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JAMMING TESTS OF THE "LOCAL OSCILLATOR OFF" FIX

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OTTAWA
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ABSTRACT

The range of an aircraft self-screened by FM-by-noise jamming was reported to have been determined by the simple expedient of switching off the local oscillator of the radar. The potential usefulness of the technique was investigated in laboratory jamming tests. The modifications to the conventional radar receiver which are required or desirable are outlined. Quantitative results of the effects of varying a number of receiver and jammer parameters are presented, and conclusions are stated.

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JAMMING TESTS OF THE "LOCAL OSCILLATOR OFF" FIX

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

INTRODUCTION

Some two years ago, a report was received from the United Kingdom stating that the range of an aircraft which was self-screened by a carcinotron jammer had been determined by the simple expedient of switching off the local oscillator of the radar. An investigation at that time in our laboratory [1] showed that for such a technique to give useful results, the power incident on the mixer crystal would have to be much larger than that which could normally be expected to be received from a barrage jammer unless it were within a mile or two of the radar. Also, some doubts were held as to the usefulness of the technique in the event that more than one jammer was present simultaneously within the radar beamwidth. It appeared to be a technique which might be employed to advantage against a single jammer if sufficient radio-frequency gain (presumably from TWT amplifiers) could be provided ahead of the crystal mixer. It was estimated that a total of up to 70 or 80 db gain could be usefully employed ahead of the mixer, and that a low-noise amplifier would be required at the input, followed by ordinary TWT amplifiers to provide the additional gain.

The investigation was undertaken in response to an informal request of the Working Group of Project "Napkin" [2] for advice as to the possible value of the technique. Because the situations in which the technique can provide a worthwhile increase in resistance to jamming were found to be very restricted, and because of the pressure of other commitments, an exhaustive study was not made. However, sufficient effort was expended to enable an outline of the principles of operation, and the advantages and limitations of the technique to be given.

THEORETICAL CONSIDERATIONS

The principal differences between the receiver discussed in this report and a conventional radar receiver are:

a) absence of the normal local oscillator input to the crystal mixer, and

b) introduction of a high-gain low-noise-figure broadband r-f amplifier preceding the crystal mixer.

The FM jamming signal is employed in the role usually performed by the local oscillator. Ideally, the local oscillator signal should be of the correct constant amplitude, and at a frequency different from the signal frequency by the intermediate frequency used. The sensitivity of the normal radar receiver, as a function of local oscillator drive, increases rapidly as the local oscillator power at the mixer crystal increases through the range -15 to -10 dbm, after which it goes through a maximum and then slowly decreases. The rapid increase can be attributed to the rapidly decreasing conversion loss at the stated levels. This occurs because the positive peaks of the local oscillator voltage become equal to and exceed the potential barrier of the metal-semiconductor junction so that the small variations in the peak voltage due to the superimposed signal voltage encounter only the relatively small "spreading resistance" of the crystal. The slow decrease at higher levels is caused by increased mixer noise temperature. The primary function of the TWT amplifiers is to raise the received jamming signal to a level greater than -10 dbm, and in so doing they should contribute as little additional noise as possible. The increase in crystal noise temperature at the higher levels is of no importance in this receiver, since crystal noise is negligible compared with the amplified TWT noise when the high gains required for best performance at low jamming levels are employed.

Even if the jamming signal is at the proper level to provide high crystal conversion efficiency, it still suffers from a number of shortcomings as a local oscillator signal. Its frequency is not constant, and with a fixed intermediate frequency it has the correct frequency only momentarily at random intervals. Therefore, only a small fraction of the jamming spectrum is effective in producing beats with the signal which lie within the I-F amplifier passband. Because of the wide bandwidth of the TWT noise, any part of the jamming spectrum is capable of producing beats with the TWT noise spectrum which lie within the frequency band passed by the I-F amplifier. That is, the I-F noise level would be the same for a fixed or a frequency-modulated local oscillator signal, provided that the amplitude of the local oscillator input was constant.

The jamming signal will possess some incidental amplitude modulation, contributions to which arise at various points between the crystal and the source of jamming. The power output of the carcinotron, and the jammer antenna pattern and transmission line reflections, all vary with frequency, as do antenna gain, TWT gain and transmission line matching in the radar. Intentional amplitude modulation could also be present on the jammer carrier. The output from the I-F amplifier will be the integral over the I-F bandpass of the envelope spectrum of the signal formed by the sum of the jamming signal, the desired radar echoes, and the TWT noise. Therefore, variations in jamming signal amplitude will contribute components to the I-F output. The greater the slopes of the amplitude versus frequency variations, and the higher the rate of sweep (proportional to jammer modulation bandwidth) of the jammer frequency, the greater will be the higher-frequency components of the envelope spectrum. The power spectrum of the amplitude variations falls off as the reciprocal of the square of the frequency and their effects should be reduced by using a higher I-F frequency*. However, if the jamming is to act as the local oscillator input, the range of possible I-F frequencies is restricted to one-half the barrage width for the case of the signal centered in the barrage, and the full barrage width for that of the radar frequency at one end of the barrage. Because the radar operator has no control over the amplitude modulation on the jamming or on the width of the barrage, there would appear to be advantages in having a variable I-F frequency. While this would entail added complexity, provision of such a facility is eased by the fact that the noise figure is not at all critical because of the high R-F gain preceding the mixer.

In the absence of jamming, the MDS (minimum detectable signal) is determined by the noise figure and noise bandwidth of the TWT amplifiers. (It is assumed that the TWT gain is so large that both mixer and I-F noise are negligible compared with the amplified TWT noise.) Because the beats between the signal and the wide-band TWT noise are equally probable over a wide range of frequencies which might be chosen as the I-F frequency, the MDS in the absence of jamming is independent of I-F frequency.

In summary then, with no jamming present the desired signal must compete with the total TWT noise on the basis of direct detection at the crystal mixer, and the sensitivity will be considerably reduced from that obtainable with superheterodyne operation. The sensitivity obtained should be independent of the I-F frequency. As the jamming level is increased from zero, the sensitivity would be expected to improve (MDS decrease) steadily from the power level at which the jamming is commensurate with the TWT noise at the crystal to that corresponding to adequate local oscillator input described previously. In the absence of amplitude modulation on the jamming signal the sensitivity should then remain constant for higher jamming levels. This constant level of sensitivity would be inferior to that obtained if a proper local oscillator signal were substituted for the jamming, by a factor related to the fractional number of cycles, n, of the jamming signal which are effective in producing beats with the radar echo which fall within the passband of the I-F amplifier. It is thought most likely that the reduction in sensitivity would vary as the square root of n. However, amplitude variations will be present on the jamming

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* The pattern of fluctuations in the jamming level at the detector (mixer) input can be approximated by a summation of small steps of amplitude, which appear as a summation of voltage steps at the detector output. The amplitude spectrum $f(\omega)$ of a unit step $\mu(t)$ is proportional to $\left(\frac{1}{\omega}\right)$ and the power spectrum to $\left(\frac{1}{\omega^2}\right)$. The power spectrum of a summation of such steps occurring at random will also be proportional to the reciprocal of the square of frequency.

signal, and at the higher jamming levels fluctuations in the mixer output envelope due to even a small percentage of amplitude modulation will become larger than fluctuations due to the wanted signal. When this occurs, further increases in jamming power must be accompanied by increases of the same ratio in the wanted signal if it is to remain detectable, and the limit in improvement in resistance to jamming has been reached. The greater the amplitude modulation on the jamming, or the wider the modulation noise bandwidth used by the jammer, the lower the jamming level at which this limit is reached. A higher I-F frequency will cause the limit to be reached at a higher jamming level. When two or more jamming signals are present at the mixer the beats between them predominate, producing a large increase in noise at the I-F frequency, so that very poor performance would be expected. Similarly, poor results would be expected if a large-percentage amplitude modulation of a random nature were encountered on the jamming signal, due to intentional amplitude modulation, the use of radio-frequency preselection in the radar or any of the other causes mentioned previously.

EXPERIMENTAL APPARATUS AND PROCEDURE

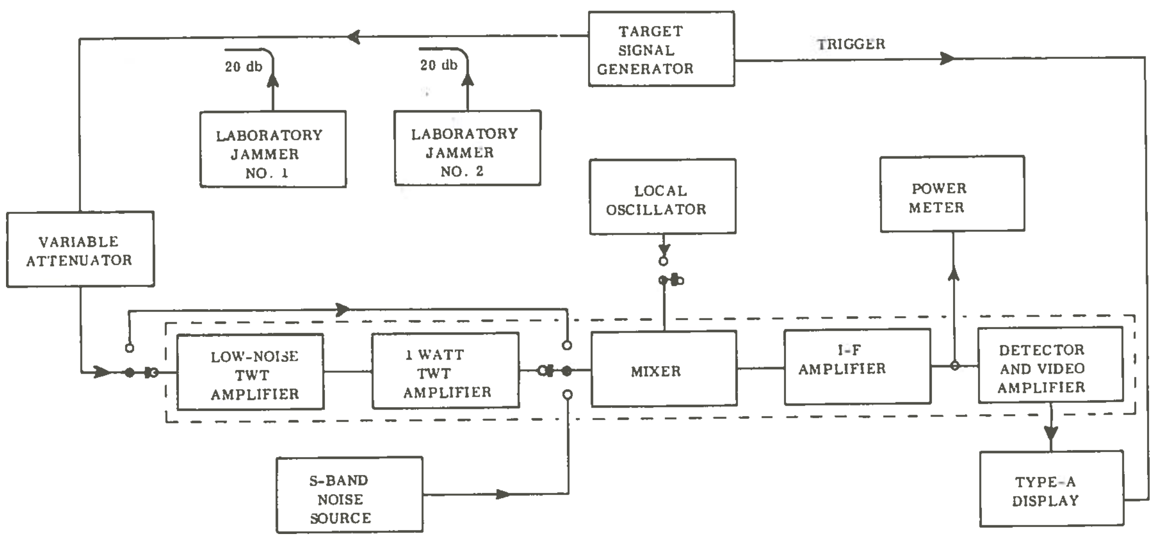

FIG. 1. BLOCK DIAGRAM OF EXPERIMENTAL RECEIVER AND TEST EQUIPMENT

Fig. 1 is a block diagram of the receiver (enclosed by the dashed line) and the experimental apparatus. At the input to the receiver was an RCA type-6861 low-noise TWT amplifier, which had a noise figure of 7 db, a gain of 25 db, and a bandwidth of about 800 mc/s. This was followed by a Hewlett-Packard type-491A TWT amplifier which had a gain of 40 db, a noise figure of about 25 db, and a bandwidth of 2 kmc/s. Thus the total radio-frequency gain was 65 db and the overall noise figure was about 8 db. The saturation power output of the second amplifier was 1 watt, so that input powers up to about -35 dbm could be accommodated without saturation of the radio-frequency amplifiers. (For a 200 mc/s uniform barrage this saturation level would be -56 dbm in terms of power in a 1.4 mc/s bandwidth.) When the I-F frequency was 30 mc/s, either a broadband (Empire Devices) mixer or a broadband crystal mount was used with similar results. When other I-F frequencies were used, the crystal mount was employed because the mixer had a built-in filter. The 30 mc/s I-F amplifier was a General Radio Unit Amplifier, which was linear over a wide dynamic range, and had a bandwidth of 0.7 mc/s. It was modified by addition of a cathode-follower-bolometer stage which was used to measure the I-F power at the input to the second detector. Also used in the experiments were a 63 mc/s amplifier with a bandwidth of 1.1 mc/s which had a similar power measurement modification, and a double-conversion amplifier (using portions of a Polarad spectrum analyser) with a center frequency variable from 10 to 100 mc/s and a bandwidth of 2.5 mc/s. The video amplifiers and type-A display were provided by a laboratory oscilloscope.

During the investigation, experiments were conducted to determine the requirements for jamming a receiver of the type which has been described. The instrumentation and the experimental procedure were similar to those described in detail in previous reports [3, 4], and only a brief summary is included here. The output of the laboratory jammers and the simulated target signal generator were calibrated by comparison with a standard S-band noise source, using a linear superheterodyne receiver with a power measuring device at the I-F output. The noise bandwidth of this receiver was 1.4 mc/s (0.7 mc/s at each image frequency), and jamming levels are expressed in decibels below one milliwatt (-dbm) in this bandwidth in order to facilitate comparison with the results of the previous studies. To obtain a minimum detectable signal reading, the target signal level was reduced well below the desired level, and one of four delays of the pulse position with respect to the start of the type-A display sweep was selected at random. The signal amplitude was steadily increased until the observer called the range of the target signal correctly. The value recorded was the average of several such readings. Considerable experience has shown that this procedure gives satisfactory repeatability of results.

One of the most useful quantities which required evaluation was the "camouflage factor", which for a given jamming signal-receiving system combination is the ratio of jamming power to minimum useful level of signal power at the receiver input. This quantity will be represented by the symbol (J/S), and is determined by measuring both J, the received jamming power referred to the receiver input, and S, the peak pulse power of the minimum detectable signal at the receiver input, and taking the ratio. FM-by-noise barrage jamming which consists of a microwave carrier swept randomly and rapidly through a band of frequencies was employed. A barrage width of 200 mc/s in the S-band was used, and various modulation noise bandwidths up to 5 mc/s were available.

EXPERIMENTAL RESULTS

While the results discussed below provide a general outline of the performance to be expected when the "local oscillator off" technique is employed in the presence of FM-by-noise barrage jamming, it is emphasized that they apply in detail only to the receiver-jammer combination used in the experiments. This is because the results depend to such a large extent on the magnitude of the incidental amplitude modulation present on the jamming signal at the mixer input, and can be expected to vary considerably from one jammer-receiver combination to another.

Fig. 2 shows the variation of camouflage factor with jamming level for jammer modulation noise bandwidths of 0.1 - 0.3 mc/s, 0.1 - 1 mc/s, and 0.1 - 5 mc/s. A single jammer producing a 200 mc/s barrage, and a 30 mc/s I-F amplifier were used. The camouflage factor for a normal narrow-band linear receiver was found [3] to be constant at about 5 db for noise modulation bandwidth greater than the receiver bandwidth. Therefore, the present receiver provides increased resistance to jamming (larger camouflage factor) over that obtainable with the normal receiver if the jamming power density is greater than about - 87 dbm in a 1.4 mc/s bandwidth, though below that level its performance is inferior to that of the normal receiver. The degree to which the amplitude modulation on the jamming signal limits the advantage to be gained by using the technique is also clearly shown. The points of departure of the various "branches" from the main "stem" of the curve correspond to those jamming levels at which the I-F noise due to components of the detected amplitude modulation on the jammer carrier replaces that due to the converted TWT noise as the major source of noise in the receiver. The ratio of the jamming levels for these points of departure varies, as expected, as the square of the inverse ratios of the modulation noise bandwidths. For example, the branch point for the 5-mc/s curve would be expected to occur at a jamming level $20 \log(5/1) = 14$ db below that at which the branch point of the 1 mc/s curve occurs. The difference, as shown in Fig. 2, is about 15 db. The close agreement supports the theory that: (a) amplitude modulation on the jamming carrier is the cause of the excess noise which limits the anti-jamming performance of the receiver, and (b) the amplitude modulation is correlated with the FM modulating voltage, and incidental to the modulation process. It should be noted that, in common with most other anti-jamming measures, the greater the modulation noise bandwidth used, the smaller the improvement which the technique provides.

In Fig. 3, camouflage factors for jamming by one and by two jammers are compared. Results for both the 30-mc/s and the 63-mc/s I-F amplifiers are presented. When compared with the performance achieved with a normal linear narrow-band receiver for which (J/S) is constant at about 5 db, the "L.O. Off" receiver shows seriously impaired performance against two jammers, but substantially improved performance at the higher jamming levels against a single jammer. It is this extreme susceptibility to jamming by more than a single jammer which most seriously limits the usefulness of the technique. The effect of the different

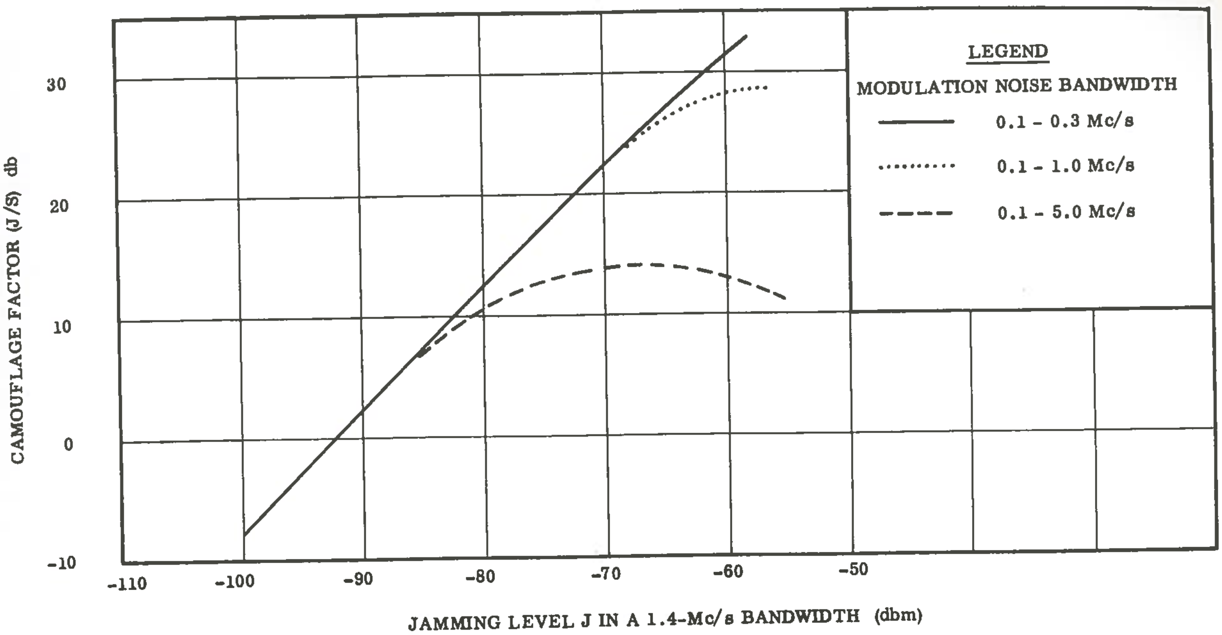

FIG. 2. VARIATION OF CAMOUFLAGE FACTOR WITH JAMMING LEVEL FOR VARIOUS JAMMER MODULATION NOISE BANDWIDTHS (FM-BY-NOISE JAMMING, 200 Mc/s BARRAGE, 30 Mc/s I-F, SINGLE JAMMER, TYPE-A DISPLAY SEARCHLIGHTING)

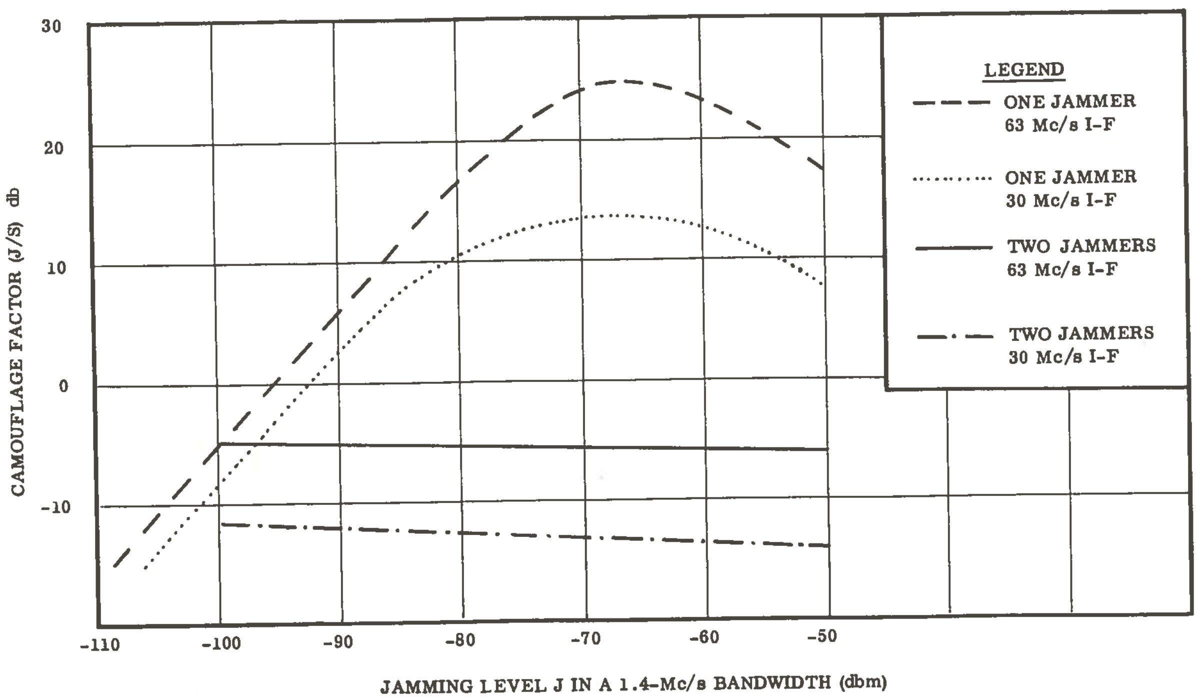

FIG. 3. COMPARISON OF CAMOUFLAGE FACTORS FOR ONE AND TWO JAMMERS WITH I-F OF 30 AND 63 Mc/s (FM-BY-NOISE JAMMING, BARRAGE WIDTH = 200 Mc/s, NOISE BANDWIDTH = 5 Mc/s, TYPE-A DISPLAY SEARCHLIGHTING)

I-F frequencies is also of interest. In both cases, the 63-mc/s amplifier gives performance which is superior to that of the 30-mc/s amplifier. The curves for the single jammer case are very similar to those of Fig. 2, and for the good reason that they provide but another view of the same phenomena. In this instance, the breakpoints at which the curves change from a straight line to a curved line, correspond to those jamming levels at which the I-F noise due to components of the detected amplitude modulation on the jammer-carrier replace the noise due to converted TWT noise as the primary source of noise in the receiver. These levels are expected to vary as the reciprocal of the square of the I-F frequency. The ratio of sensitivity at the "break" in the 30-mc/s curve to that of the 63-mc/s curve, should be -20 log(63/30) = -6.4 db. The difference shown in Fig. 3 is about -7.5 db. The 3-db difference between the ordinates of the two curves in the straight line region has not been satisfactorily explained. It is too large to be attributed to experimental error entirely, or to the difference in bandwidth of the amplifiers, though perhaps a combination of the two is responsible. When two jammers are used, the camouflage factor is almost independent of jamming level because the amplitude variations due to beats between the two jamming signals are so large that components of these rather than the TWT noise provide the sensitivity limit at all jamming levels, and an increase in jamming level must be accompanied by a similar increase in signal level if it is to remain detectable. In this case also, an average difference of 7 db exists in the ordinates of the curves for the 30 mc/s and the 63 mc/s intermediate frequencies, which agrees with the expected difference of 6.4 db mentioned previously.

The data used in preparation of Fig. 4 was obtained using the variable center frequency I-F amplifier. The variation of the minimum detectable signal with I-F center frequency at a jamming level of -70 dbm is shown. The solid line is the best fit curve of the type $10 \log[K/(F_i - f)^2]$ db. It is seen to fit the experimental points fairly well, except at the very high I-F frequencies. The decrease in sensitivity for I-F frequencies greater than 70 mc/s has not been accounted for quantitatively, though it is undoubtedly connected with the decrease in the number of excursions of the jamming signal into the frequency regions near the barrage edges, where it must be located to act as local oscillator when the high I-F frequencies are employed.

Fig. 5 affords a comparison of camouflage factors for receivers of various types against a single jammer with a 5-mc/s modulation noise bandwidth, as a function of jamming level. It is possible to see at a glance the relative merits of typical receivers of the Dicke Fix type, both with and without radio-frequency preselection (image suppression), the receiver using the "local oscillator off" technique with both 30 and 63 mc/s I-F amplifiers, and the normal linear narrow-band receiver. The curves show very clearly that the performance of the Dicke Fix type receiver is superior to that of the local oscillator off type, if radio-frequency preselection is employed in the former. Since the curves for the L.O. Off receiver were for the case with no intentional amplitude modulation, and low

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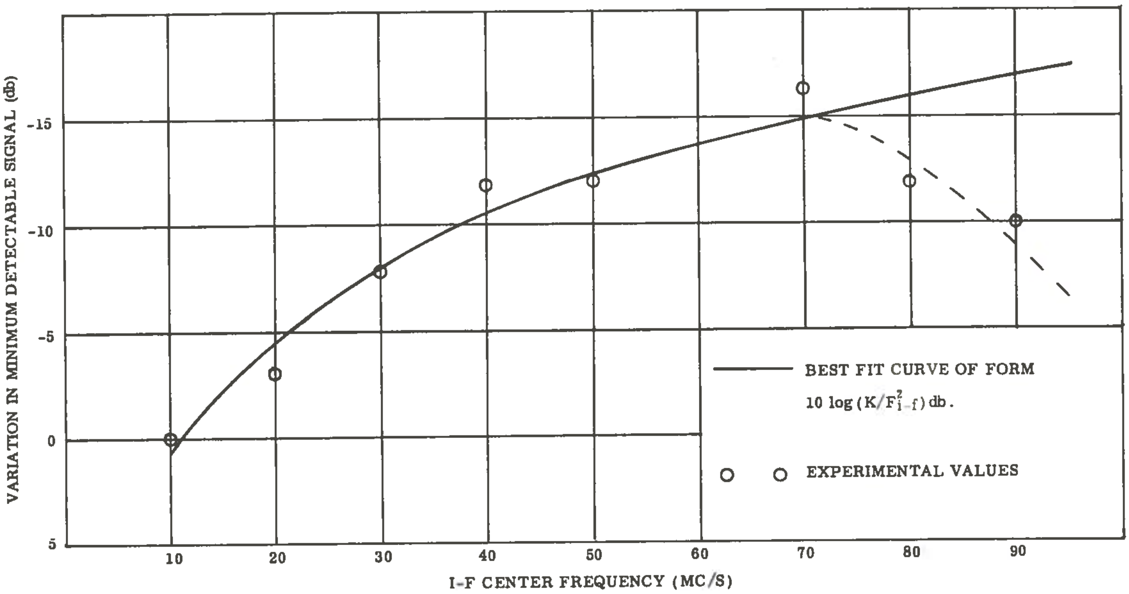

FIG. 4. VARIATION IN MINIMUM DETECTABLE SIGNAL WITH I-F CENTER FREQUENCY
JAMMING LEVEL = -70 dbm (IN A 1.4 Mc/s BANDWIDTH), I-F BANDWIDTH = 2.5 Mc/s, BARRAGE WIDTH = 200 Mc/s, NOISE BANDWIDTH = 5 Mc/s

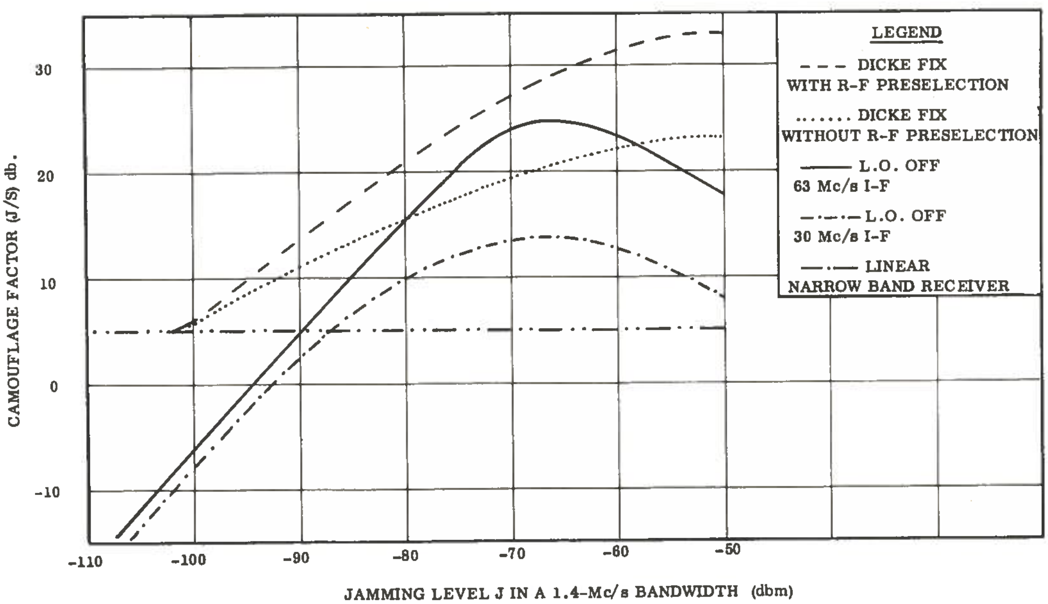

FIG. 5. COMPARISON OF CAMOUFLAGE FACTORS AS FUNCTION OF JAMMING LEVEL FOR VARIOUS RECEIVERS
(FM-BY-NOISE JAMMING, 200 Mc/s BARRAGE, NOISE BANDWIDTH = 5 Mc/s, SINGLE JAMMER, TYPE-A DISPLAY SEARCH LIGHTING)

incidental amplitude modulation compared with what might be expected in practice, they probably represent a rather optimistic view of its performance. If curves for two or more jammers were compared in a similar manner, the L.O. Off receiver would be shown to perform poorly compared with even the normal linear narrow-band receiver as was evident in Fig. 3.

Before conclusions are stated, a few other points which were noted in the course of the experiments remain to be reported or discussed.

1) R-F Gain The above results were obtained using 65 db of TWT amplifier gain. It was observed that, while the performance increased with increased gain, it did not increase in the same ratio as the gain. For example, at low jamming levels, a decrease in gain by 6 db to 59 db caused a 3-db decrease in camouflage factor. Very little additional improvement would be expected for gains in excess of that required to increase the amplified TWT noise level at the crystal to about -10 dbm which would be obtained with between 65 and 70 db gain for the noise bandwidth and noise figure employed in the experiments.

2) Crystal Bias To some extent a deficiency in radio-frequency gain can be offset by the application of forward bias voltage to the crystal. Gains in excess of 10 db in camouflage factor have been obtained owing to the application of about 1/10 volt forward bias. By the same token, back bias is avoided, and for this reason the resistance in the crystal current circuit should be kept to a minimum.

3) TWT Gain Control It will be noted in Figs. 2 and 3 that the camouflage factor tends to decrease at the high jamming levels. It should be possible to avoid this by decreasing the radio-frequency gain when high jamming levels are encountered. This could be done automatically by the application of a voltage to a TWT amplifier grid which prevents the crystal current from exceeding a predetermined value.

4) The fall-off in camouflage factor at the higher levels of jamming has not been completely explained, though a number of factors may contribute to it. These include:

a) Back bias on the crystal

When the crystal current becomes large at high jamming levels, even a small amount of resistance in the crystal current circuit can cause the development of detrimental back bias voltage.

b) Change in crystal impedance

At high input levels the crystal presents a poor match to the TWT output. When this occurs, a line stretcher or resistance pad between TWT and crystal can give substantial improvement in performance.

c) Saturation in the TWT amplifiers

This did not occur within the range of jamming levels reported, but when present it has a similar effect to that under discussion. In this connection, the TWT amplifier was found to be a fair mixer within 10 db of saturation level. For example, at a c-w output from the TWT amplifiers of 50 milliwatts, the minimum detectable signal was found to be -110 dbm with the crystal mount, and -106 dbm when it was replaced by an ordinary connector.

d) Increased conversion loss

At high input levels an increase in crystal conversion loss may occur owing to the slope of the forward current characteristic having reached a steady value while that of the backward current is increasing.

e) Increased crystal noise temperature

This would be expected if the TWT gain were not sufficiently high that the amplified TWT noise is much larger than the mixer noise.

5) R-F Preselection With a single jammer, radio-frequency preselection does more harm than good. The decrease in converted TWT noise is more than offset by the components of the direct detection of the amplitude modulation on the jamming which is produced by preselection. Some improvement would be expected from use of a filter located between the TWT amplifiers and the mixer, the passband of which just encompasses the jamming spectrum, but this presents practical difficulties. When more than one jammer is present, however, the major source of noise is the detected amplitude modulation due to beats between the jamming signals. This can be reduced by radio-frequency preselection, though performance would still be inferior to that obtainable using other methods.

6) Compatibility with Dicke Fix Performance is reduced drastically when the I-F amplifier is converted to a Dicke Fix type by addition of a wide-band amplifier and limiter between the mixer and the narrow-band I-F amplifier. Evidently the action of the limiter removes the small beat frequency amplitude variations which contain most of the target signal information, so that the sensitivity is deteriorated by about 30 db for the single jammer case. In the event that two or more jammers are used, much of the amplitude modulation due to beats between jamming signals also is removed by the limiter, with the result that at some jamming levels a slight improvement is obtained. However, performance is always considerably worse than that obtained from the normal linear receiver with the local oscillator switched on.

7) I-F Bandwidth The experimental data obtained do not contain sufficient information about the effect of I-F bandwidth on the performance to permit conclusions as to the optimum value. The MDS using c-w jamming at the correct local oscillator frequency was -110 dbm, while the best value obtained

with the jamming acting as local oscillator was -100 to -102 dbm. The very limited data at hand suggests that this degradation in sensitivity for $\beta << W$ varies as $10 \log\left(\frac{W}{2\beta}\right)^{\frac{1}{2}}$, where W is the barrage width and β is the I-F bandwidth. The factor $\left(\frac{W}{2\beta}\right)$ represents the fractional number of jammer cycles that produce beats with the signal which fall within the I-F bandwidth. As β becomes equal to $\frac{W}{2}$, however, all jamming cycles will be effective, but the noise level would be $\left(\frac{W}{2\beta_o}\right)$ times as large as would be the case for a receiver of optimum bandwidth β_o (approximately equal to twice the reciprocal of the pulse width) with a proper local oscillator. The degradation expected for $\beta = \frac{W}{2}$ would therefore be expected to be $10 \log\left(\frac{W}{2\beta_o}\right)$ db. Thus for bandwidths in the vicinity β_o, the sensitivity appears to increase with increasing bandwidth, but in the limit of very wide bandwidths it would be expected to be considerably lower. It is therefore concluded that an optimum I-F bandwidth exists for the case of the jammer acting as the local oscillator, which is several times the optimum which applies when a proper local oscillator is used.

CONCLUSIONS

In general, there appears to be no advantage in using the "Local Oscillator Off" technique in radar receivers. It was found to be adversely influenced by amplitude modulation on the FM jamming signal, whether produced intentionally, incidentally, or by simultaneous reception of more than one jamming signal. There are very few situations in which it can provide any improvement at all over normal linear narrow-band receiver operation, and the improvement obtained was found to be no better than that which can be obtained more easily with presently available Dicke Fix receivers.

ACKNOWLEDGMENT

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