DECLASSIFIED

NRL Report 4547

[redacted]

OPERATIONAL FACTORS AFFECTING THE RADAR JAMMING PROBLEM

[UNCLASSIFIED TITLE]

J.M. Miles

Countermeasures Branch
Radio Division

DECLASSIFIED by NRL Contract
Declassification Team
Date: 10 MAR 2017
Reviewer's name(s): [redacted]
[redacted]
Declassification authority: NAVY DECLASS GUIDE/NAVY DECLASS MANUAL, 11 DEC 2012
608 SERIES

June 27, 1955

[redacted]

DISTRIBUTION STATEMENT A APPLIES
Further distribution authorized by
UNLIMITED only.

Naval Research Laboratory
Washington, D.C.

[redacted]

DECLASSIFIED

[redacted]

DECLASSIFIED

[redacted]

CONTENTS

[redacted]

DECLASSIFIED

[redacted]

ABSTRACT

[redacted]

Since weight and space have always been at a premium in high average power jammers, e.g., noise-modulated transmitters, the designers of early equipment tended to disregard control and set-on problems in favor of maximum power. With constantly improved and increasingly sophisticated radar equipment, as well as vast developments in aircraft performance, there is a corresponding demand for increasingly complex jamming devices. As a result, the already limited space and weight factors have been further aggravated. To ameliorate such difficulties it is suggested that a possible review of presently accepted power requirements may be in order.

In substantiation, attention is drawn to recent tests of airborne jamming equipments, the results of which were better than a theoretical evaluation would indicate. Such a deviation from theory is shown to be a function of operational factors ordinarily not fully considered, and it is recommended that field studies be undertaken to evaluate such factors with the specific hope that the power requirements may be found less rigorous than supposed.

Another means of lessening the power requirement is by better modulation techniques. A study of three radars shows that individual equipments vary widely in vulnerability to jamming which is amplitude modulated by random noise and that not one type of amplitude modulation is equally effective against all radars. However, when random noise with unequal positive and negative excursions was considered as the variable, it was concluded that a dissymmetry of 4:1, i.e., a peak r-f voltage that is five times average, was preferred over symmetrical modulation which is used in most presently available noise jammers. Since less average power and thus less power supply equipment are required for a given peak power, unsymmetrical modulation is attractive because it affords advantages in size and weight.

PROBLEM STATUS

This is an interim report; work on the problem is continuing.

AUTHORIZATION

NRL Problem R06-12
Projects NL460-017, NL 460-041, and NL 460-052
BuAer Problem EL-9A-334

Manuscript submitted April 6, 1955

[redacted]

[redacted]

OPERATIONAL FACTORS AFFECTING THE RADAR JAMMING PROBLEM
[UNCLASSIFIED TITLE]

INTRODUCTION

When future requirements for airborne jamming systems of high average power are under consideration, it is necessary to examine new techniques that utilize tubes and components which can be electronically controlled to provide fast action, multiple signal possibilities, and improved signal generation and amplification. As one possibility, traveling-wave tube (TWT) power sources offer many appealing advantages for automatic search and jam systems, but are, nevertheless, inferior to more conventional microwave power sources from the standpoint of efficiency and available power output. Present design trends indicate practical beam efficiencies of 10 to 20 percent, and r-f heating of the helix limits the power output, in proportion, to roughly the square of the wavelength. Present developments discourage an anticipation of average power in excess of 200 watts at S-band. Hence, with present TWT design methods, something considerably less may be expected at X-band frequencies—the very range where the most dangerous signals are expected.

True, the newly developed carcinotron-type power oscillator offers a much more favorable comparison from the standpoint of both efficiency and power output. Nevertheless, the auxiliary equipment needed for its more demanding requirements largely offset this advantage. Even overlooking this additional equipment for the power source, the increasing complexity of near-instantaneous automatic systems that require more space and weight in the aircraft still demands a compromise with power. The extent of such a compromise depends largely upon (a) an exact evaluation of the power requirements and (b) the vulnerability of various radars to different modulation types.

EVALUATION OF POWER REQUIREMENT

For some years an apparent standard of 200 watts of r-f output has been accepted as the design requirement for airborne noise-modulated jammers. It is not entirely clear where this figure originated, but it is perhaps the maximum considered possible for airborne equipment. Whether modulation effectiveness or the propagation problem was considered is not clear, but considerable evidence is accumulating to indicate that a power level of this order, although fine if available, may not be altogether necessary for many tactical situations.

Of particular interest in substantiating the foregoing statement are the results of Navy tests on two airborne jammers—the AN/ALT-2 and the AN/APT-16—at NATC, Patuxent, Maryland (1, 2). Both jammers are nominally 200-watt noise-modulated equipments that operate at X-band and S-band, respectively.

For the X-band tests the AN/ALT-2 was flown in a P2V-type aircraft against a Mark 25 Mod 2 radar that had a peak pulse power of 50 kw and an antenna gain of 40 db. The jamming antenna, which was mounted in the nose of the plane and directed forward, had a gain of 7 db. Although the power output is nominally 200 watts, the magnetron type that is used as the power source actually developed not more than 150 watts of cw and could not be modulated beyond a peak of two times average (300 watts). In addition, to prevent excessive FM at low current, the peak swing in the negative sense was limited to about a third of the cw value. For 100-percent symmetrical modulation as normally defined, the power must

[redacted]

swing from four times the cw value to zero. Hence, the effective modulation was the equivalent of less than 75 watts, 100-percent modulated.

Later it will be shown theoretically that a jamming transmitter of this type should be marginally effective against the Mark 25 radar for a closing course at about 800 yards. In actual tests, however, the jammer was fully effective at all ranges. In other words, the jamming effectiveness was not only better, but much better than anticipated.

The same situation held in the S-band tests when the AN/APT-16 jammer was used against the SG-3 S-band search radar, which had a peak pulse power of 400 kw and an antenna gain of 30 db. Here, on the basis of present theory, 200 watts of peak power modulated to 100 percent should afford marginal protection at 1300 yards but again jamming was effective at all observed radar ranges.

These and similar tests throughout the services point to the need for a re-evaluation of the power requirement for jammers. They certainly enhance the prospect of utilizing less powerful r-f sources with more flexible design features. But although it is certainly desirable to reduce the jamming power requirement, a thorough understanding of the various ramifications of the problem beforehand is even more desirable. It should be emphasized that such tests as those described are evaluation tests of the equipment and not quantitative measurements. True, they indicate that power requirements may have been overestimated; but to what extent and how will better and more powerful radars modify present requirements? To develop optimum effectiveness and flexibility in radar and missile airborne jamming systems there must be available design data based on a theory corroborated by field test data. Although current literature provides basic solutions for the jamming problem, the results for the most part are largely unverified. This report summarizes and extends some of this information to serve as a background for proposed airborne field studies of the operational problem. Of particular interest is the radar receiver jamming factor, which shows the r-f power relationship between the jamming signal and the radar pulse at the radar receiver input.

UTILIZATION OF OPTIMUM MODULATION TECHNIQUES

The second part of this study involved an investigation of various modulation types as a means for optimizing the jammer's effectiveness against various radars. A quantitative study, undertaken for three radar types, was limited to an evaluation of noise amplitude modulation with various degrees of unsymmetrical clipping. This limited investigation was necessary at the time as an aid in designing an experimental TWT jamming transmitter as part of the automatic search and jam system under development. A more extensive NRL study (3) of the modulation problem has been undertaken. In addition to the immediate design information accrued, the results—essentially a tabulation of the jamming factor for the three radars—should be of value in an operational field study involving these radar types.

PROBLEM DEVELOPMENT

The problem of immediate and primary interest is self-protection; for this particular application the jammer is required to protect a target at the jammer position. In Appendix A a brief discussion is given of the problem of remote protection whereby the jammer must extend its coverage to a convoy not at the jammer position. The requirement for this second problem is shown to be so severe that it is impractical for general airborne operations.

The problem of self-protection, which is widely discussed in the literature, will be developed in order to introduce and define terms, particularly the various k-factors not so universally familiar.

To avoid overcomplexity, free space propagation is assumed. This does not account for recurrent variations of signal strength with range due to surface reflections but accepts a mean locus lying between the nulls and peaks. Assume a jammer aboard a target, say a bomber approaching a radar position, and let

P_t = Peak pulse power of the radar transmitter in watts

G_t = Radar-antenna gain ratio

R = Distance to the target in meters

s = Radar signal strength impinging on the target in watts per square meter at the range R.

If, ideally, the beam is accurately directed toward the target and there are no other transmission losses, then

$$s = \frac{P_t G_t}{4\pi R^2}.$$

Two factors, however, modify this result. The first, angular beam error, is the ratio by which the signal is attenuated because of angular search error and it applies particularly to fire-control and guidance systems. Let this factor be k_1. The second, the propagation factor, k_2, is the attenuation of transmission through the atmosphere—a factor that becomes more serious with increasing frequency. Below X-band frequencies this factor is of little consequence; at X-band it is still of minor importance except in the presence of fog, mist, or rain. Hence, to avoid an overly complicated analysis, the propagation factor will be treated as a constant that has a value close to unity. For validity at frequencies higher than X-band or for extreme ranges this factor must take the form of

$$k_2 = \epsilon^{-aR}$$

where a is a constant that depends on frequency and atmospheric conditions (4).

When modified by these two factors the signal strength impinging on the target is

$$s = \frac{P_t G_t}{4\pi R^2} k_1 k_2. \tag{1}$$

The target intercepting the beam generally reflects r-f pulse energy nonuniformly in all directions. To reduce this complication, it is considered that the target is replaced by a perfectly reflecting sphere whose size is sufficient to reflect the same energy to the radar position as does the particular aspect of the target. Such a sphere would reradiate the intercepted energy uniformly in all directions (isotropically). Its intercepted energy is defined by the hemispherical cross section of the sphere, σ, which is called the radar area of that target aspect. Consequently, the equivalent intercepted energy is

$$P_t' = s\sigma$$

and since isotropic reradiation is assumed, the echo field strength at the radar for the range R is

$$S = \frac{s\sigma}{4\pi R^2}.$$

This again is the idealized expression. The radar area σ, however, varies with the motion and aspect of the target. For instance, the broadside of a plane will, in general, reflect more power to the radar than head-on; hence, any momentary change in aspect will cause a corresponding fluctuation in σ. For a given aspect, the ratio by which the peak value of the radar area is multiplied to obtain the average value is the factor k_3. As before (Eq. (1)), the propagation factor, k_2, must be included with the result that

$$S = \frac{s\sigma}{4\pi R^2} k_2 k_3. \tag{2}$$

Substituting Eq. (1) into Eq. (2),

$$S = \frac{P_t G_t \sigma}{(4\pi)^2 R^4} k_1 k_2^2 k_3, \tag{3}$$

which is essentially the familiar radar equation.

In like manner for the jammer, assume that the sideband content of the jammer signal is fully contained within the radar receiver bandpass and let

P_j = Jammer carrier power in watts

G_j = Jammer antenna gain ratio

R = Range (an identity with R in Eq. (3)) in meters

J = Jammer signal strength at the radar in watts per square meter.

Ideally,

$$J = \frac{P_j G_j}{4\pi R^2},$$

but again, assuming evasive action on the part of the plane, there is a good possibility that ideal beam directivity may not accrue with a fixed jammer antenna even though it has a relatively broad beam, and an additional directivity factor, k_4, must apply to the jammer antenna. Hence,

$$J = \frac{P_j G_j}{4\pi R^2} k_2 k_4 \tag{4}$$

where k_2 is again the propagation factor.

Adequate jamming will occur when the jamming signal strength is sufficient to disable the radar function. The ratio by which the reflected pulse level is multiplied to obtain the jamming level is the radar-receiver jamming factor, k_j, more familiarly known as J/S and

$$J = k_j S. \tag{5}$$

Substituting Eqs. (3) and (4) into Eq. (5),

$$P_j = \frac{P_t G_t}{4\pi R^2 G_j}\left(\frac{k_1 k_2 k_3}{k_4}\right) k_j.$$

[redacted]

[redacted]

At least one other factor must be considered before this expression becomes valid. In the last equation it is assumed that there is a constant pulse level equal in value to the average echo; from this it might be deduced incorrectly that each pulse contributes equally to the radar control functions. In the presence of marginal jamming, however, and with pulse fluctuations more rapid than the integrating time of the radar, the weaker pulses will be lost to the radar. Ridenour (5) has given a figure which indicates that a radar's effectiveness is directly proportional to the square root of the number of pulses integrated. When the integrating period is some radar function—for example, the time required to break track or perhaps screen persistance—and the average to the maximum number of pulses integrated during an average period is N_{av}/N_{max}, then

$$P_j = \frac{P_t G_t \sigma}{4\pi R^2 G_j} k_t k_j k_n \qquad (6)$$

where

$$k_n = \left(\frac{N_{av}}{N_{max}}\right)^{1/2}$$

and

$$k_t = \frac{k_1 k_2 k_3}{k_4}.$$

The part of Eq. (6) here shown as fractional is thoroughly familiar to the countermeasures field and indicates that the jamming power requirement becomes more rigorous as the range closes. When range is the only variable, it follows that there is a range for which jamming effectiveness is marginal so that a further decrease results in inadequate jamming. This is termed the "crossover range." Rearrangement of Eq. (6) shows this range to be

$$R = \left(\frac{P_t G_t \sigma}{4\pi P_j G_j} k_t k_j k_n\right)^{1/2}. \qquad (7)$$

PROBLEM ANALYSIS

Equations (6) and (7) are essentially a complete mathematical statement of the jammer problem as related to the power requirements for self-protection. For example, the jammer power requirement (Eq. (6)), must be found in terms of operation range against a given radar when the radar area (σ) is known for the airplane in which the equipment is to be installed. A satisfactory utilization of Eq. (7) is possible only when all of the factors are known with sufficient accuracy, and it is concluded that past analytical evaluations of the problem have failed to agree with recorded data because these factors have not been fully explored. In general, the measurable quantities have been reasonably well known, but a constant, K, has been assumed and its value has combined all of the factors k_t, k_j, and k_n. In other words,

$$K = k_t k_j k_n.$$

Without considerable knowledge of the general operational problem, such assumptions can never be valid and it would be the specific object of a field study to clarify the various ramifications of K. Hence, the field study of the problem is stated mathematically by still another rearrangement of Eq. (6), specifically

$$k_t k_n = \frac{4\pi R^2 P_j G_j}{P_t G_t \sigma k_j}. \qquad (8)$$

[redacted]

Here, the purpose is to evaluate the translation and integration factors for various operating conditions. The radar-receiver jamming factor, k_j , remains on the right side of the equation because it is a measurable factor of the radar receiver and the jammer, and hence would hardly be affected by operational conditions.

The procedure then is to measure or determine the quantities on the right side of Eq. (8) for the particular radar, jammer, and type of operation involved. The determination of the directly measured quantities—power and antenna gains—may be dismissed with the acknowledgment that for the study to be valid, such quantities must be known or measured to a satisfactory degree of accuracy.

The determination of the radar area, σ , is a complete field study in itself. Considerable work has been done (6 through 18) and a reasonable evaluation should be available, but it should be remembered that the factor σ in Eqs. (6) and (7) is the peak value for a given aspect. Where the average value must be substituted without knowledge of the peak value, Eq. (6) becomes

$$P_j = \frac{P_t G_t \sigma_{av}}{4\pi R^2 G_j} k_t' k_j k_n$$

where

$$K_t' = \frac{k_t}{k_3} = \frac{k_1 k_2}{k_4}$$

and $\sigma_{av} = k_3 \sigma$. Ideally, an operational field study of the jammer problem should be made with relation to all aspects of the aircraft involved, and this is a lengthy undertaking. If, however, it can be assumed that k_3 is constant with changing aspect—certainly a fairly reasonable assumption—then the investigation can reasonably be confined to the most convenient aspect, which is probably head-on. In this event, the resulting data would apply for any angle around the target provided σ is modified as necessary for use with the desired aspect. For example, consider a jammer with a directive antenna intended for broadside as well as coverage of other aspects. The factor σ must be much greater than for the head-on aspect only—assuming, of course, similar plane types. Ridenour (19) shows typically how radar echoes vary with aspect.

The radar-receiver jamming factor, k_j , may be measured directly at the input of the radar receiver or at the input of the radar's i-f amplifier. An NRL investigation of this problem for three radars located at the Chesapeake Bay Annex has already been completed, and the results, which are included in this report, should be helpful in the proposed field study.

Finally, crossover ranges are determined by flight-testing the jammer against the radar for various operating conditions; hence by substitution, the value of $k_t k_n$ becomes available.

Obviously, these factors can probably never be resolved into any semblance of a fixed value. It should be possible, however, to fix the value within certain limits for any one category of operational conditions. For example, the echoes from propeller-driven planes show wide variation from pulse to pulse, and 20-db fluctuations between adjacent pulses are not unusual. The NRL photographic recordings (20) of pulse-by-pulse echoes (Fig. 1) illustrate the wide variation in echo stability between the propeller-driven and jet-type aircraft

[redacted]

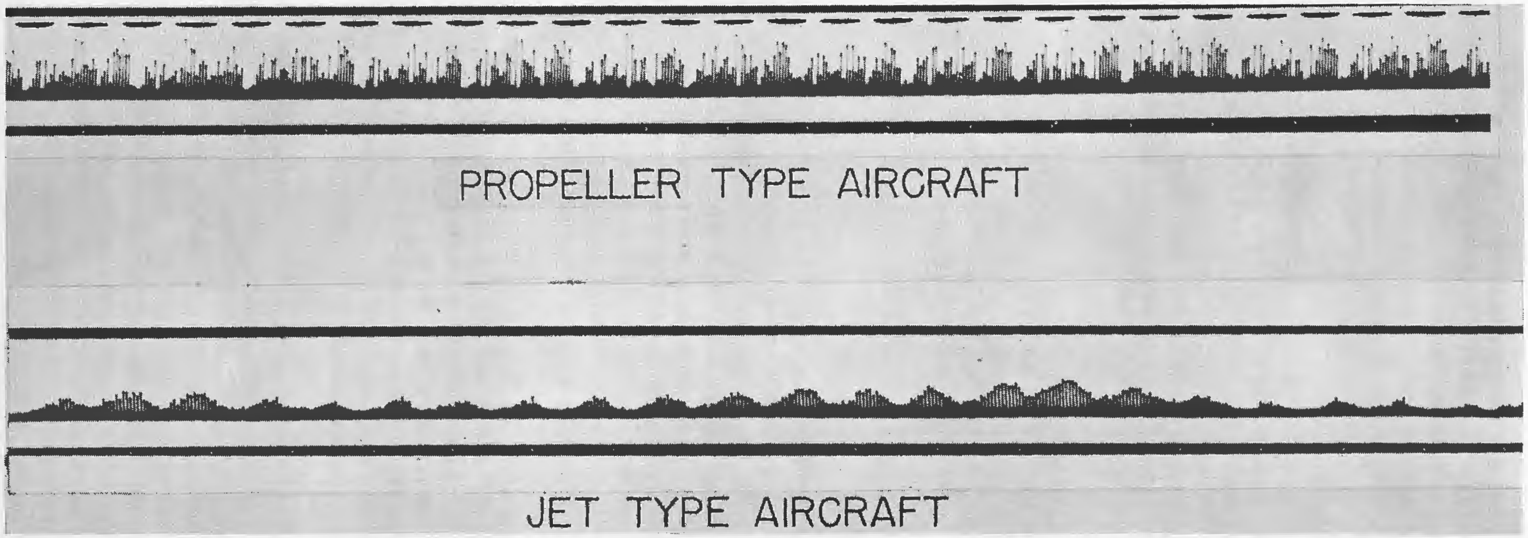

Fig. 1 - Pulse-by-pulse recordings of fire-control radar echoes

and lead to the conjecture that the integrating fractional factor, k_n, will be increased to nearer unity for the propellerless plane. This does not imply that the jet type is more difficult to jam, because, in general, the value of the radar area, σ, is reduced for equivalent streamlined propellerless planes. However, the single factor k_n is apparently a function closely associated with plane type and other factors that contribute to rapid echo fluctuation.

On the other hand, k_t is probably more a function of operating conditions—target motion, atmosphere, and antenna stabilities—and these parameters are in turn closely associated with the type of mission. Again as an example, compare high-altitude bombing with the low-level attack. When the former method, with less jitter introduced into the search function, is employed and the use of larger planes reduces the possibility of evasive action, k_1 and k_3 will be maximized as compared to the latter operation when the opposite will be true.

Thus, for operation against fire-control and search radars it would seem that the translation and integration factors of the jamming equation could be evaluated primarily in terms of plane types and mission types. No doubt additional categories exist for operation against other systems (e. g., AI radars and guidance equipments). Such problems must consider the additional motion of the radar equipment.

JAMMING FACTOR

The radar-receiver jamming factor, k_j, is of prime interest because it is a direct function of the radar itself and, in fact, the figure of merit of the radar's antijam capabilities. As such it is additionally useful as a measure of the jammer's modulation effectiveness. Because of the limited average power available from traveling-wave tubes, it has been suggested that unsymmetrical amplitude modulation be used with the average power at a level which is lower than when conventional modulation is used, i. e., an increase in relative sideband power. A study of three radars was undertaken at CBA to (a) evaluate various degrees of modulation symmetry and (b) determine the value of the factor, k_j, for several radar types as an aid to a field study problem.

In the early part of the work, a TWT amplifier was grid-modulated to provide a local jamming signal at the radar. Since the TWT was designed for S-band operation and the available radars were X-band equipments an elaborate combination of pulse generators, oscillators, and mixers was provided for the necessary frequency conversion. Subsequently, the jamming signal was provided at the radar i-f by a pentode with suppressor grid modulation (Fig. 2). In comparing the two methods, no significant difference was observed and i-f injection became the standard because of its simplicity.

Another rather elaborate device used for the early work was a moving-target generator, which was essentially an r-f pulse generator with a motor-driven continuously variable delay. The pulse amplitude of the generator was adjusted until it was equal to the echo amplitude of the Sharps Island lighthouse, a fixed target located across the Chesapeake Bay. Later the echo from the lighthouse was used directly. To compensate for lack of a moving target, the early and late gates in the fire-control radars were unbalanced slightly so that when track was broken the gates drifted, and as a result, an equivalent variation of the target was provided with respect to the range function. The lighthouse was found to be a reasonably stable target that usually held well within three db. The peak value was chosen as the reference level. The jammer signal without modulation was applied to the radar's i-f input. The output from the first detector was observed, and the level was equated to the peak pulse level.

[redacted]

The desired type of modulation was then applied and the jamming level increased until the function of interest was disabled. The ratio by which the jamming signal was increased is expressed as J/S (factor k_j of Eq. (5)) in Tables 1, 2, and 3.

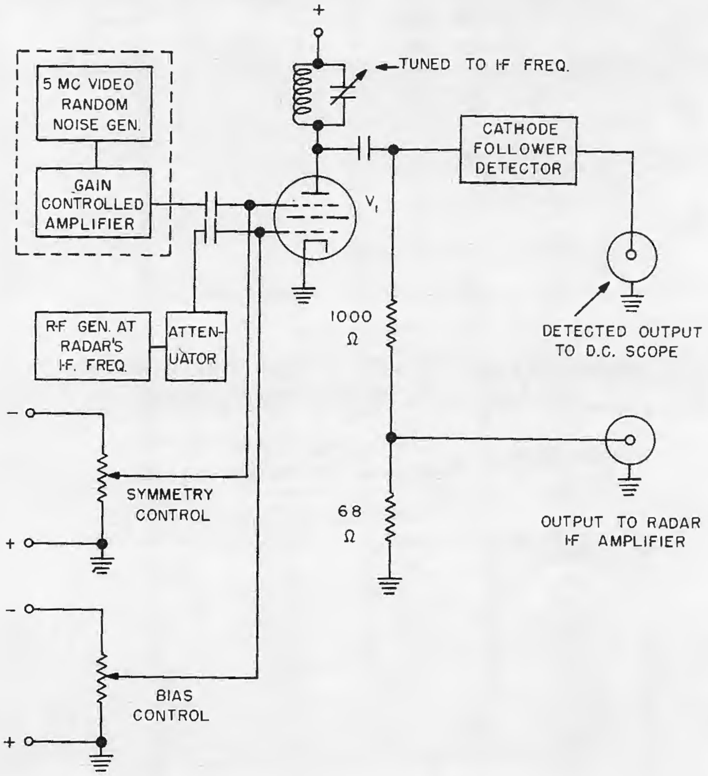

Fig. 2 - Jamming-signal test generator for i-f injection into the radar

TABLE 1
Vulnerability of a Mark 25 Type Fire-Control Radar to Amplitude-Modulated Jammers

Modulation Type	Jamming Factor (J/S) for Tracking Relay Release (db)	Jamming Factor (J/S) for Video Screening (db)
cw	-3.3	>13.7
1:1	1.0	>17
2:1	1.7	>15
4:1	4.0	>12

[redacted]

[redacted]

TABLE 2
Vulnerability of a Mark 35 Type Fire-Control Radar to Amplitude-Modulated Jammers

Modulation Type	Jamming Factor (J/S) for Break Track (db)	Jamming Factor (J/S) for Video Screening (db)
cw	23	>26
1:1	12	> 8.5
2:1	7	> 9
4:1	4	>13

TABLE 3
Vulnerability of an SU-2 Type Search Radar to Amplitude-Modulated Jammers

Modulation Type	Jamming Factor (J/S) for A-Scope Screening (db)	
	1-μsec Pulses	1/4-μsec Pulses
cw	34	23
1:1	21	18
2:1	20	13
4:1	15	10

Here the modulation type is given either as cw (unmodulated r-f) or as a ratio that expresses the degree of amplitude (e.g., voltage) dissymmetry as defined by

$$\text{Dissymmetry ratio} = E_{peak} - E_{av} \qquad E_{av} - E_{min}$$

where E_{peak}, E_{av}, and E_{min} are the peak, average, and minimum amplitudes of the modulated r-f. Only upward dissymmetry was investigated; that is, the peak amplitude was always at least

$$E_{peak} = 2\ E_{av}$$

and the minimum amplitude was essentially zero in all cases. This last equation then expresses the limiting condition of no dissymmetry (i.e., symmetrical modulation) where the ratio is 1:1 and also defines conventional 100-percent ampltiude modulation—the peak limits of many familiar types of transmitters and frequently the design objective for noise-modulated jammers. Hence, in a general sense the J/S factor for 1:1 symmetry is the value to be expected from many current jamming equipments.

For these tests the detected jamming signal was observed directly on the oscilloscope at the output of the cathode follower detector (Fig. 2) where the relative zero and peak excursions as well as the average amplitude could be observed and any adjustments to the test equipment evaluated.

[redacted]

[redacted]

Of outstanding interest is the wide variation in J/S for different combinations of the various radars and jamming types. The Mark 25 type, which is relatively easy to jam is more susceptible to cw than to noise-modulated r-f; conversely, the Mark 35 is considerably less vulnerable but is most susceptible to high peak-to-average noise-modulated signals. Except against highly unsymmetrical noise, the Mark 35 will track the pulse through jamming as well as can be done visually on the A-scope of the radar. Of the three types, the SU-2 radar, which has only visual search functions, was most invulnerable to jamming. Visual screening of the A-scope was considered that degree of clutter which obscured the pulse to the extent that its position if unknown could not be determined within three seconds. An increase in receiver gain was found to be an effective anticountermeasure on this radar. The pulse, which was normally jammed for a linear system, stood out more clearly as the receiver became saturated by the high-level jamming signal in the latter stages. To some extent Table 3 is misleading since the noise spectrum extended to 5 Mc, whereas the over-all video acceptance of the SU-2 receiver was of the order of 1.2 Mc. If the jamming spectrum were limited to the same extent, a probable decrease of 6 db in J/S would accrue. Since other studies of noise jamming were in progress (3), no attempt was made to further reduce this factor, especially since a general purpose jammer will provide a noise spectrum tailored to the demands of the short-pulse fire-control radars, which require wideband noise for optimum jamming.

Unsymmetrical noise, particularly modulation that has a dissymmetry of 2:1 (Tables 1, 2, and 3) is usually better and certainly never much worse than symmetrical noise. Too much optimism, however, is unwarranted as the factor J/S is based on a comparison of the peak pulse power with the average power; i. e., the peak jamming power must be greater than the average by 10 db (14 db in the case of 4:1 noise). For example, consider substitution of an equivalent 2:1 noise-modulated jammer for a 200-watt conventional jammer that has 100-percent peak symmetrical modulation. For argument's sake, assume that the new jammer can be designed for six db less power because J/S may be that much better for the particular service requirements; then its power is 50 watts but the peak power is 450 watts. For 4:1 noise the peak power is 25 times the average. Most of the currently available power sources are not capable of such extreme power excursions, and present TWT design requires constant beam current based on the peak power—a prohibitively severe requirement. With negative grid control of the TWT gun, the use of low average noise modulation becomes considerably more attractive, since modulation can then be applied via the beam and a reduced average current will result (21). Even more important, the r-f heating of the helix—which consitutes a serious problem as the frequency increases—is reduced.

The fact that the Mark 25 type radar is more susceptible to cw and high average power is not a valid argument against unsymmetrical modulation since (a) this radar is highly vulnerable to jamming and (b) the addition of peak detection in the radar's video circuits would probably provide operation equivalent to that of the Mark 35 type. The present Mark 25 video system amplifies the pulse directly from the detector output before applying it to the balanced gates in the range-gate discriminator. Hence, when a second r-f signal such as jamming is present, a beat note appears at the detector output for the pulse duration, and as a result, no polarity information is given to the range-gate discriminator. Conversely, the Mark 35 has an additional peak pulse detector following the video detector. This added circuit functions as a rectifier which eliminates the beat note and restores the original pulse form and is an effective antijam measure against high average power interference. Presumably, if a circuit of this type were combined with the Mark 25 it would give this radar anitjam qualities equivalent to those of the Mark 35 equipment. Thus, the more difficult problem should be considered for the jammer design since it would be unreasonable to assume that future radar designs would be less jam-proof than the best present designs.

[redacted]

DECLASSIFIED

[redacted]

EXAMPLES OF THE JAMMER PROBLEM

To illustrate the importance of the various factors to the jammer problem, it is necessary to analyze the jamming requirement for specific radar types. To simplify the problem, Eq. (6) will first be evaluated by letting the combined factors

$$k_t k_j k_n = 1.$$

It will then be possible to discuss the results in terms of deviation from this value.

Two radar types are considered for the extreme requirements—the high beam-power surface installation and the low beam-power airborne radar. For the surface radar assume that

$$P_t = 0.5 \times 10^6 \text{ watts peak pulse power}$$

$$G_t = 10{,}000$$

and for the airborne radar assume that

$$P_t = 0.01 \times 10^6 \text{ watts peak pulse power}$$

$$G_t = 100.$$

The former values are typical of radars such as the Mark 25 Mod 3, which is the high-power version of the Mod 2 type equipment, whereas the latter values are representative of the AN/APG-30 airborne ranging radar.

Then, assuming a medium bomber with a peak radar area (head-on) of 25 square yards, substitute the preceding values into Eq. (5) with the result that

$$P_j = \frac{2000 \times 10^6}{R^2}$$

for the high-power radar, and for the minimum requirement

$$P_j = \frac{0.4 \times 10^6}{R^2}$$

where the range, R , is in yards.

These values are given as a function of range in Table 4.

Until the proposed field studies shed more light on the combined factor $k_t k_n$ of Eq. (6), a fully valid analysis is impossible. It is of interest, however, to compare the results of an over-water study (11) made at CBA by this Laboratory. In this study the over-all factor, K , for screening a surface craft was measured at X-band. For this operation additional factors must be considered—especially that factor which defines the effect of surface reflection. It is not surprising that a comparison of the two types of operation shows them to be in disagreement on the value of a combined factor. Withrow found that

$$K = -3.1 \text{ db}$$

against the Mark 25 fire-control radar. Since the value of k_j (Table 1) is known, it is possible to deduce $k_t k_n$ for the surface operation as follows. The jamming transmitter was the AN/ALT-2 and it will be recalled that 100-percent modulation was not possible; hence, the value of k_j (Table 1) should be somewhere between the value for 1:1 symmetry

[redacted]

[redacted]

DECLASSIFIED

and that for cw, say probably about -1.0 db. For the over-water operation then,

$$k_t k_n \text{ (db)} = -3.1 - (-1.0) \approx -2 \text{ db.}$$

It should now be possible to apply this value to Table 4 which would give a general result for the over-water operation. A rational assumption would indicate the use of the most advantageous jamming signal against a radar that has the better antijam features, for example, 4:1 noise modulation against a Mark 35 type receiver. Factor k_j for this category is 4 db (Table 2). Recombining the three factors gives

$$k_t k_j k_n \text{ (db)} = -2 + 4 = 2 \text{ db}$$

or a power ratio of 1.5 times. This is the factor to be expected for over-water operation of a jammer of optimum design against a radar with good antijam features. In other words, this result indicates that the jammer power requirement for over-water operation is one and a half times greater than shown in Table 4 and that a well-designed 200-watt jammer is capable of operation against the well-designed high-power radar at ranges exceeding about 4000 yards.

TABLE 4
Jammer Power Requirement vs. Range
for $k_t k_j k_n = 1$

Range (yd)	Required Jammer Power (watts)	
	High-Power Surface Radar	Low-Power Airborne Radar
250		6.4
350		3.2
500		1.6
700		0.8
1,000	2,000	0.4
1,400	1,000	0.2
2,000	500	0.1
2,800	250	0.05
5,000	80	
7,000	40	
10,000	20	
14,000	10	
2,000	5	
28,000	2.5	
50,000	0.8	

Certainly, if for the airborne operation the factors are of the same order, the use of low-power devices such as traveling-wave tubes that have power output capabilities on the order of 20 watts is not to be encouraged. On the contrary, to show that this conclusion based on calculated values for an aircraft target is not confirmed in practice, select an actual example as follows:

P_t = 50×10^3 watts peak pulse power
G_t = 10,000
σ = 25 square yards (head-on aspect of medium bomber)
P_j = 150 watts
G_j = 5.

These values represent the airborne operation of the AN/ALT-2 against the Mark 25 Mod 2 radar. Hence, if the combined factor value for over-water surface operation (-3.1 db) were used, then Eq. (7) would yield

$$R = 800 \text{ yards.}$$

Airborne results, however, were much better; the jammer was fully effective at all ranges including directly overhead at 1000 feet even though the radar was at an additional advantage by virtue of being well below the jamming antenna's 60-degree beam and by the intensified pulse reflections from the underside aspect of the plane.

Further, when the airborne AN/APT-16 S-band jammer is used against the SG-3 search radar, the following values apply.

P_t = 0.4×10^6 watts peak pulse power
G_t = 1000
σ = 25 square yards
P_j = 200 watts of noise-modulated r-f
G_j = 5.

For over-water operation using a jammer on a surface target against a typical search radar it was found that

$$k_t k_j k_n = +3.0 \text{ db (2 times).}$$

Hence, from Eq. (7) the over-water results would indicate a crossover range of

$$R = 1300 \text{ yards}$$

but again the airborne jammer was fully effective at all ranges. Evidently, the combined translation and integration factor, $k_t k_n$ was considerably more favorable for the airborne jammer.

CONCLUSIONS

Space and weight requirements for naval airborne jamming equipments presently set a preferable output limit below 100 watts and certainly not over 200 watts. On the other hand, should it be necessary to protect propeller-driven aircraft to within a mile or so of the radar, then present design data indicate that the 100-watt level is insufficient to cope

[redacted]

with future high-power radars, especially if these radars have the better antijam features of some equipments presently available. In completely or almost completely automatic search and jam systems, the complexity of the circuitry has greatly increased the airborne jammer's auxiliary equipment until the further weight and space increase attendant upon maintaining presently accepted r-f power output levels is unacceptable. Power wise, increased jammer effectiveness is limited to the following approaches:

1. Increased modulation effectiveness

2. Increased antenna gain

It has been shown in this report that unsymmetrical noise modulation is better than conventional symmetrical modulation against radars that have good antijam designs. In the example, however, this function was maximized in favor of the jammer and no significant improvement is considered possible.

An increase in antenna gain offers some hope but also results in narrow beam propagation with a further increase in space and weight because of increased antenna size and the increased servo requirements for directing the beam accurately.

However, there is still the possibility that because the translation and integrating factors for the airborne operation favor the jammer rather than the radar, less stringent power requirements may exist. An operational field evaluation of the problem, such as outlined, is highly recommended. This Laboratory can conduct evaluation measurements within a limited scope, but it is felt that the coordinated efforts of the Navy Bureaus and the Operations Groups with the Laboratory are necessary to derive the full benefit from extended operational trials.

* * *

[redacted]

REFERENCES

1. Flight Evaluation Tests on Proj. No. EL 9129, NATC, Patuxent River, Maryland, January 27, 1953

2. Voisich, J., NATC, Patuxent River, Maryland, Proj. No. PTR EL 993, final report, March 20, 1952

3. Hollweck, F. H., "Noise Modulation Studies," NRL Report (to be published)

4. Fink, D. G., "Radar Engineering," (1st ed.), Ch. 4, p. 279, New York: McGraw-Hill, 1947

5. Ridenour, L. N., "Radar System Engineering," (1st ed.), Ch. 2, p. 41, New York:McGraw-Hill, 1947

6. Ringwalt, D. L., MacDonald, F. C., and Katzin, M., "Quantitative Measurements of Radar Echoes from Aircraft, I. B-36, B-45, F-51, and F-86," NRL Letter Report Serial C-3460-73A/50 (Confidential), October 24, 1950

7. Ringwalt, D. L., MacDonald, F. C., and Katzin, M., "Quantitative Measurements of Radar Echoes from Aircraft, II. Formation of Three F-86's, B-29, F-80 with Wing Tanks and F-80 without Wing Tanks," NRL Letter Report Serial C-3460-18A/51 (Confidential), February 12, 1951

8. McDonald, F. C., "Quantitative Measurements of Radar Echoes from Aircraft, III. B-36 Amplitude Distributions and Aspect Dependence," NRL Letter Report Serial C-3460-94A/51 (Confidential), June 19, 1951

9. Ament, W. S., MacDonald, F. C., and Passerini, H. J., "Quantitative Measurements of Radar Echoes from Aircraft, IV. F-86 Amplitude Distributions and Aspect Dependence," NRL Letter Report Serial C-3460-138A/51 (Confidential), September 5, 1951

10. Ament, W. S., Katzin, M., MacDonald, F. C., Passerini, H. J., and Watkins, P. L., "Quantitative Measurements of Radar Echoes from Aircraft, V. Correction of X-Band Values," NRL Letter Report Serial C-3460-132A/52 (Confidential), October 24, 1952

11. Ament, W. S., MacDonald, F. C., and Passerini, H. J., NRL Letter Report Serial C-3460-143A/52 (Confidential), December 15, 1952

12. Ament, W. S., and MacDonald, F. C., "Quantitative Measurements of Radar Echoes from Aircraft, VII. B-36 and F-86 Spectrums," NRL Memorandum Report No. 107 (Confidential), January 15, 1953

13. Ament, W. S., MacDonald, F. C., and Passerini, H. J., "Quantitative Measurements of Radar Echoes from Aircraft, VIII. B-45," NRL Memorandum Report No. 116 (Confidential), January 28, 1953

14. Ament, W. S., MacDonald, F. C., and Passerini, H. J., "Quantitative Measurements of Radar Echoes from Aircraft, IX. F-51," NRL Memorandum Report No. 127 (Confidential), March 4, 1953

15. Ament, W. S., MacDonald, F. C., and Passerini, H. J., "Quantitative Measurements of Radar Echoes from Aircraft, X. Three F-86 Aircraft in Formation," NRL Memorandum Report No. 144 (Confidential), April 6, 1953

16. Ament, W. S., MacDonald, F. C., and Passerini, H. J., "Quantitative Measurements of Radar Echoes from Aircraft, XI. B-29," NRL Memorandum Report No. 164 (Confidential), May 25, 1953

17. Ament, W. S., MacDonald, F. C., and Passerini, H. J., "Quantitative Measurements of Radar Echoes from Aircraft, XII. F-80," NRL Memorandum Report No. 221 (Confidential), October 19, 1953

18. Link, J. C. and Trautvetter, R. S., "A Method for Measuring Radar Reflective Qualities of Aerial Tow Targets," NRL Memorandum Report No. 406 (Confidential) Feb. 1, 1955

19. Ridenour, L. N., "Radar Systems Engineering," (1st ed.), Ch. 3, p. 76, New York:McGraw-Hill, 1947

20. Miller, B. W., NRL Report 4170, May 21, 1953

21. Cosby, L. A., "The Traveling-Wave Tube as an Amplitude-Modulated Amplifier for Countermeasures Applications," NRL Report 4262 (Confidential), December 18, 1953

22. Withrow, W. E., "Study of Power Requirements for X-band Jamming from Surface Vessels," NRL Report 4455 (Confidential), December 17, 1954

* * *

[redacted]

APPENDIX A
Radar Jamming of Pulse Echoes not at the Target Position

The problem of remote protection, i. e., the condition that the jammer is not at the target position, is handled in much the same manner as the problem of self-protection. The quantities P_t, G_t, σ, P_j, and G_j and the factors k_t, k_j, and k_n have already been defined for Eqs. (6) and (7) of the text. The range, R, however, is not the same for the radar as it is for the jammer. Hence, R in Eq. (3) becomes R_t, which is the radar-to-target range, whereas in Eq. (4) the range is expressed as R_j, which is the radar-to-jammer range. Combining as before, where

$$J = k_j S$$

leads to

$$P_j = \frac{P_t G_t \sigma R_j^2}{4\pi R_t^4 G_j} k_t k_j k_n . \tag{A1}$$

If it were feasible to always keep the target in line with the radar and the jammer, then Eq. (A1) would hold. But for the most part the jammer will not be in the radar beam, and as a result, the jammer power must increase by a factor A, which represents the attenuation between the radar antenna's main lobe and its least sidelobe gain. Hence,

$$P_j = \frac{A P_t G_t \sigma R_j^2}{4\pi R_t^4 G_j} k_t k_j k_n . \tag{A2}$$

Tables A1 and A2, which are an extension of Table 4 of the text show the jamming power requirements for both self-protection and remote protection as developed from Eq. (A2). Except for range and the factor A, the quantities are identical with those set up to calculate Table 4, and for comparison the results in that table are repeated in the columns under "self-protection." Table A1 shows the power required to jam high-power radars (surface type), whereas Table A2 indicates the requirement against low-power airborne radars. The main lobe to sidelobe ratio, A, is assumed to be 20 db.

Once again it should be emphasized that Tables A1 and A2 are based on the ideal equation and that in preparing them no consideration was made of the operational factors. However, even if these factors should prove to be favorable toward a reduction, the problem of remote protection would be extremely severe unless the reduction was of the order of 20 db or better—a rather unlikely possibility. Otherwise remote protection is apparently of value only when the jammer can be operated at ranges that are close, as compared to the target range, or where the jammer can be located in line with the radar and the target. In the latter case a condition 20 db more favorable exists for the jammer. In general, however, the jammer with high average power appears to have little application for this service. A deceptive jammer such as the high peak-power pulse repeater is recommended as the more suitable device from the standpoint of the power requirement.

[redacted]

[redacted]

TABLE A1
Jammer Power Requirement vs. Range for Operation Against High-Power Radar
$(k_t k_j k_n = 1)$

Target Range (yd)	Required Jammer Power (watts)								
	Self* Protection	Remote Protection							
		1000-yd jammer range	2000-yd jammer range	4000-yd jammer range	8000-yd jammer range	10,000-yd jammer range	20,000-yd jammer range	40,000-yd jammer range	50,000-yd jammer range
1000	2000	200×10^3	800×10^3	3.2×10^6	12×10^6	20×10^6	80×10^6	320×10^6	500×10^6
1400	1000	50×10^3	200×10^3	800×10^3	3.2×10^6	5×10^6	20×10^6	80×10^6	125×10^6
2000	500	12.5×10^3	50×10^3	200×10^3	800×10^3	1.25×10^6	5×10^6	20×10^6	31×10^6
2800	250	3×10^3	12.5×10^3	50×10^3	200×10^3	300×10^3	1.25×10^6	5×10^6	7.5×10^6
5000	80	320	1280	5000	20×10^3	32×10^3	128×10^3	500×10^3	800×10^3
7000	40	80	320	1280	5000	8000	32×10^3	128×10^3	200×10^3
10,000	20	20	80	320	1280	2000	8000	32×10^3	50×10^3
14,000	10	5	20	80	320	500	2000	8000	12.5×10^3
20,000	5	1.25	5	20	80	125	500	2000	3.1×10^3
28,000	2.5	0.3	1.25	5	20	30	125	500	750
50,000	0.8	0.032	0.128	0.5	2.0	3.2	12.8	50	80

*Jammer range = target range

[redacted]

[redacted]

TABLE A2

Jammer Power Requirement vs. Range for Operation Against Low-Power Radar

$(k_t k_j k_n = 1)$

Target Range (yd)	Required Jammer Power (watts)								
	Self* Protection	Remote Protection							
		500-yd jammer range	1000-yd jammer range	2000-yd jammer range	4000-yd jammer range	8000-yd jammer range	10,000-yd jammer range	20,000-yd jammer range	40,000-yd jammer range
250	6.4	2.5×10^3	10×10^3	40×10^3	0.16×10^6	0.64×10^6	1.0×10^6	4.0×10^6	16×10^6
350	3.2	640	2.5×10^3	10×10^3	40×10^3	16×10^6	0.25×10^6	1.0×10^6	4.0×10^6
500	1.6	160	640	2.5×10^3	10×10^3	40×10^3	64×10^3	0.25×10^6	1.0×10^6
700	0.8	40	160	640	2.5×10^3	10×10^3	16×10^3	64×10^3	0.25×10^6
1000	0.4	10	40	160	640	2.5×10^3	4×10^3	16×10^3	64×10^3
1400	0.2	2.5	10	40	160	640	1000	4×10^3	16×10^3
2000	0.1	0.64	2.5	10	40	160	250	1000	4×10^3
2800	0.05	0.16	0.64	2.5	10	40	64	250	1000

*Jammer range = target range

* * *

[redacted]