr. W.L. Haney and Mr. R.S. Richards for helpful advice and discussion, and to Mr. D.T. Bradley and Mr. R.S. McClean who constructed the apparatus and assisted in the measurements.

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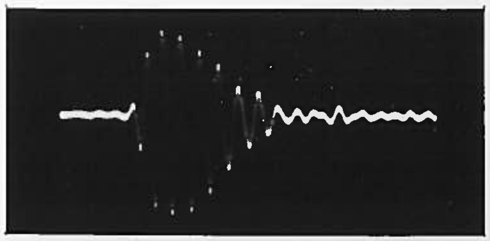
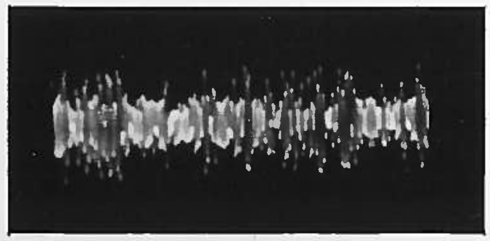
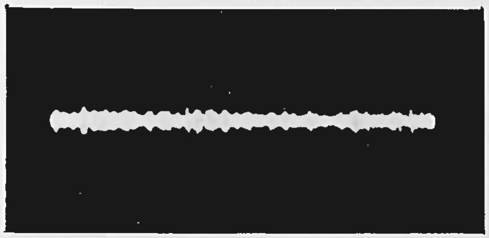


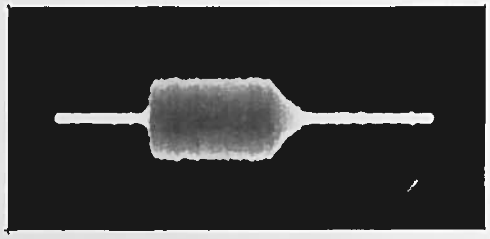
(a) Response to single FM impulse



(b) Receiver noise only

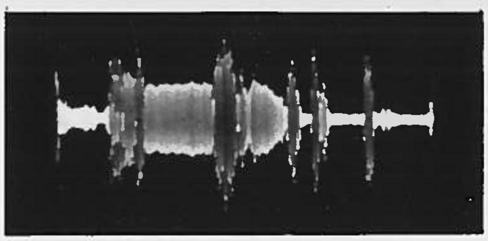


(c) Receiver noise reduced 25 db

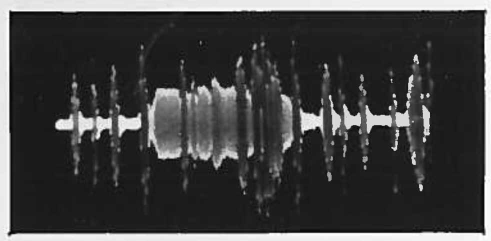


(d) Signal plus receiver noise

Signal in Presence of Jamming (video noise bandwidths as indicated below)

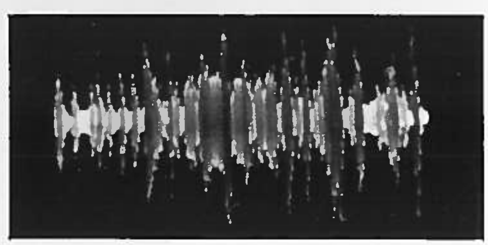


(e) $B_n$ = 0.1 - 0.3 mc/s



(f) $B_n$ = 0.1 - 1 mc/s

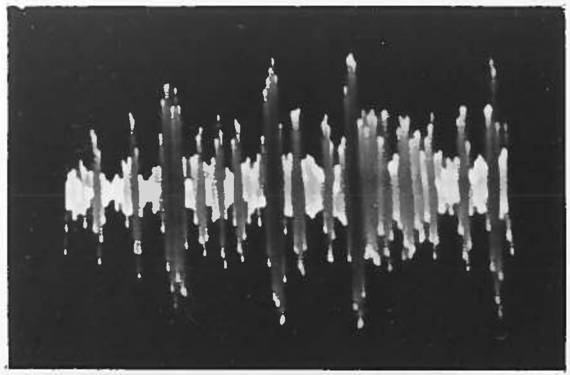
(g) $B_n$ = 0.1 - 3 mc/s



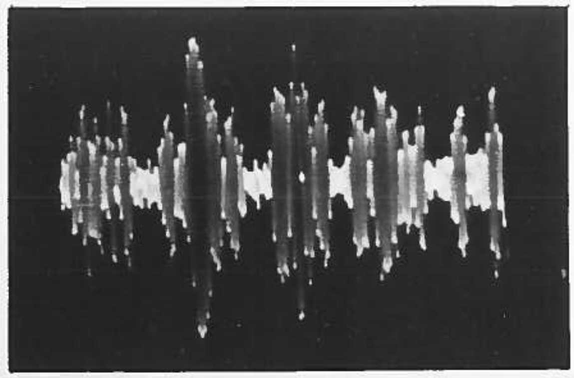
(h) $B_n$ = 0.1 - 5 mc/s

PLATE I

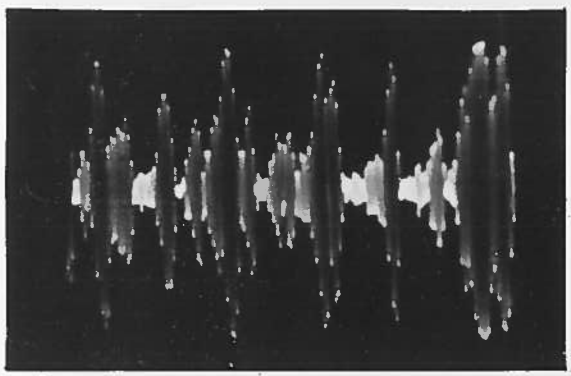
WAVEFORMS AT INPUT TO LIMITER



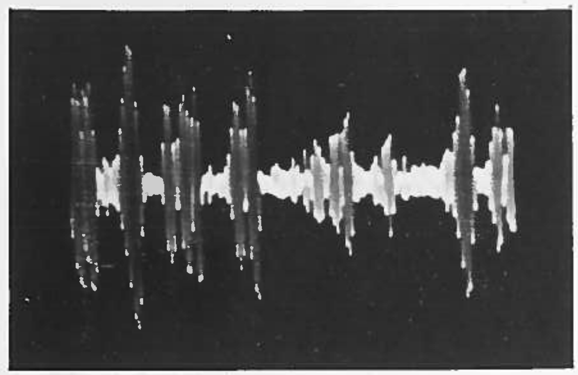
(a) Zero displacement



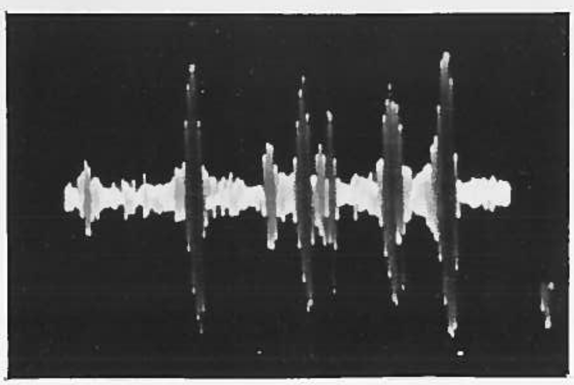
(b) 20 mc/s displacement



(c) 40 mc/s displacement



(d) 60 mc/s displacement



(e) 80 mc/s displacement

PLATE II

VARIATION IN NUMBER OF JAMMING IMPULSES
WITH POSITION OF RECEIVER NO. 2 FREQUENCY IN JAMMER SPECTRUM

(a)

(b)

(c)

(d)

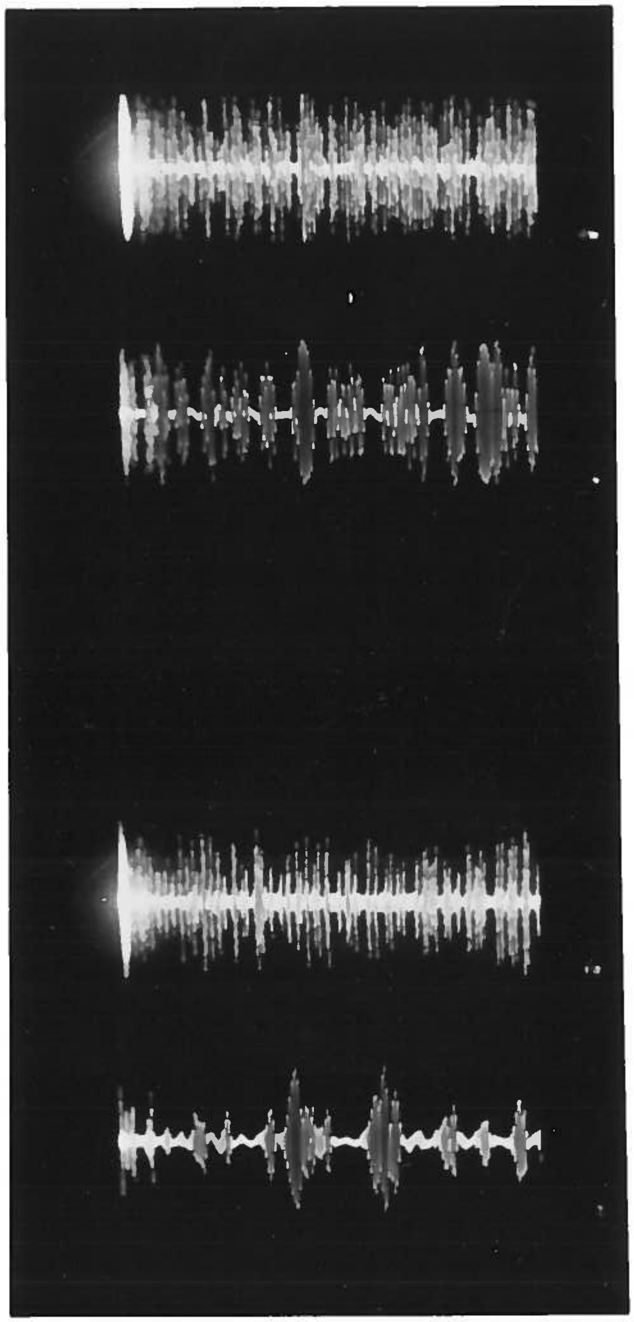
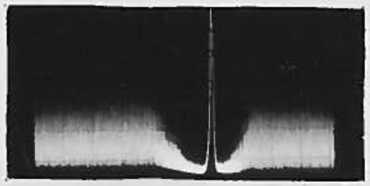


PLATE III

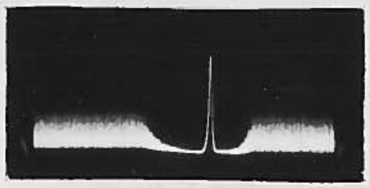
REDUCTION OF JAMMING IMPULSES DUE TO RF PRESELECTION

INPUT CARRIER LEVEL

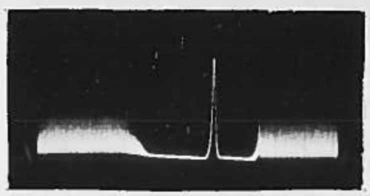
a) -103 dbm



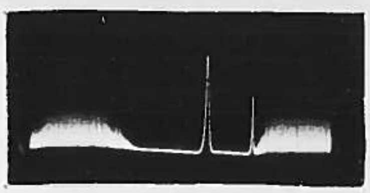
b) -85 dbm



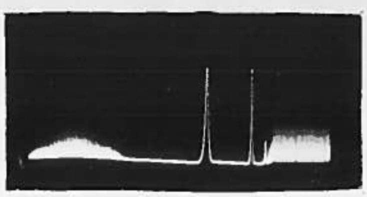
c) -74 dbm



d) -52 dbm



e) -42 dbm

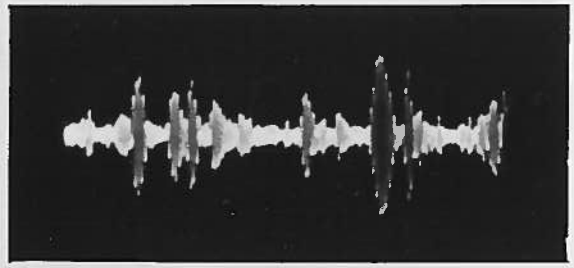


f) -27 dbm

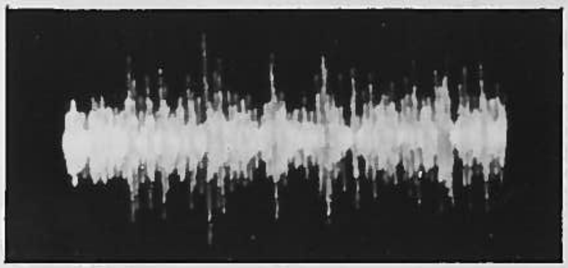
PLATE IV

RESPONSE OF RECEIVER NO. 2 TO A SLOWLY SWEEPING CARRIER
OF VARIOUS AMPLITUDES SHOWING SUPPRESSION OF LOW LEVEL SIGNALS

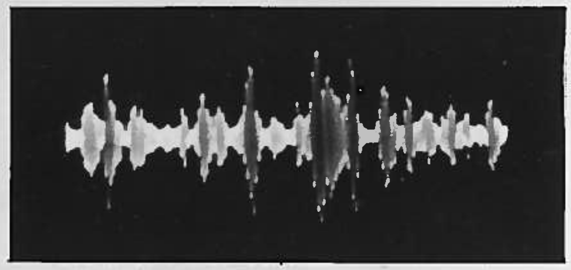
(a)



(b)

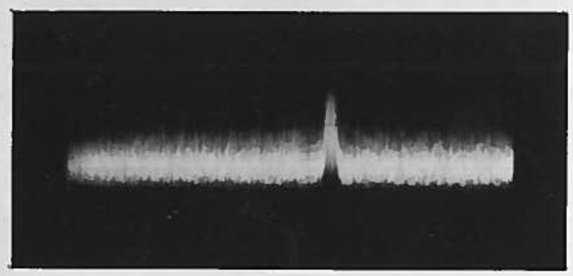


(c)



(d)

(e)



(f)

PLATE V

(a)-(d) INCREASE IN NUMBER OF JAMMING IMPULSES DUE TO ADDITIONAL NOISE JAMMER

(e), (f) EFFECT OF OPTIMIZING CLIP LEVEL IN THE PRESENCE OF CW AND NOISE JAMMING