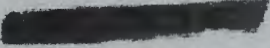


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CONTINUOUS LOOK-THRU AS APPLIED TO
AIRBORNE AUTOMATIC SEARCH AND JAM SYSTEMS
[UNCLASSIFIED TITLE]

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ABSTRACT

Two major functions are inherently involved in an automatic search and jam system - reception of enemy radiation and transmission of a jamming signal. It is highly desirable that these major functions occur simultaneously; however, to the present, all developments have relied on time-sharing techniques. With the presumed rapid development and improvement of the radar system, it becomes increasingly important to achieve "continuous look-thru," i.e., simultaneous surveillance for various enemy radiations and jamming those known to be present.

Techniques for obtaining continuous look-thru are being reinvestigated. Whereas in the past only certain parameters were controllable, present system capabilities yield several new freedoms. In terms of these newly considered variables such as controllable power output, cross-polarization and some already available techniques such as orientation and separation, a relationship is derived from which the necessary and sufficient isolation requirement can be predicted. In a typical long range case, for a 200-watt jammer in a medium bomber attempting to jam a typical tracking system, it is shown that by properly controlling the power output, isolation between reception and transmission antennas of only 50 db is required instead of a predicted requirement of greater than 70 db for noncontrolled power output case under the same conditions. Experimentally, it was found that this reduced value of isolation could be achieved at a separation of only about 6 wavelengths with conventional antennas. While this degree of isolation is sufficient for the case considered, it is shown that, theoretically, even greater isolation can be achieved by utilization of cross-polarization effects. This predicted capability would be important for larger targets or in cases where controlling the power output was not feasible.

It is concluded that three factors of great importance in achieving continuous look-thru are separation, controlled radiation power, and cross-polarization where applicable. By method of deduction and experimentation, it is shown that the conditions for continuous look-thru are achievable in the case of the airborne countermeasures system. A concentric antenna system is recommended for further development.

PROBLEM STATUS

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

AUTHORIZATION

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TO AIRBORNE AUTOMATIC SEARCH AND JAM SYSTEMS
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INTRODUCTION

An airborne automatic search and jam system necessarily involves two major functions - reception of enemy radiation and transmission of a jamming signal. Control functions, such as analysis and decision, are dependent upon successful accomplishment of the above major functions. Hence, in order to meet the above conditions at the jammer position, a means of constant surveillance of the frequency spectrum in the immediate vicinity of the radiated jamming frequency is required. Methods of obtaining this condition, i.e., isolation between the reception and transmission functions are generally described as "look-thru." Continuous look-thru, has proved to be difficult to accomplish since the transmission and reception signal levels may be vastly different and available separation is limited. Random, time-sharing look-thru has been used and has proved to be a somewhat successful expedient. This technique involves gating the transmitter off at random intervals, the gate period being of sufficient duration for the receiver to recover from saturation and yield the necessary information to the control networks, and to recommence appropriate jamming radiation from the transmitter.

Another technique for look-thru which has been tried experimentally is that of rf phase cancellation of the transmitter output at the receiver input (1). Here a balancing signal of the same frequency as the transmitter is required at the receiver input that has both amplitude equality and phase opposition to the transmitter output to a high degree of accuracy. The combination of this signal and the leakage signal should yield cancellation. Although it is apparent that such a technique could fulfill the system requirements, difficulty has been experienced in obtaining successful operation over wide frequency ranges under operational conditions.

With the advent of tunable pulse magnetrons and klystrons for radar applications, it has become necessary to obtain a more nearly continuous set of received data. Toward this end, it has been proposed by the British and others to use an improved look-thru of the time-sharing type, i.e., a more rapid yet shorter transmitter gate than that employed in the conventional longer duration slow repetition rate system (2) in early use at NRL. Although this new system would appear to yield a high pulse intercept probability and, further, a more continuous set of frequency change data, and although the jamming effectiveness would be equivalent to the conventional look-thru scheme for countering existing frequency-shift radar types, there is no assurance that this technique will be successful against the ultimate system utilizing higher rates of frequency change. In addition, means for keying the jamming transmitter in a manner suitable for this look-thru becomes quite complex and difficult to accomplish.

Certainly, continuous look-thru is the most desirable mode of operation. Hence, techniques for obtaining continuous look-thru are being reinvestigated, although many reports have been written which would tend to discourage this approach. The major impasse confronting system design based on continuous look-thru is the high order of isolation required between the reception and transmission channels. For instance, while radiating a jamming signal on the order of 200 watts, the receiver may have a required sensitivity of an order

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greater than 100 microwatts.* If the receiver is able to detect, and the system to operate, when the received signal is 6 db greater than the leakage from the transmitter, then the required isolation is of the order of 69 db in power. To achieve this isolation in a conventional fashion would require utmost care in locating the receiving and transmitting antenna equipment, and reliance on this possibility alone for airborne installations is not considered feasible.

There are, however, certain factors which are new to the basic problem of continuous look-thru such as controllable power output from the jammer, the ability to rapidly tune the jamming transmitter electronically and improved antennas. When integrated into the jamming system, these factors give rise to a new system problem which can be treated analytically in terms of measurable system parameters. From this analysis, it can be shown that continuous look-thru can be obtained successfully in the case of airborne jamming systems.

PROPAGATION CALCULATIONS FOR SELF-PROTECTION

The problem outlined that should be solved is the determination of the magnitude of the jammer leakage into the receiver. If the transmitter antenna is other than isotropic, there is theoretically no leakage into the receiver for the antenna orientation considered, i.e., both receiving and transmitting antennas axes parallel, their apertures in the same plane, and looking in the same direction. However, there is side lobe coupling between practical antennas and its computation is difficult, particularly in the absence of near zone radiation patterns.

The inverse problem, however, is more suitable to analytic means, i.e., it is easier to determine the required isolation for a given orientation from the operational conditions than to determine directly the anticipated leakage. Knowing the required isolation, then if by no other means, the available isolation can be determined experimentally.

Assume that a necessary and sufficient condition for system operation is that, at the receiver, the signal strength must be K_1 times the leakage from the transmitter. This condition may be denoted as

$$S_{rr} = K_1 S_{rx} \quad (1)$$

where S_{rr} is the peak power density of the radar pulse at the jammer receiver, and S_{rx} is the average power density of the jamming signal at the jammer receiver. In terms of the parameters of a typical radar such as the Mk 25 Mod 2, this pulse power density (3) is given in watts/m² by

$$S_{rr} = \frac{G_r P_r}{4 \pi r^2} \quad (2)$$

*The figures given correspond to the one of several typical 200-watt jammers with 6-db gain antenna, working against a typical fire-control radar such as the Mk 25 Mod 2 at a range of 20 nautical miles. Even greater isolation would be required at greater ranges.

where r is the range in meters from radar to target (jamming position in this case), G_r is the radar antenna gain, and P_r is the radar transmitter peak power output in watts. The power in watts received by the jamming receiver is

$$P_{rr} = S_{rr} A_r$$

where A_r is the cross section of the receiver antenna in square meters. In general, it is necessary to consider the relative polarization of the transmitting and receiving antennas. A polarization factor, $0 < f < 1$, can be defined to account for this condition, i.e., for plane polarization, where planes of polarization are parallel, $f = 1$, etc. A discussion of this factor is given later. Then in general,

$$P_{rr} = S_{rr} A_r f_1 \quad (3)$$

where f_1 is the relative polarization factor for the radar transmitter and the jammer receiver antennas.

The next problem which arises is the determination of the jamming power which must be radiated in order to successfully jam the radar in question. A conventional jamming transmitter, because of the nature of the magnetron power oscillator, is designed to radiate a fixed average power, and little effort has been devoted to controlling this power output because of the difficulties involved. Presently available power devices, such as the traveling-wave tube, klystron, or carcinotron, however, are provided with control elements suitable for controlling the power output and hence more thought can be given to the possibilities of controlled power output from the jammer. This ability will certainly contribute to the success of the proposed system because it would then be possible to specify a radiated power in terms of range and the system parameters, rather than an arbitrary maximum power as is now required.

In order to determine this power required to successfully jam the radar receiver, further use of the radar equation is made. At the radar receiver,

$$S'_{rr} = \frac{G_r P_r \sigma}{(4\pi)^2 r^4} \quad (4)$$

where σ is the cross section of the target in square meters and S'_{rr} is the peak power density in watts/m² of the radar echo at the radar receiver. The maximum average jamming power density at the radar receiver is

$$S'_{rx} = \frac{G_j P_j}{4 \pi r^2} \quad (5)$$

where P_j is the average jamming power radiated and G_j is the jammer antenna gain. In order to successfully jam the radar, S'_{rx} must be greater than S'_{rr} by a factor K_2 , called the screening factor, which is the maximum J/S ratio for either screening or breaking track as the case may be and is usually 0 to 14 db. Then

$$S'_{rx} = K_2 S'_{rr}$$

and from Eqs. (4) and (5),

$$S'_{rx} = \frac{G_j P_j}{4 \pi r^2} = K_2 S'_{rr} = \frac{K_2 G_r P_r \sigma}{(4\pi)^2 r^4} \quad (6)$$

or

$$P_j = \frac{K_2 G_r P_r \sigma}{4 \pi r^2 G_j} .$$

When the relative polarization between the jammer and the radar is considered, the jammer, which is at the target position, must radiate a power given by

$$P_j = \frac{K_2 G_r P_r \sigma f_2}{4 \pi r^2 G_j} \quad (7)$$

in which losses due to attenuation, etc., are neglected.*

At the same time, the jammer receiver receives a signal power given by Eq. (3) and the isolation required would be

$$\frac{P_j}{P_{rr}} = \frac{K_2 G_r P_r \sigma f_2}{S_{rr} A_r f_1} \quad (8)$$

Since the effective absorption cross section A_r of the jamming receiver in square meters is

$$A_r = \frac{G_{rr} \lambda^2}{4\pi} \quad (9)$$

where G_{rr} is the gain of the jammer antenna and λ is the signal wavelength in meters,

$$\frac{P_j}{P_{rr}} = \frac{\frac{K_2 G_r P_r \sigma f_2}{4 \pi r^2 G_j}}{\frac{G_r P_r G_{rr} \lambda^2 f_1}{4 \pi r^2}} = \frac{4 \pi \sigma}{\lambda^2 G_{rr} G_j} \frac{f_2}{f_1} K_2 . \quad (10)$$

Then from the requirement of Eq. (1), the required isolation between the transmitter and the receiver at the jamming position is

$$\frac{P_j}{P_{rx}} = \frac{4 \pi \sigma}{\lambda^2 G_{rr} G_j} \frac{f_2}{f_1} K_1 K_2 \quad (11)$$

*A discussion of these factors is given in NRL Report 4547, "Operational Factors Affecting the Radar Jamming Problem" (Confidential), by J. M. Miles.

where P_{rx} is the jammer signal power at the jammer receiver. It remains to be determined whether, under operational conditions, sufficient isolation can be obtained. For example, a typical radar, the Mk 25 Mod 2, has the following pertinent characteristics:

$$K_2 = 0 \text{ db}$$

$$\lambda = 3 \text{ cm}$$

$$f_1 = -3 \text{ db}$$

At the jammer position, the following conditions are assumed:

$$\sigma = 25 \text{ square meters (medium bomber)}$$

$$G_j = 6 \text{ db (circularly polarized)}$$

$$G_{rr} = 6 \text{ db (circularly polarized)}$$

$$K_1 = 6 \text{ db}$$

$$f_2 = -3 \text{ db}$$

From Eq. (11), the isolation required for this case is 8.7×10^4 or 49.5 db.

EFFECTS OF VARIABLE JAMMER POWER

A necessary condition assumed in this analysis is controlled transmitter power output. If power greater than that specified by Eq. (7) is radiated, then the required isolation is increased in the same ratio. The manner in which the power must vary in order for Eq. (10) to hold can be obtained directly from Eq. (7) and is

$$P_j = \frac{\rho}{r^2}; \quad (12)$$

i.e., the power radiated must vary inversely as the square of the range. If however, the available isolation is somewhat greater than that specified by Eq. (11), then the transmitter output can exceed the power given above by the ratio of the available to required isolation. This implies that a step function control characteristic* is applicable where the step amplitude is less than or equal to the excess isolation available.

It is important to have, at the jammer position, a mechanism which will control the radiated power in accordance with Eq. (12). Although it may be readily noted that the power varies inversely with the square of the range, usually this parameter is not known. A parameter which is available, however, is P_{rr} , the peak pulse power received at the jammer position from the radar. If Eq. (10) is rewritten with P_j as the dependent variable,

$$P_j = P_{rr} \frac{4 \pi \sigma}{\lambda^2 G_{rr} G_j} \frac{f_2}{F_1} K_2$$

*This technique was first suggested to the author by J. M. Miles.

a linear relationship is obtained between the required radiated power and the peak pulse power received from the radar. This is a very fortunate result in that many simple networks may be used to achieve this correspondence. In particular, a system can be visualized which operates directly from the pulse amplitude into a constant-gain amplifier, the gain being

$$G = \frac{4 \pi \sigma K_2 f_2}{G_j G_{rr} \lambda^2 f_1}$$

A very simple repeater would inherently have this characteristic; other systems might involve a regulation network operating from the received pulse amplitude.

By comparison of the figure arrived at from Eq. (11), where the jamming power is controlled, with that given earlier for the same operational problem (except that the jammer power radiated was held constant at 200 watts), it is readily seen that the required isolation is reduced from about 69 db to about 50 db at a range of 20 nautical miles. This reduction would be even greater at increased ranges.

EFFECTS OF ANTENNA POLARIZATION

Reference was made earlier to a polarization factor which must be considered when computing the field density available at a receiver from a radiator. No discussion was given at that time except that $0 < f < 1$. A rigorous treatment of elliptical wave propagation has been given by Kales and Bohnert (4), and a result in their paper of significance here is a general definition of this polarization factor in terms of system parameters and is given by*

$$f = \frac{(1+r_i^2)(1+r_t^2) \pm 4r_i r_t + (1-r_i^2)(1-r_t^2) \cos 2x}{2(1+r_i^2)(1+r_t^2)} \quad (13)$$

in which r_t is the elliptical axial ratio of the transmitting radiator ($r_t \geq 1$), r_i is the elliptical axial ratio of the resolver ($r_i \geq 1$) and x is the relative angle between the orientations of the major axes of the elliptical radiator and resolver. The quantity $4r_i r_t$ is either positive or negative depending on whether the fields have the same or opposite senses of polarization. The polarization factor f is then the ratio of the power received from an incident field in a given state of polarization to the power received when the polarization of the incident field is adjusted for maximum received power, the intercepted energy and the power density of the incident field being held constant (4).

Several interesting results may be observed from Eq. (13). If $r_i = r_t = 1$ and $4r_i r_t$ is negative as would be the case for conjugate circularly polarized antennas, then the coupling is zero. Likewise, the coupling between the circularly polarized and a plane-polarized system is $1/2$. Similar results for certain relative angular orientations for elliptic radiators and receivers also exist.

A transmission and reception system based on this relationship, if the conditions could be established, could yield a system capable of continuous look-thru. The arrangement of interest here is a pair of cross-polarized or conjugate antennas for the jammer receiver and transmitter. Under this condition, the isolation between the receiver and the transmitter should be infinite and the coupling to or from a plane-polarized radar would be $1/2$. There

*Note error in equation of Ref. 4 which has been corrected here.

is one case where the radar is cross-circularly polarized to the jammer and may theoretically yield evasion, however, there is considerable evidence that this possibility may be negated.

Exploratory investigation has indicated that the field of a typical circularly polarized radiator in the region where the receiver would be placed is not circular, but is quite elliptic. For one orientation of interest where the apertures are in the same plane and the antenna axes parallel, theory prohibits a circular field at the aperture of the receiver, as a result of a circularly polarized field radiated from the transmitter. This was readily verified by experiment.

For this orientation, which would be desirable operationally, it is quite evident that cross-polarization effects will not be applicable. There is one case, however, where the analysis could be useful in which the radiator chosen is circularly polarized, and the two receiver antennas, which are plane polarized, are orientated as in Fig. 1.* The relative orientation of the receivers is such as to be crossed to the field from the radiator at that position. This implies that evidently the plane-polarized antennas are cross-polarized, but more important the plane-polarized antennas have no coupling to the radiator. An array of this type, while involving three antennas, and some phasing problems, should be capable of at least about 40-db isolation due to cross-polarization. Since the isolations due to cross-polarization and separation are additive, then large values of isolation should be readily achieved.

An orientation of interest, as far as cross-circularly polarized antennas are concerned, is that shown in Fig. 2. Here the axes of the antennas are perpendicular and the apertures lie tangent to a circle drawn from the intersection of the axes. For this orientation, the field from one radiator at the aperture of the other can, theoretically be made circular, although practically speaking, this did not appear to be so, as far as existing antennas are concerned. This particular orientation is believed to have application in the case of high altitude targets against land installations such as beam-riding missiles or anti-aircraft fire control systems (5).

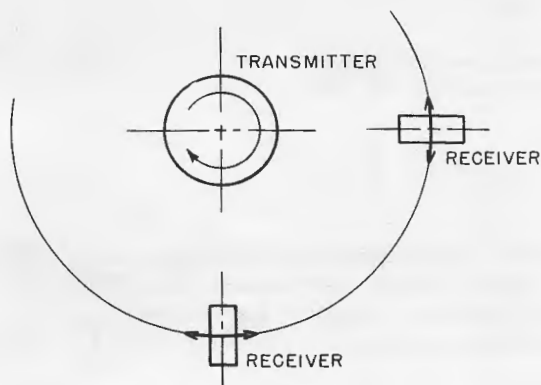


Fig. 1 - Orientation of a circularly polarized and two plane-polarized antennas capable of isolation because of cross-polarization

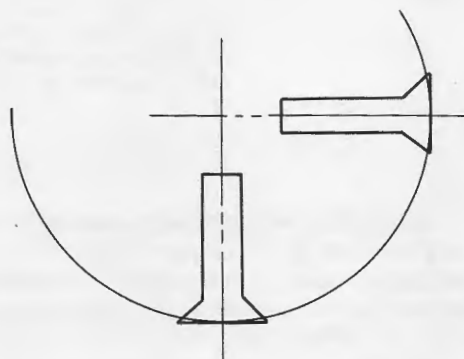


Fig. 2 - Orientation of two cross-circularly polarized antennas capable of isolation because of cross-polarization

*This particular orientation was suggested to the author by J. M. Miles.

Another orientation which might be feasible is concentric cross-circularly polarized receiving and transmission antennas. While no applicable antennas are available, it is apparent that if such antennas could be constructed, the field due to one should be circular at the aperture of the other, and hence a high degree of isolation due to cross-polarization could be established.

EXPERIMENTAL DETERMINATION OF AVAILABLE ISOLATION

Since it is difficult to calculate the leakage from the transmitter antenna into the receiver antenna, an experimental measurement was made over a 2:1 bandwidth for two AS-259/AP circularly polarized antennas mounted on a ground plane 6 by 4 feet. The centers of the axes of the antennas were separated from each edge and from each other by 2 feet. The results using this pair of typical antennas (Fig. 3) show that the isolation varied from about 55 db at the low frequency end of the band to about 70 db at the upper end of the band. Similar tests to those at S-band were conducted at X-band using two AT-242/AL circularly polarized antennas (5). At the spot frequency chosen, comparable isolations were obtained at the same electrical length of separation, i.e., at approximately 7 in. at X-band (6λ), the isolation was comparable with that at 24 in. at S-band (6λ) as may be seen from Figs. 3 and 4. It may be deduced that the isolation is directly proportional to the electrical length of the separation path. The data taken agrees with that reported recently by Federal Telecommunications Laboratories (6).

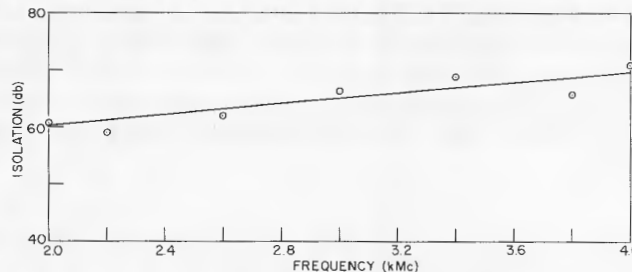


Fig. 3 - Isolation between two circularly polarized S-band antennas on the same ground plane at a separation of 24 in.

While the isolation obtained in this experiment is marginal for the case assumed, i.e., a minimum of 55 db available with a requirement of 50 db, greater values of isolation are certainly available by greater separation and by a judicious location of the antenna, such that the physical orientation materially improves the situation.

No data were taken for the normal axis case, since for the antennas available it was found that the ellipticity of the off-axis field was considerable (> 10 db) and it was apparent that much antenna design work would have to be accomplished before such an arrangement could be successfully tested.

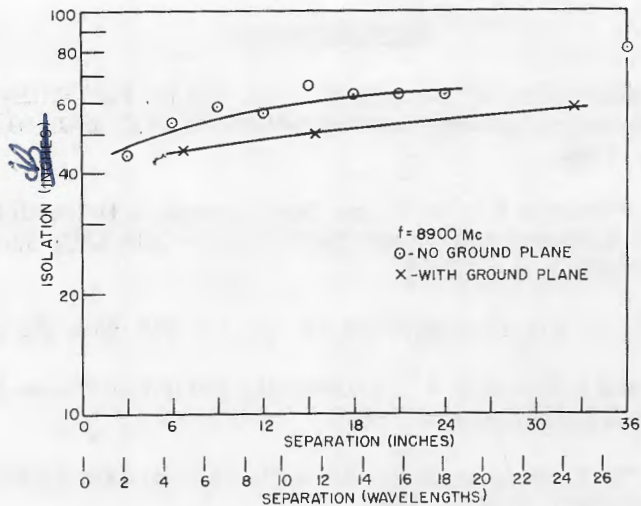


Fig. 4 - Isolation between two circularly polarized X-band antennas at varying separations

CONCLUSIONS

An airborne jamming antenna system based on the requirements set forth in this report appears to be capable of continuous look-thru. Three factors are believed to be of great importance: separation, controlled radiation power, and cross-polarization where applicable. Where an array of three antennas is permissible, it is believed that isolations greater than 95 db can be achieved, but a system based on isolation by separation and controlled radiation is believed sufficient for the proposed application.

An antenna design problem directed toward producing a coaxial cross-circularly polarized array would appear feasible from a system point of view. If the isolation problem, as well as pattern requirements could be met, this would appear to be an attractive objective, and would yield a compact installation.

Application of the analysis to other systems such as repeaters and transponders would follow directly, and as a matter of fact, the controlled power output problem would be solved directly, in the case of a repeater, if the system could be visualized as a constant gain device, i.e., independent of range.

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