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COUNTERMEASURES AND ANTIJAM CONSIDERATIONS FOR AIRBORNE INTERCEPT RADARS

[UNCLASSIFIED TITLE]

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ABSTRACT

An investigation is being conducted at NRL to determine the susceptibility and vulnerability to both intentional and environmental countermeasures of the various links of the overall air-to-air missile system loop. Information space links of the overall system loop include those used by CIC search radar, communications, IFF, airborne intercept radar, missile guidance, and warhead fuze. The study program has been divided into three phases: (1) Countermeasures and Antijam Considerations for Air-to-Air Weapon Systems, (2) Countermeasures and Antijam Considerations for Airborne Intercept Radars, and (3) Countermeasures and Antijam Considerations for Air-to-Air Missile Guidance Systems.

This report is on phase 2. The overall weapon system study has indicated that the AI radar is not the most vulnerable of the several links in the system loop. Current AI radars, however, leave much to be desired in regard to performance in their natural environment, as well as in the presence of deliberate jamming. Primary emphasis has been placed upon analyses to disclose these weaknesses. Most of the recommendations made to alleviate these weaknesses should result in improvement of AI radar performance in the natural environment, with incidental improvement in the presence of intentional jamming.

PROBLEM STATUS

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

AUTHORIZATION

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COUNTERMEASURES AND ANTIJAM CONSIDERATIONS
FOR AIRBORNE INTERCEPT RADARS
[Unclassified Title]

INTRODUCTION

The Naval Research Laboratory was requested to investigate the countermeasures (CM) vulnerability of current Navy airborne weapon systems. This report details work undertaken as a part of the overall study and relates to the vulnerability of current Navy AI (airborne intercept) radars. In this report, current AI radar susceptibility to CM is explored with the objective of establishing design criteria and specific modifications leading to systems which are more secure. The AN/APQ-50 radar is used as the primary example in this study because it is representative of the Navy's operational equipment which will be used in the AI radar field during the early phases of the time era considered. It is realized that the design philosophy in the AI radar field has been undergoing rapid changes. Moreover, this particular radar design appears to be approaching the point where it is of extreme importance to optimize its performance in its natural environment in order to obtain the theoretical performance latent in the basic radar concept.

This report is the result of cooperation between BuAer, the equipment contractors, and NRL. The contractors have been kept informed of the proceedings and findings of this study and are in general agreement. In fact, during the study an effort was made to have a continual exchange of information in order that AJ modifications could be implemented in advance of this published report. Some contractors already have programs directed toward incorporation of many of the AJ modifications recommended here.

The AI radar, when used operationally, becomes an element of the system loop of Fig. 1. Each space-link of this loop is susceptible to jamming and will remain so despite incorporation of AJ features. The terms susceptibility and vulnerability used in jam-antijam discussion are defined for the purposes of this report as follows. Susceptibility is the resulting degradation on an isolated element of a system when extraneous signals are introduced, and results from the design concept. Vulnerability is the system weakness and results from a comparison of the susceptibilities of the various elements composing the system. The term "system" in these definitions is not restricted to mean only the overall weapon system. For this report it will generally mean the complete airborne fire control equipment. Entry of CM into AI radars is made through their space-intelligence links. The resultant degree of degradation is a function of the jammer's ability, first, to enter the system with spurious energy and, second, his skill in tailoring this energy to maximize the error of the generated fire-control information. The objectives of AJ design are, thus, to make entry difficult and the system response as insensitive to extraneous signals as is practicable. Since it is possible to jam any electronic space-intelligence link, these objectives cannot be completely achieved and become less important as their attainment results in increased complexity.

The CM designer considers that he is involved in a tactical game. His strategy calls for continuous analysis of weapon system vulnerability as the premise for specifying requirements for effective jamming devices. Thus CM equipment development should be guided by weapon system characteristics and trends. The expression "for every measure there is a countermeasure" is valid, though not necessarily economic.

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It can be argued that enemy CM activity will be the primary deterrent to high system kill probability. When viewed statistically, however, this argument is false because natural environmental noise has a high probability of occurring on every mission, whereas effective enemy CM has a low probability of being encountered.

COUNTERMEASURES THREAT TO AIRBORNE INTERCEPT RADARS

Technological advance is resulting in weapon systems which are increasingly dependent upon electromagnetic information links. As this dependence grows, and as jamming techniques improve, the potential of CM to degrade or destroy air-to-air weapon system effectiveness is correspondingly increased. Department of Defense activity in the CM and AJ fields has recently been stimulated for this reason. Certain new techniques and devices appear to permit fundamental advances in jamming effectiveness. Traveling-wave tubes, carcinotrons, and backward-wave oscillator tubes, for example, have opened new horizons for the jammer. Rapid and automatic methods for signal detection, analysis, and jamming will materially reduce demands upon the human operator of jamming equipment. Countermeasures currently pose a real threat to the security of existing and developmental weapon control systems and constitute an important challenge to designers of such systems to make equivalent advances toward improvement in system security.

Intelligence information concerning the CM capability of the potential enemy is very limited. For this reason, this study assumes that the enemy has the same CM potential as the United States. The following estimate of the CM threat is based upon numerous discussions with CM personnel. In support of the opinions expressed, the appendix is a detailed description of the threat as seen by an expert in the CM field.

SHORT-TERM THREAT (2 to 3 YEARS)

The jamming techniques which will be used against AI radar in the short-term era (2 to 3 years) are of the brute force variety. Methods to be expected are chaff, spot frequency jamming, barrage jamming, and slow sweep frequency jamming. Equipment development at X-band in the electronic CM field has lagged development in lower frequency bands. However, there are X-band spot frequency and sweep frequency jammers with low tuning rates which can be employed. Modification of existing S-band jammers by changing the rf head to allow operation at X-band is underway.

LONG-TERM THREAT (3 to 5 YEARS)

The advent of new techniques and devices, including the traveling-wave tube, have made predictable the long-term development (3 to 5 years) of wide-open repeat-back systems, fast-tuning spot frequency jammers, and rapid-scan sweep jammers. Equipments are currently available in limited quantities having little delay between signal interception and the transmission of a jamming signal. Developmental techniques, along with contemporary chaff and barrage, sweep, and spot jammers, will make the AI radar AJ problem a difficult one.

In the deception field, large-scale developmental effort is underway. One deceptive technique which probably will be employed against the AI radar uses a wide-open receiver and a repeat-back system. By appropriate pulse delays, the enemy will attempt to pull the range gate off the target, thus causing loss of lock. A second deceptive technique to be

used is that of angle pull-off. Here several types of systems will be employed. One system uses a wide-open receiver. The scan modulation will be detected, changed in phase, amplified, and repeated back, causing angle pull-off and eventual loss of angle tracking. Another system also employs a wide-open repeat-back system, but the output signal will be modulated at or near the lobing frequency of the radar. One other system (code name "Crosseye") utilizes a wide-open receiver, a traveling-wave-tube amplifier, and simple circuitry to distort the received rf signal phase front. This has the effect of making the target appear at a different azimuth or elevation angle than the true angle. This system will be effective against monopulse and search radar as well as conically scanning radar.

DESIGN REQUIREMENTS FOR AI WEAPON CONTROL SYSTEMS

In the design of a weapon system, many parameters must be considered. Some of these quantities are under the control of the system designer. Other quantities are beyond the control of the designer, and in most cases design must be predicated on educated guesses as to the state of the art in the time era in which tactical use of the weapon system is expected.

The following sections list the quantities of interest to the designer of the system. It will be shown later how well the design has been accomplished in the case of a typical AI radar equipment.

SYSTEM INPUTS NOT UNDER THE CONTROL OF THE DESIGNER

The quantities not under the control of the designer are propagation conditions, the airframe to house the equipment, the types of targets to be expected, and CM to be encountered.

Propagation Conditions

Propagation conditions include weather effects, ground clutter, and sea return. These inputs help determine the choice of radio frequency, power output, pulse-repetition frequency, pulse width, antenna size, beamwidth, beam shape, and circuit complexity.

Housing

It is unfortunate that the parameters connected with the airframe which houses the radar equipment are at present not under the control of the designer. Ideally those quantities of an aircraft which involve fire control and weapons handling, stowage, and launching should be under the control of the weapon system designer. In the usual situation, however, the development of the radar and airframe proceed concurrently; but the airframe has been specified much earlier than the rest of the weapon system and has been considered as an independent design problem. The radar system designer is left with very meager information as to vibrational and shock inputs, cockpit integration, conditions of ambient light, airframe response characteristics, and structural compliance of the airframe.

Types of Targets

Some insight concerning the types of targets to be expected can be obtained from intelligence reports and the assumption that the technical progress of the potential enemy will match our progress. Other factors not directly under the control of the designer include such items as target speed, target maneuvers, altitude advantage, and interceptor position with respect to the target at time of detection. The last two items are a direct function of the accuracy of the ground controlled intercept system. Such items appear in the radar design problem as quantities connected with search scan patterns, search and track ranges, angle and range tracking bandwidths, and display presentations.

Countermeasures

The designer can assume that the CM to be encountered will approximate those in use by our own forces and friendly allies. By judicious use of intelligence reports and the above assumption, the designer can include in the radar design the necessary features to minimize the effects of these CM.

SYSTEM INPUTS UNDER THE CONTROL OF THE DESIGNER

System inputs under the control of the designer fall into two general classes: those for search mode of operation and those for track mode of operation.

Pertinent Parameters Related to Search Operation

In the search mode of operation the design requirements of the pertinent parameters are as follows.

1. Peak power - to be maximum, consistent with the space, weight, and magnetron limitations.
2. Radio frequency - to be compatible with magnetron availability, performance in weather environment, and antenna size.
3. Pulse-repetition rate - to be optimized for number of hits per scan (target illumination consistent with optimum volume of search) and minimization of second-time-around echoes (STAE).
4. Pulse width - to be the maximum consistent with the available magnetron duty cycle.
5. Beamwidth - to be compatible with the required detection, acquisition, tracking resolution, and size vs frequency requirements. In general the antenna requirements will be determined almost entirely by the tracking problem. The antenna pattern as applied to search operation will be a compromise with the pattern used for track operation. The ideal method of design would be to optimize the patterns for search and for track conditions. This, however, leads to very complicated and usually impractical mechanical and rf designs.
6. Antenna gain (one way) - to be compatible with the beamwidth selected, and consistent with high aperture efficiency.
7. Scan pattern - to provide a sufficient number of looks per scan to insure a high probability of detection and to provide an optimum volume to be searched as dependent upon tactics and CIC (combat information center) capabilities.

8. I-F bandwidth - to obtain best possible signal-to-noise (S/N) ratio consistent with AFC (automatic frequency control) design problems (bandwidth should be an optimum compromise for both search and track operation).
9. Search presentation - to supply all needed information to pilot operator in the clearest and most usable forms.
10. Bandwidths of search angle loops and stabilization loops - to be consistent with search scan pattern, manual search requirements, and the expected inputs from own ship's motion.
11. Weight and size - currently specified by the airframe. This area of system design needs improvement. The aircraft and the electronic portions of the system are in fact parts of a weapon system. Weight and size of system components is a subject for mutual compromise between elements.

Pertinent Parameters Related to Track Operation

The preceding statements concerning weight and size also apply to the track mode of operation. Peak power and the choice of radio frequency will be the same in track operation as in search operation, because these are not important parameters in the solution of the tracking problem, and thus a design simplification results. The design requirements of the other pertinent parameters are as follows:

1. Pulse-repetition rate - to provide an adequate information rate, be compatible with the track ranges selected, and at the same time achieve optimum average power from the magnetron, consistent with the pulse width chosen.
2. Pulse width - to be chosen for optimum average power output from the magnetron (considering repetition rate and the range desired) and to provide adequate range discrimination.
3. Lobing frequency - to be chosen so that the frequency lies in the area of least target return noise. The design should also be predicated on the problems attendant to the design of rotating machinery. The band of least target noise occurs at approximately 20 to 40 cycles per second (1,2). An additional point in the selection of the lobing frequency concerns the AGC (automatic gain control) design.
4. Beamwidth and antenna gain - to be consistent with frequency and antenna size. Beamwidth should also be consistent with optimum angle discrimination and the error characteristics of the nutating field pattern.
5. Antenna pattern crossover point - should be 1.5 db (one way) (3).
6. Antenna polarization - should be chosen so as to optimize S/N. At the present state of the art, vertical polarization seems to be the preferred type. The use of vertical polarization results in reduced effects from ground and sea return, but only limited improvement over horizontal polarization under certain weather conditions. Circular polarization, where the circularity of the radiated field is of high quality will result in some advantage under adverse weather conditions. Although it is easy to generate high-quality circular polarization in a waveguide, it is very difficult to radiate a high-quality circularly polarized field through a practical antenna and radome.

7. I-F bandwidth - to obtain best S/N consistent with pulse width chosen, magnetron pulling factor, and AFC design.
8. Track presentation on pilots indicator - to be one which is flyable under all conditions of combat and ambient light.
9. Angle, range, and stabilization bandwidths - to be consistent with expected target maneuvers, so as to guarantee a specified probability of kill. This probability must take into account such items as radar and computer errors and ballistic errors. In other words, a logical assignment of portions of total system error is necessary to specify tactically usable values for the various system bandwidths.

CURRENT STATUS OF AI RADARS

The AI radar is a necessary link in the overall system loop. Vectoring inaccuracies of CIC are such that the chance of intercept without an airborne fire control system is remote. As the speed and altitude capability of the interceptor and target increases, the probability of successful intercept without the airborne fire control system becomes even lower. This study will concern itself primarily with all-weather fire control systems. Many of the findings, however, apply equally well to the radars used in conjunction with optical systems. In the analysis of current AI radars, the AN/APQ-50 will be used as the primary example of a system which will be operational during the short-term period indicated. This radar is intended for widespread Navy use.

Radars of the AN/APQ-50 vintage represent a major advance in the airborne fire control field over those that were available in the past. The advance was accomplished through attention to details. The major problem was to modify an inadequate radar in the shortest time possible using as much of the original radar as practicable. A major improvement was made in detection and lock-on capability in the presence of many forms of CM such as clutter, altitude line, and chaff. A usable airborne intercept radar has resulted from one which previously was inadequate for the fire-control-problem solutions required.

Full utilization, however, has not yet been made of potential capability. The system can be further optimized for better performance in the presence of CM of both the intentional and environmental types. Such an improvement program is currently underway. Continuous exchange of information between the contractor and NRL has occurred throughout this study. Such exchange between development and application activities is desirable because, if successful, it will lead to a more suitable system.

FUNCTIONAL DESCRIPTION OF A TYPICAL AIRBORNE FIRE CONTROL

The AN/APQ-50 is used as the typical airborne fire control radar in this report. Radars of almost identical design as this typical example (AN/APQ-72 and AN/APQ-74) will be used in missile systems. Because of unrealistic time scheduling these radars may have subtle differences in design from that of the model system which will make them more susceptible to CM, both environmental and intentional. This model system will be used as an example of the state of the art in AI radars throughout this study because of its advanced design and the fact that the AN/APQ-72 and AN/APQ-74 radars could easily incorporate its improvements.

Figure 2 is a block diagram for the search and track modes of a typical A1 radar. A system using this radar would have the following capabilities.

1. Detection and evaluation of targets
2. Acquisition and automatic tracking of targets
3. Automatic computation of lead angles
4. Presentation to pilot of steering information
5. Subsidiary operations for safety and support of overall operation.

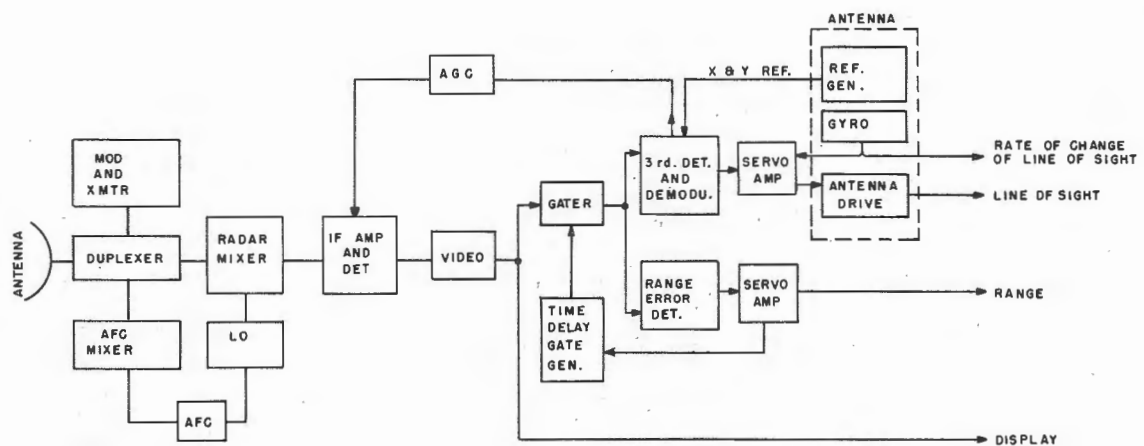


Fig. 2 - Typical AI radar

The following is a description of the displays seen by the pilot-operator.

B-Scope Search Display

During the search mode the pilot's indicator, shown in Fig. 3 (4), displays a continuously scanned sector in accordance with the scan pattern of the antenna. Vertical distance measured from the base is proportional to range. Horizontal distance on each side of the center line of the scope is proportional to the azimuth position of the target with respect to the longitudinal axis of the aircraft projected in a plane parallel to the earth's surface.

Two lines, one at the top and the other along the right side of the B-scope presentation indicate the azimuth and elevation position that the antenna will assume when the acquisition sequence is initiated. A line to indicate the attitude of the horizon relative to the aircraft in roll and pitch is superimposed on the B-scope presentation. The line is 2-3/4 inches in length with a blanked center of one inch.

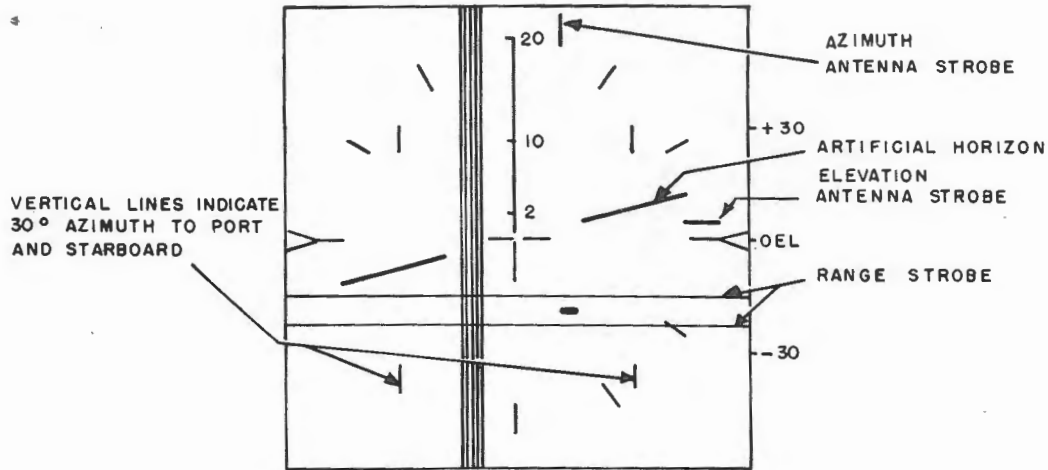


Fig. 3 - Typical search presentation

Track Display Information

The B-scope presentation in the track mode, shown in Fig. 4 (4), is fixed in azimuth at the antenna tracking position. The normal azimuth sweep is replaced by the lobing generator voltage. Steering information, in azimuth and elevation, is presented in the form of a circle (1/4-inch diameter) and a dot. The circle sensitivity is 20° per inch, and the dot sensitivity is 5° per inch.

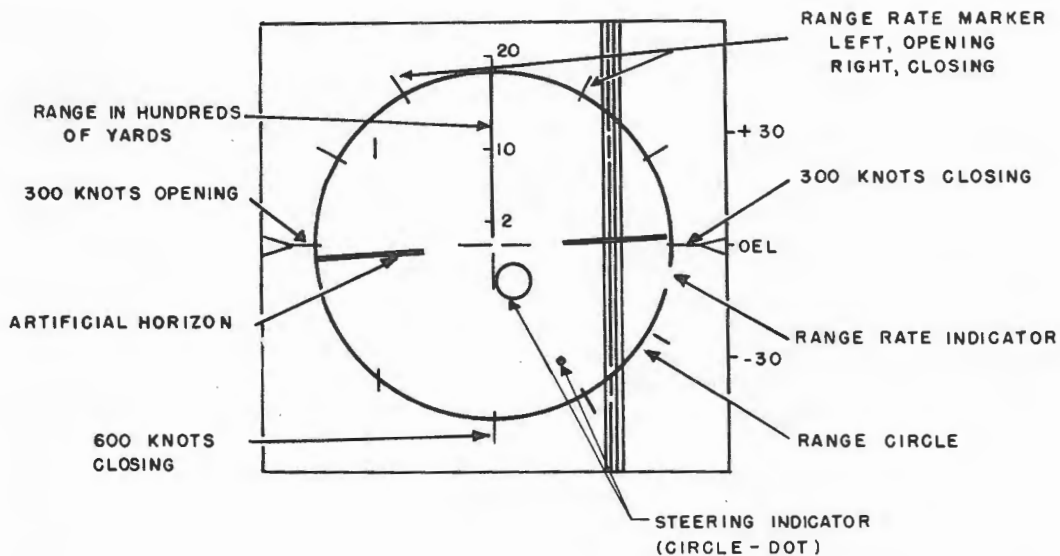


Fig. 4 - Typical attack presentation

Range to the target is indicated by the diameter of a range circle. The diameter for ranges over 2000 yards is 3-1/4 inches, and decreases linearly to a 5/16-inch diameter for a range of 200 yards. Accuracy of the displayed range is ± 75 yards.

Range rate information is indicated by a 1/4-inch break in the range circle. Zero rate occurs at the 12-o'clock position. Opening rates are presented in a counterclockwise direction to a maximum of 300 knots at the 9-o'clock position. Closing rates are presented in a clockwise direction to a maximum of 600 knots at the 6-o'clock position. The artificial horizon presentation is the same as in search. The following signal lights are provided:

1. Range - 12, 24, 100, and 200 mile ranges
2. Breakaway
3. Low altitude warning
4. In Range - for missile or rocket firing
5. "P" - computer in lead pursuit mode
6. "C" - computer in lead collision mode.

Tactical usage of the AI radar involves three modes of operation. The first mode is that of detecting the target. The second mode of operation is that of target acquisition. In this mode the pilot brackets the target with a pair of range strobes spaced one mile apart. This one-mile range interval is automatically scanned by an acquisition gate. When this sweeping gate coincides with the target, lock-on occurs. The third mode of operation is that of tracking. In this mode the pilot flies the circle and dot to the center of the scope. These modes of operation are important from the CM aspect. This will be discussed in more detail in subsequent sections.

A résumé of the time sequence of typical AI radar operation follows. Assuming the radar system has been operating in the search mode and a target has been detected, lock-on is then attempted. The tracking gate in acquiring the target will require approximately one second, if lock-on occurs on the first pass of the tracking gate over the target. The time required for the system to achieve complete lock-on (including the time above) is approximately three seconds. This assumes zero pilot reaction time. The 3-second sequence from search to track occurs in the following manner: phase I, search; phase II, the first phase of the lock-on sequence, persists for 25 milliseconds after the nominal one-second strobe sweep time; phase III, the second phase of the lock-on sequence, persists for two seconds. The radar at the end of this three seconds is in phase IV, a full automatic track mode (5). The average time from detection to lock-on is under ten seconds. This figure is the result of the average of numerous flight tests (6). The settling time for typical complete systems including airframe, pilot, radar, and computer is approximately 14 seconds. Thus the total time required between detection and weapon launch is a minimum of 27 seconds.

Figure 5 gives typical attack zones for missiles of the Sparrow III type (7). The upper half of this figure gives the attack zone for 30,000 feet altitude and the lower half for 5000 feet altitude. The target is of B-47 size. The interceptor velocity is Mach 1.2 and the speed ratio between target and interceptor is approximately 0.9. In the figure R_D is the range of the AI radar at which 90% probability of detection occurs derived from available test data of the AN/APQ-50 radar, R_p represents the range at the end of 27 seconds preparation time, R_{max} and R_{min} are the aerodynamic ranges for the missile based upon

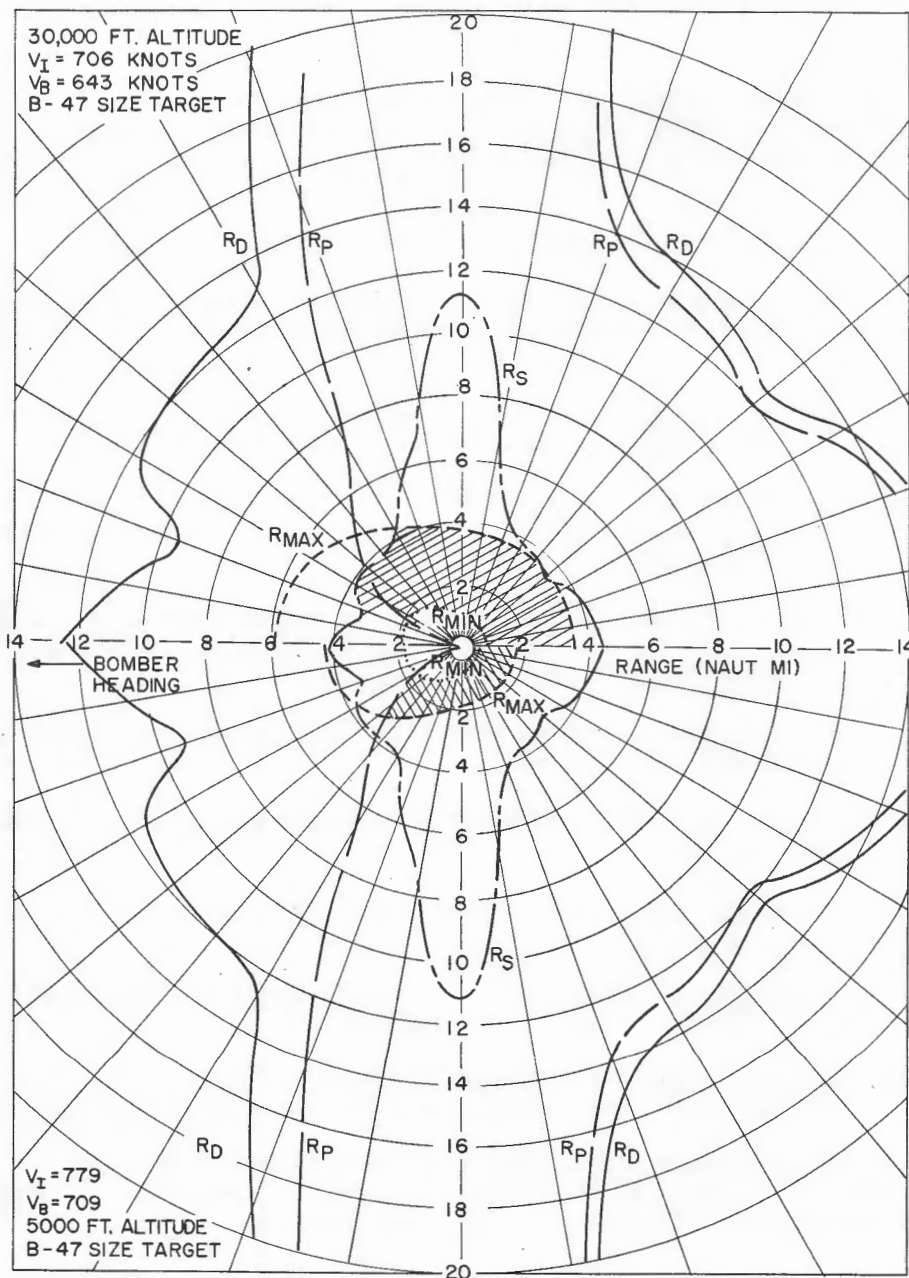


Fig. 5 - Typical attack zones for Sparrow III

equations supplied by the contractor, and R_S is the seeker range capability based upon service tests. These attack zones are based upon pure collision courses and represent the maximum capability of the system. These zones will be further degraded by maneuver requirements, g limits, vectoring inaccuracies, pilot errors, and both environmental and intentional CM.

TYPICAL AI RADAR PARAMETERS

The typical AI radar is comprised of the antenna, transmitting, receiving, range tracking, angle tracking, and presentation subsystems. The following sections list the pertinent parameters associated with each of these subsystems.

Antenna Subsystem

The parameters associated with the antenna subsystem are the rf characteristics, the scan pattern used for each mode of operation, and the frequency at which the rf field is nutated.

Search Scan Pattern - In the search mode of operation either a wide scan or a narrow scan pattern can be used. In addition, the pilot can use search manual.

Wide Scan - In wide scan the center line of the antenna beam scans a region $100^{\circ} \times 6^{\circ}$ in 2 seconds. This scan is symmetrical about 0° azimuth. The center of the scan can be positioned through $\pm 30^{\circ}$ in elevation.

Narrow Scan - In narrow scan the center line of the antenna beam scans a region $30^{\circ} \times 6^{\circ}$ in 2 seconds. This scan is normally symmetrical about 0° azimuth, but the center of the scan can be positioned $\pm 30^{\circ}$ in azimuth and in elevation.

Search manual - In search manual the pilot can control the position of the antenna through $\pm 50^{\circ}$ in azimuth and $\pm 30^{\circ}$ in elevation.

Each of these search patterns is stabilized by the aircraft gyro so that it is in a plane parallel to the earth's surface.

Track - In the automatic track mode of operation, the antenna limits are $\pm 50^{\circ}$ in azimuth and $\pm 50^{\circ}$ in elevation.

Spin Generator Frequency - In all modes of operation the rf field is nutated. The nominal rate is 50 cps with limits between 47.5 cps and 52.5 cps.

Antenna RF Characteristics - The antenna gain at crossover is 1.5 db (one way) below the gain at the peak of the lobe. The antenna gain at the peak of the lobes is 33.5 db.

The beamwidth of the main lobe is $3.7 \pm 0.1^{\circ}$ at the half power points one way. The first sidelobes of the antenna pattern are 25 db below the gain of the main lobe. The peak of these sidelobes are approximately 12° from the peak of the main lobe.

The cross-polarization response of the antenna subsystem is 20 db below that of the main lobe at the operating frequency (9375 Mc). The main cross-polarized lobe is concentric with the main lobe.

The antenna has a squint angle of 1.3° . The 90° elevation lobe, which causes the altitude line problems (discussed later) when in level flight, is at least 40 db below the main lobe.

Transmitting Subsystem

The parameters associated with the transmitting subsystem are as follows.

1. RF Power - the peak power output is nominally 180 kw.
2. Operating Frequency - the magnetron has a design center frequency of 9375 Mc with tolerance of ± 30 Mc.
3. Pulse - Repetition Frequency (PRF) -
 - Search Mode: 12-mile range - 550 or 1200 cps
24-mile range - 550 or 1200 cps
100-mile range - 550 cps
200-mile range - 330 cps.
 - Track Mode: 1200 cps.
4. Pulse Width as Measured at 50% Amplitude Points -
 - Search Mode: 12-mile range - 0.5 or 1.75 μ sec
24-mile range - 0.5 or 1.75 μ sec
100- and 200-mile range - 1.75 μ sec.
 - Track Mode: 0.5 μ sec.
5. Standing-Wave Ratio -
 - Transmitting: 1.5 from 9300 to 9405 Mc
 - Receiving: 1.8 from 9300 to 9405 Mc.

Receiving Subsystem

1. Receiver Center Frequency - The center frequency is 30 ± 0.5 Mc.
2. Bandwidth - The bandwidth is 4 ± 0.5 Mc and is flat within 3 db.
3. Noise Figure - Under service conditions the noise figure is 12.5 db maximum for a 4-Mc bandwidth. The nonoptimum bandwidth in search mode (1.75- μ sec pulse width) results in an effective noise figure of 15.6 db.
4. Receiver Gain - The nominal gain of the receiver is 110 db.
5. AGC Characteristics - For signals between -86 dbm and 0 dbm the AGC provides sufficient signal regulation to maintain specified range and angle tracking characteristics (+6 db and -1 db error signal regulation). The AGC bandwidth is designed to suppress target amplitude noise so that it does not degrade tracking. The actual bandwidth is about 3.5 cps. The incremental phase shift of the 50-cps error signal is $+5^\circ$. This results in low crosstalk noise, and is one of the contributors to the 8% allowable overall crosstalk.
6. AFC - The follow rate of the AFC is between 160 and 240 Mc/sec.

Range Tracking Subsystem

The circuit which forms the range tracking subsystem is designed to acquire and lock-on to a nonfading signal with a closing velocity of 1600 knots and S/N of +12 db at least 99% of the time in a single pass. In the absence of interfering signals, the acquisition circuitry is mechanized to return the system to the search mode if the target fade time exceeds 2.7 seconds. In order to have a reasonable safety factor, the range tracking circuitry is designed to coast for a minimum of 4 seconds.

The range strobe sweep length (the range automatically searched) is 1.23 naut mi (15 μ sec) and the strobe sweeps this interval in 1 ± 0.4 seconds. This range segment is manually positionable to the range of interest.

The sequence from search to full lock-on occurs in the following manner.

Phase I - Search.

Phase II - This is the first phase in the lock-up sequence and persists for 25 milliseconds. During this time the range servo has a velocity constant of $K_V = 750$ for S/N of 20 db and above.

Phase III - This is the second phase of the lock-on sequence and persists for 2 seconds. In this condition, $K_V = 180$ for S/N of 20 db (a bandwidth of 30 cps).

Phase IV - This is the final phase in the lock-on sequence. When in this phase, the equipment is in complete autotrack operation. In this condition the range tracking system is of the double integrator type and is designed to take advantage of the limited target tactical capability (5,8). The acceleration constant (K_a) is 0.9. The range tracking bandwidth for a strong signal is approximately one radian per second.

Angle Tracking Subsystem

The transfer characteristic of the angle tracking subsystem also is a double integrator type, and is designed to pass all normal tactical maneuvers. During the tracking phase, the antenna is space stabilized to allow a reduction in the radar tracking bandwidth. The stabilization loop is designed to remove the inputs resulting from own ship's maneuver and to reduce the tracking line disturbance to below 1 mil. The bandwidth of the stabilization system is 40 rad/sec.

Azimuth and elevation unity gain bandwidth is 6 rad/sec.

The maximum crosstalk between azimuth and elevation channels is 8%.

Presentation Subsystem

The pilot's indicator has been described previously under "Functional Description of a Typical Airborne Fire Control Radar."

Weight, Size, and Power Requirements

The radar weighs 598 lbs and occupies a volume 29.8 inches in diameter and 28.15 inches in depth. The rear one-third of this volume is available for a computer. The equipment requires 28-volt dc at 400 watts and 115-volt 3-phase 400-cps ac at 4500 volt-amperes.

SUSCEPTIBILITY OF CURRENT AI RADARS

The susceptibility of an AI radar is a function of the state of development of the radar and of CM equipment. The system is affected by the susceptibility of each of its subsystems. Thus in a CM study the system concept must be utilized at all times. All of the subsystems are interrelated and will be affected by reduced performance of any one. Figure 2 is a signal flow diagram of a typical AI radar. The following will describe the signal flow under the two basic modes of operation and will describe the effects of CM (intentional and environmental) on each of the subsystems and the resulting effect on the overall system.

SUSCEPTIBILITY OF THE SUBSYSTEMS DURING SEARCH

The objective of the typical AI radar in the search mode is to locate an expected target (designated by CIC vectoring) at the optimum range required to complete a tactical mission and to display information to the pilot in such a manner so as to permit the earliest possible target lock-on and tracking. In Fig. 2, the blocks labeled modulator and transmitter, antenna, radar mixer, local oscillator, AFC, AFC mixer, i-f amplifier and detector, video amplifier, and display apply to the search mode. Signal flow follows a series path through these blocks, and any environmental or intentional CM which tend to obscure the signal, overload the circuit elements, or provide deceptive signals will interfere with detection of the target.

Modulator and Transmitter

The purpose of the modulator and transmitter is to provide suitable coded energy so that an identifiable echo can be obtained from the target. The introduction of a jamming signal into the system does not affect the modulator or transmitter. The manner in which the transmitted signal is generated, however, very definitely affects the jammer's capability to get into the system with harmful energy.

The AI radars presently employed in the fleet are operated on only one or two frequencies. The tolerances on these frequencies are very stringently held. As an example, the AN/APQ-50 has a design requirement of 9375 ± 40 Mc. Production methods used in the fabrication of magnetrons have resulted in the unfortunate situation of having a frequency spread of only 10 Mc. It is obvious that utilizing one transmitted frequency provides the jammer with an ideal situation of not having to look for the signal or tune to jam. In many tactical situations one jammer will be effective against several AI radars. Thus the power-to-bandwidth ratio works to the advantage of the jammer.

In addition, mutual interference between radars becomes a problem as an environmental CM. Under these conditions, a squadron utilizing several of these radars should experience severe interference problems. It has long been the practice in the fleet, where mutual interference is troublesome, to select magnetrons with a maximum frequency spread. The current manufacturing process, however, makes this impractical in the AI radar case unless the procurement process for magnetrons makes allowances for this problem.

Pulse-repetition frequencies are stable for a relatively long period of time (a matter of seconds) so that mutual interference, STAE, and enemy repeater jammers could become a problem. Deliberate time modulation of the prf can reduce this problem materially.

Antenna

The purpose of the antenna in the search mode is to provide a scanned unidirectional lobe for the purpose of obtaining course information on the position of the target. The practical design of antennas results in a nonoptimum main-lobe structure with numerous sidelobes. Figure 6 gives a linear plot of the antenna pattern in the elevation plane for a typical AI radar (9). These sidelobes permit entry of environmental CM such as altitude line and clutter and for intentional CM of the brute force type. In addition, the sidelobes make the mutual interference problem more severe. From the jammer's viewpoint, it takes 25 db greater signal to get into the first sidelobe than it does to get into the main lobe.

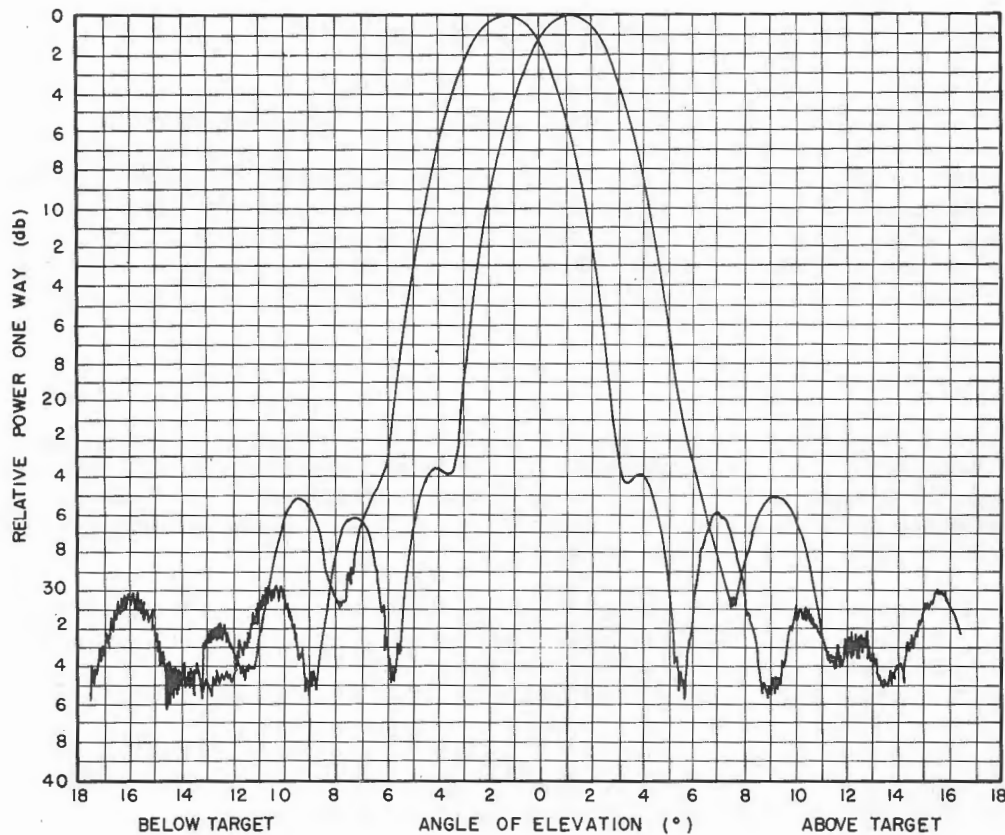


Fig. 6 - Antenna pattern in the elevation plane for a typical AI radar

In level flight, with the antenna searching dead ahead, current radars are in serious trouble at altitudes of 5000 feet and less due to clutter. From Fig. 7, it is seen that for these conditions clutter echo returns for ranges less than approximately 7 naut mi will be due to sidelobes. As shown by this figure, for ranges of more than 7 naut mi the clutter return is mainly via the main lobe.

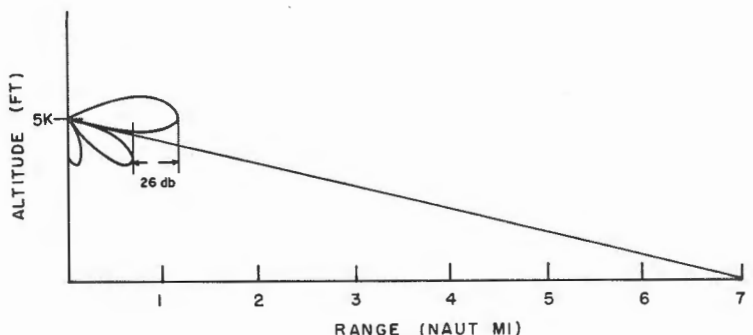


Fig. 7 - Geometry of the sidelobe clutter problem

Available data indicate that for the above conditions, the altitude line does not present a problem in the detection of targets except under very unusual and limited conditions. At 8000 feet the equivalent target return from the altitude line is 14 db below that presented by a 5-square-meter target. Contemporary radars, however, are known to have much less clutter rejection.

There has been some indication that in contemporary radars the altitude-line problem is caused by radome reflection and refraction. It is believed that this is the case, because laboratory tests on the antenna without radome indicates that the 90° lobe is not large enough to cause this trouble. Further tests have shown that the radome used with the AN/APQ-50 in the F4D installation is unusually good from the standpoint of not producing signals such as the altitude line.

The search patterns currently used are not optimum and thus represent built-in CM. Figure 8 illustrates the azimuth coverage needed to detect 91% of the targets at 30 naut mi (10). The total azimuth angle required is 15.2° . To detect 99.4% of the targets would require an azimuth coverage of 23° . These figures are based upon a 2-naut-mi standard deviation between actual and vectored target positions. Currently the search pattern employed is approximately 100° in azimuth and 14° in elevation. As shown later, the uncertainty in target position could be included in a search pattern having dimensions of 40° in azimuth and 20° in elevation at detection ranges being obtained by current AI radars. It is thus obvious that with the current coverage ($100^\circ \times 14^\circ$) the power per unit search area around the target is much lower than necessary with a resultant decrease in detection range over the optimum situation. Additionally, this extraneous search coverage increases the confusion effects of mutual interference, clutter, and enemy CM. The optimum search patterns for the expected tactical situation will be derived later in this report.

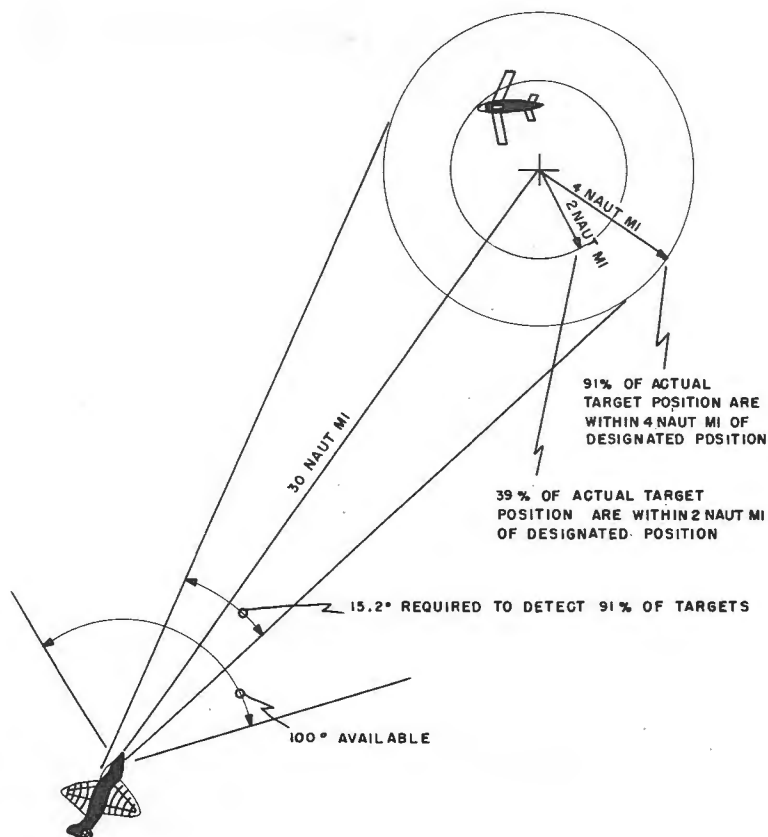


Fig. 8 - Required search coverage for AI radars

Receiving Subsystem

The signal has been traced from its origin at the transmitter through the antenna, and the degradation resulting from environmental and intentional CM has been described. The next element in the signal path is the receiver. The receiver consists of the blocks labeled mixer, local oscillator, AFC, and i-f amplifier and detector (Fig. 2).

It is obvious that any signal (environmental or intentional CM) which can compete with the target signal will reduce the system's capacity to detect that target. A gradual reduction in capability occurs as a function of increasing noise signal until the noise signal overloads the i-f amplifier. The pilot normally is instructed to set his manual gain control to a point which allows high probability of detection of a signal having a power level of -86 dbm. At a jam-to-signal ratio (J/S) of +10 to +17 db for cw and 0 db for pure noise-modulated cw (on frequency) the i-f amplifier is overloaded and no capability for detecting a target remains. Clutter signals above 10% of the target amplitude can be expected to be troublesome if they occur at the same range as the target.

Since intentional CM (brute force) are of the same nature as long blocks of clutter, they can be expected to have a similar effect. Other forms of intentional CM (chaff, deception, sidelobe jamming, etc.) merely present a confusing effect to the pilot. Little can be done

in the receiver to isolate the signal from these noises. Although the signal on the indicator may appear to be hopelessly covered by jamming, it is actually at a discrete range, not jammed, but lost in a confusion of signals.

It is relatively easy for an enemy to provide a power level of -76 dbm at the radar to jam the search mode. This has the effect at the normal receiver gain adjustment (near wide open) of denying information in the presence of jamming. Later AJ discussion will treat the recommended pilot action to alleviate overloading to allow homing on the jamming, if not target detection. It is likely that range information will be denied the interceptor in the presence of mild brute force jamming.

Video Amplifiers, Indicator, and Cockpit Layout

The signal flow in the search mode of operation is from the receiver to the video amplifiers and display. These video amplifiers essentially represent the current state of the art in this field. They are easily overloaded by transient signals, and require two to three pulse lengths to recover. For mutual-interference, clutter, and pulse-type jamming, the overload and recovery characteristics of these amplifiers result in an area of susceptibility and will tend to cause the signal to be obscured. An attempt to reduce this deficiency resulted in the addition of a fast-time-constant (FTC) circuit designed to reduce, by differentiation, all pulsed input signals to the expected length. The use of FTC is a poor substitute for adequate system design to take care of clutter and enemy CM. A better system design (operating on the signal prior to the second detector) having wider dynamic characteristics of the same general type as the FTC will be described later.

In contemporary cockpits, the indicator is difficult to read at best. It is often poorly positioned, as for example in the F4D where it is below the instrument panel and partially hidden by the joystick and pilot's hand. It has been estimated that 20% of the scope area is obscured during the search mode.

In day flights the pilot must continually shift his eyes from scanning the flight instruments to searching outside, to watching the radar scope. In addition to losing time because of unnecessary motion, the pilot's eyes must accommodate themselves from the high light intensity outside to the darker interior of the cockpit. Under these conditions it is extremely difficult for the operator to distinguish targets in noise or jamming. Bright spots in the surroundings of the cockpit and specular reflections from the face of the scope or other instruments add to the confusion and result in effective jamming of the system capability. For example, at 10,000 feet altitude, the outside background light intensity may be 7000 to 8000 foot-lamberts. Under typical attack conditions, with the sun behind the interceptor, the brightness of different areas in the cockpit may vary from 16 to 10,000 foot-lamberts. The ambient light intensity as measured at the scope for various positions of the sun relative to an interceptor flying at 30,000 feet altitude is shown by Fig. 9 (11). The maximum light output of the AN/APQ-50 display is about 250 foot-lamberts and may be as low as 20 to 30 foot-lamberts in the area of a target to be detected. As can be seen, this presentation subsystem of the AI radar is already jammed by a natural CM. In the presence of such confusion, any enemy CM effort is likely to deny what little usefulness remains.

The ground-based radar operator may often counteract jamming by judicious use of his set controls. The pilot, however, has less time to devote to proper adjustment. He is also at a disadvantage since he has less practice and fewer known targets against which to tune. The result is that controls are often incorrectly turned full clockwise in the hope that mere gain and brilliance may override jamming and noise.

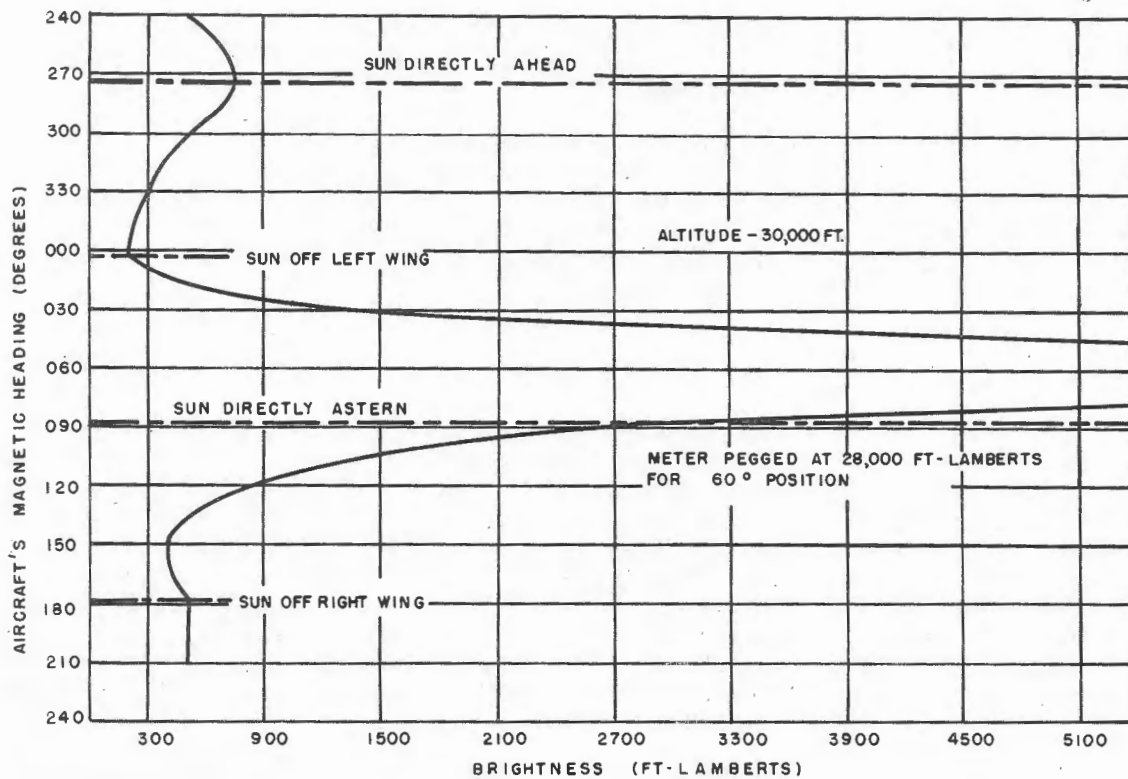


Fig. 9 - Ambient light intensity as measured at the radar scope

In acquisition mode of operation the pilot's problem is increased by the fact that he must not only see the target through noise, ambient light, and jamming but must also position the antenna to "searchlight" and must lock on the target.

Poor location, crosstalk, and awkward movement of the radar joystick makes it difficult for the pilot to make the acquisition. In the F4D, the radar-set control containing the joystick is located aft of the pilot's hip on the left side of the aircraft. In this location the pilot cannot see the set control unless he opens his shoulder harness. Operating by feel he has to move the joystick in both azimuth and elevation to bracket the target with the acquisition strobes as seen on the indicator. In addition, he must use a thumb wheel to bracket the target in range. It is nearly impossible while reaching behind one's hip (with shoulders rigidly attached to a chair) to make coordinated orthogonal movements. As a result, a small change made by the pilot in the azimuth strobe position results in the introduction of an error in the elevation strobe position. In correcting the elevation error, he again inadvertently introduces a new azimuth error. This design fault in the F4D cockpit results in self-jamming before the enemy even starts. The penalty paid for lack of harmonization is loss of attack capability of the weapon system; an effective "jam."

SUSCEPTIBILITY OF THE SUBSYSTEM DURING TRACKING

As in the search mode, the system in the track mode is affected by the susceptibility of each of its subsystems. The importance of following a systems concept in a CM study cannot be overemphasized.

The objective of the equipment in the track mode is to provide noise-free signals which indicate, relative to own ship, the line-of-sight angle, the rate of change of the line-of-sight angle, and the range to the target. These signals need to be derived and usable at all ranges up to maximum detection range of the search mode as required by the weapon system. Because of the nature of back-up weapons (guns or rockets) the quality of the radar output signals must be maintained to a minimum range of about 200 yards. The computer utilizes the radar output signals to generate appropriate lead angles. The track mode utilizes the blocks in Fig. 2 labeled modulator and transmitter, antenna, local oscillator and AFC, i-f amplifier and detector, and the blocks utilized in the tracking circuits including range and angle, and display.

Modulator and Transmitter

The purpose of the modulator-transmitter combination in the track mode is to provide rf signals of the proper time duration and purity and at the optimum prf for use in the tracking problem. The manner in which the transmitted signal is generated definitely affects the jammer's capability to get into the system with harmful energy.

Comments made in the section dealing with the search mode concerning frequency apply equally here. Manufacturing processes for magnetrons aid the enemy in that the frequency of most of the magnetrons falls very near the design center frequency (9375 Mc) instead of being spread throughout the tolerance band (± 30 Mc) as would seem to be indicated by the intent of the magnetron specification. The mutual interference problem is even more severe in the track mode than in the search mode. Several radars operating on or near the same frequency will result in additional noise being added to the already difficult tracking problem. Proper distribution of transmitter frequencies by prior choice is an effective AJ.

In the track mode of operation, the use of a stable prf (matter of seconds) introduces the same problems as those described for the search mode (mutual interference, STAE, and enemy repeater jammers). The use of a higher prf in the track mode (1200 pps) makes the STAE problem more likely. In addition, the repeater type of jamming is more likely to be encountered during the track mode of operation. Repeater jamming of the range- and angle-pull-off types represents a definite threat to current AI radars. If the pulse-to-pulse prf is stable, the enemy is allowed to use the information contained in the previous pulse packets (past history) to program deceptive jamming signals anywhere within the range bracket. Conversely, an unstable prf can virtually eliminate intentional jamming.

In the track mode of operation typical AI radars use a 0.5- μ sec pulse. During the tracking phase, signals which fall within the time duration of the range tracking gate are the only ones of interest to the radar. Thus the tracking gate represents the time interval during which the jamming signal (intentional or environmental) can get into the system. From the AJ standpoint it is important to make the range gate as narrow as possible. Ideally (for optimum S/N and transmitted power utilization) the tracking gate should fit the target pulse width. Thus the pulse width should be the same as the range gate width. Current repeater jammers have between 0.15 and 0.2 microsecond delay between reception and transmission of the jamming signal. This means that the jamming will fall within the current range gate length. Thus it is important to shorten the gate and transmitted pulse consistent with the tactical problem. This will be discussed later in the report.

Antenna

The purpose of the antenna in the track mode of operation is to provide directional envelope signals to be demodulated in other portions of the radar. Modern conically scanned fire control antennas developed for this purpose have the following specified characteristics:

1. Beamwidth
2. Symmetry - Beamwidth as a function of scanner position
Crossover - Modulation factor at scan fundamental frequency
Noise - Noise modulation factors at harmonics of scan frequency
3. Sidelobes
4. Polarization
5. Scan frequency and its regulation.

Proper design values for most of these characteristics can result in greatly reduced susceptibility to environmental or intentional CM. These specified quantities are developed on the basis of sharing the system-accuracy load in the most equitable fashion consistent with the state of the art.

Beamwidth - The beamwidth of a fire control radar is a compromise between the desire for definition and the necessity for acquisition of the target. If the definition is poor, the antenna receives information from sources other than the target such as clutter, attitude line, and enemy CM. If the definition is greater than necessary, it will be difficult to place the resulting narrow beam on the target for tracking purposes. For X-band antennas of about 24 inches diameter, this beamwidth becomes about 3.7° and is reasonably consistent with both definition and acquisition problems.

Symmetry and Crossover (Modulation Factor at Scan Fundamental and its Harmonics) - The envelope signal at the fundamental frequency at which the antenna conically scans is crosscorrelated in the radar circuitry with a pure sinusoidal reference signal received from a generator mechanically coupled to the scanner. The comparison method most commonly used is a correlation method which results in noise outputs for harmonically related input signals. It becomes important to reduce the input noise generated by the nonlinear actions of an antenna whose beamwidth varies with scanner position. Such a nonsymmetrical antenna has a crossover point which varies with beam position and as a result generates large scan-frequency harmonic outputs (noise). Control of this parameter is an important deterrent to CM.

Sidelobes - Any practical antenna system has sidelobe responses through which intentional and environmental CM can enter the radar. A sidelobe level of about -25 db is thought to be representative of the state of the art for a production device. Contemporary antennas have similar sidelobe specifications.

Polarization - From the standpoint of intentional jamming there seems to be little to be gained by using any particular form of polarization. Choice of polarization is almost always determined by problems resulting from propagation conditions.

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Scan Frequency and its Regulation - The choice of conical scan frequency is governed to a large extent by the nature of target amplitude noise (12). Figure 10 shows a typical plot of amplitude noise power as a function of frequency. As stated earlier, noise power is a minimum at frequencies between 20 and 40 cps for a mixture of propeller and jet targets. Any further real reduction in the effects of target amplitude noise can be had under certain conditions by using the monopulse technique. Tactical use of this technique, however, does not result in appreciable reduction of the effects of target noise at AI radar ranges of interest. This fact is shown in Fig. 11. For short-range and for long-range conditions the noise encountered is set by the target size and receiver sensitivity respectively. At medium range the systematic noise could be reduced a small amount through the use of the monopulse technique. Unfortunately the weapons of the present and immediate future must be usable at ranges such that the target size or "glint" noise governs. Additionally, monopulse radars are susceptible to jamming on the image frequency. In contemporary AI radars the scan frequency used is 50 cps or higher. This is shown in Fig. 10 to be out of the optimum frequency band in terms of target amplitude noise.

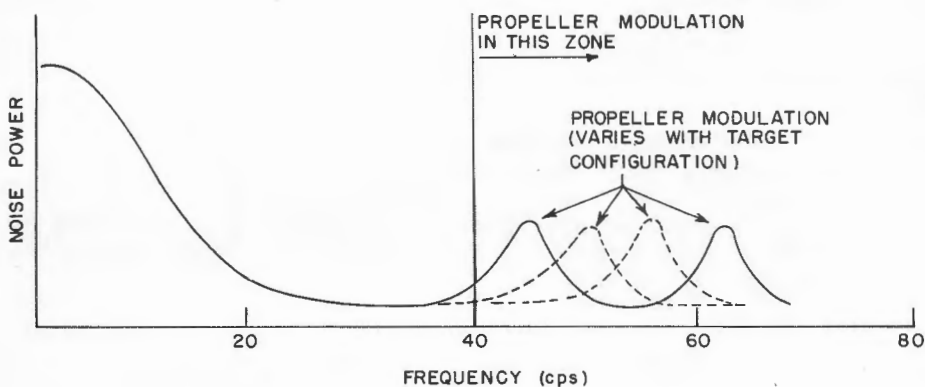


Fig. 10 - Target amplitude noise

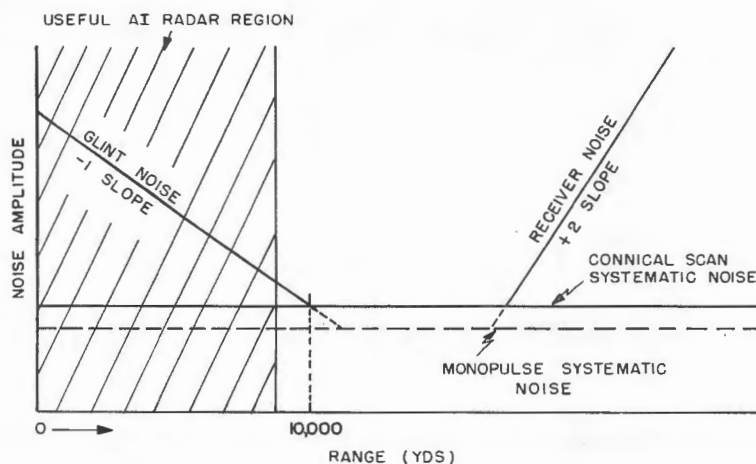


Fig. 11 - Comparison of noise in conical-scan and monopulse radars for a 100-ft target and modern radar designs

The scan frequency regulation is usually too precise and is of the order of ± 2.5 cps. The popular CM scheme of transmitting a jamming signal modulated at or near the conical scan frequency of the AI radar will not be effective unless the jammer is within 1 cps of the conical scan frequency. Currently the radar scan frequency varies at random within the above limits. This variation is not predictable and may result in a stable scan frequency for relatively long periods of time. Deliberate variation of the conical scan frequency can be an effective AJ feature and will be discussed later.

A current jamming technique which will be effective against the AI radar is that of detecting the scan modulation, inverting its phase and transmitting it back as a jamming signal (inverse gain). Any AI radar which conically scans on transmitting is vulnerable to this type of jamming. This is a form of angle deception jamming and will be discussed in detail in the section on the angle tracking subsystem.

All antennas develop directional information by orienting themselves normal to the average phase front of the signal reflected from the target. If the Crosseye (13) technique of distorting the rf phase front is to be defeated at the antenna, a state-of-the-art improvement must be made by developing an antenna working on some other physical principle.

Receiving Subsystem

The purpose of the receiving subsystem in the track mode of operation is to provide time-selected, distortion-free (both phase and amplitude) envelope information to the angle and range tracking circuitry. The receiving subsystem includes the duplexer, radar mixer, local oscillator, AFC, i-f amplifiers and detector, video amplifier, gater, 3rd detector, and AGC (Fig. 12). The signal is operated on by the gain of the AGC-controlled i-f pre-amplifier and i-f postamplifier.

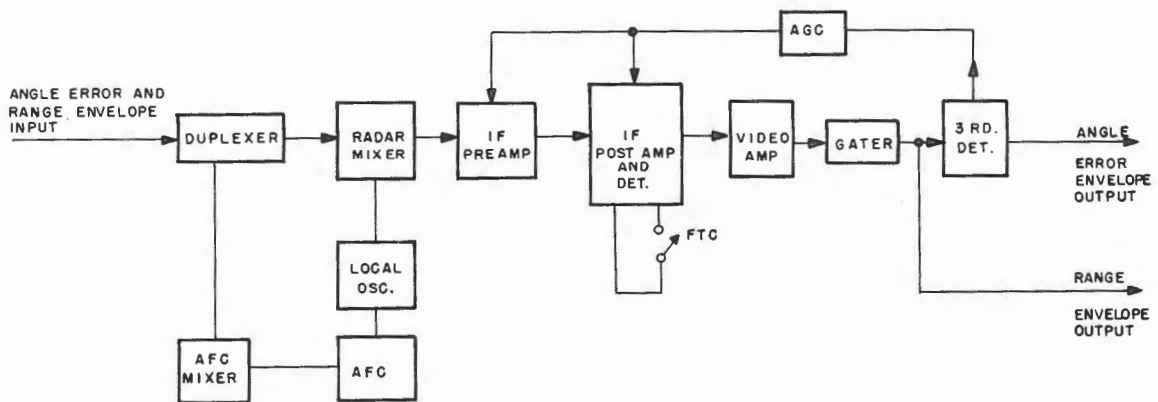


Fig. 12 - Typical receiving subsystem in the track mode of operation

Improper design of the AGC has resulted in inadequate regulation of the angle and range output signals for input signals at the antenna greater than -20 dbm. It can be shown that signals greater than -20 dbm are received at the antenna during typical tactical situations (14).

During the re-evaluation of the problem, it was found that duplexer recovery time and the mixer overload characteristics tended to mitigate the problem. With the above fortunate situation and as a result of minor changes as explained below, a more usable system has been evolved.

The gain of a radar receiver can be adjusted to handle weak signals and saturate on strong signals, or to handle strong signals and provide inadequate outputs for weak signals. A greater range of signal handling ability, or dynamic range, is provided by the use of AGC which continuously adjusts the receiver gain to provide a constant average input to the angle-error demodulators, even as the echo's amplitude changes as a result of change in target range, size, and attitude. This insures that the angle demodulators will be a percentage angle-error measuring device, and that they will provide correcting signals to the antenna drive system in proportion to its true misalignment. This also maintains an angle sensitivity that is constant with changes in signal strength, thereby preserving the stability margins of the angle tracker. While increasing the receiver dynamic range, faithfully preserving percentage angle-error modulation and holding the angle sensitivity constant, the AGC system should suppress the accompanying target-generated amplitude noise modulation (within the bandwidths of interest to the servo designer).

For example, AGC technical specification (6) are (a) to provide, over a dynamic range of input signals of -96 to 0 dbm, output signals with a regulation of ± 1 db; (b) to hold the angular error signal incremental phase angle to ± 5 ; (c) to suppress noise in a band from 0 to 2.1 rad/sec by greater than 30 db; and (d) to introduce no more than 0.5 mil or 0.5 mil/sec rms angle and angle rate noise due to intermodulation between low frequency amplitude noise and the lobing frequency.

The verification tests on the system show that the specifications are met in all respects except in regulation of the output signal over the desired dynamic range of inputs. The regulation actually obtained is ± 1 db for signals from -80 to -20 dbm and +6 to -2 db for signals from -20 dbm to zero dbm.

Investigations have shown that at about -10 dbm the crystal mixer begins to saturate, causing modulation suppression for all stronger signals. Some modulation enhancement in the i-f then is desirable to offset the crystal suppression effect and to hold the output modulation factor constant. The excessive enhancement realized was found to be a function of the transfer characteristic of the i-f amplifier tubes. For strong signal levels, the control voltage developed causes the tubes to operate in their nonlinear region, which distorts the signal envelope. At the same time, the AGC loop gain is lowered, reducing the ability to regulate, thereby resulting in enhancement.

Figure 13 shows a typical crossproduct detector characteristic (15). It is interesting to note that the response at the even harmonics of the scan frequency is small. The even-harmonic modulation (principally the second harmonic) is generated by the target and the antenna. These harmonic signals represent noise in that they do not give desired information concerning the location of the target. The crossproduct detector and antenna used in the typical system have been designed to passively reject the even-harmonic modulation.

Figure 14 gives the AGC isolation characteristic as mechanized in the radar (8). It should be noted that the servo bandwidth is in the frequency region which is adequately isolated from target-generated amplitude noise. Reasonable design has been employed to reduce the susceptibility to environmental CM.

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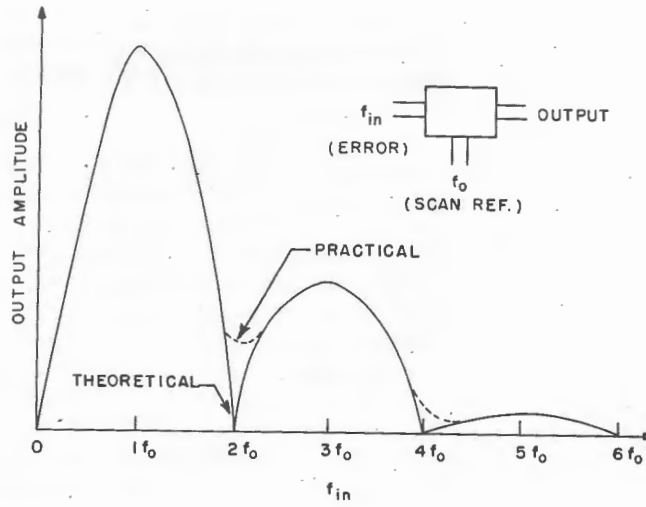


Fig. 13 - Full wave response characteristics of a crossproduct detector

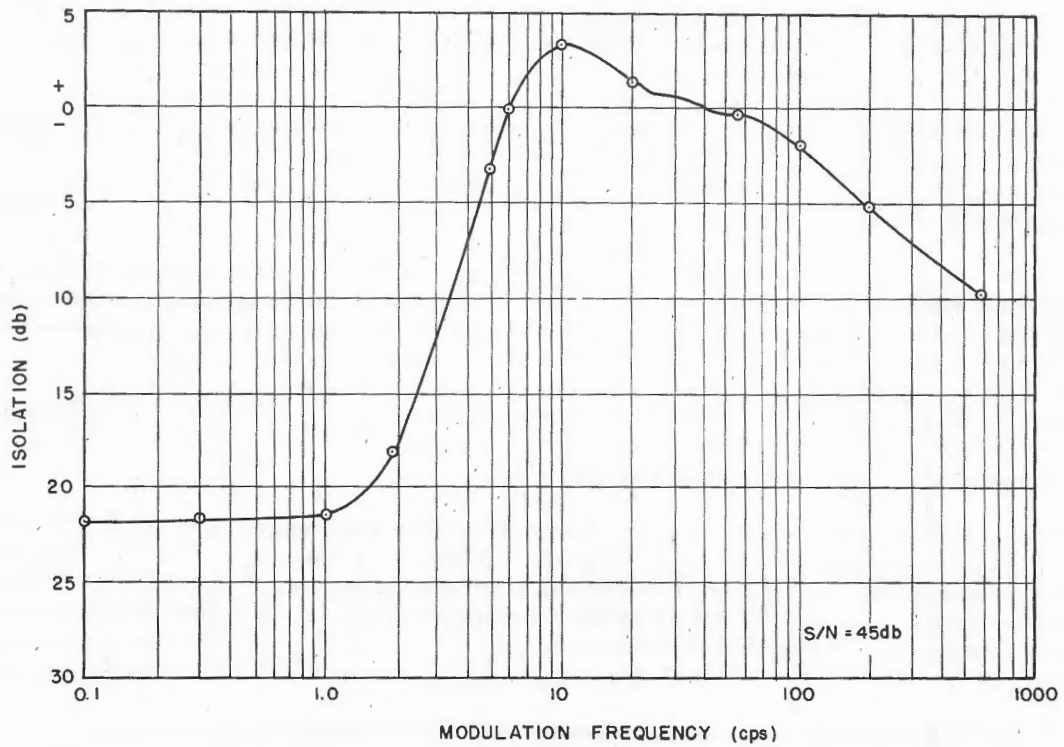


Fig. 14 - AGC isolation as a function of frequency

The preceding discussion has described the performance of the radar in its normal noisy environment. In this environment, the performance of the receiving subsystem is marginal in some tactical situations (short-range attacks against large targets). The overload characteristics for input signals above 0 dbm are certain to cause susceptibility in the presence of jamming in spite of the improvement programs to be described later. In addition, there are susceptible areas to intentional CM which can be corrected in the improvement program. These are as follows:

1. Nonoptimum bandwidth - The bandwidth of the present receiver, given a perfect AFC, is approximately twice as wide as required. The current bandwidth is 4 ± 0.5 Mc; a 2-Mc bandwidth is required to pass the $0.5\text{-}\mu\text{sec}$ tracking pulse width at optimum S/N and fidelity, and a 0.57-Mc bandwidth is required to pass the $1.75\text{-}\mu\text{sec}$ search pulse width under the same conditions.
2. Lack of i-f gating - The subsystem is designed so that non-pulsed signals (cw and noise-modulated signals) will not operate the AGC and therefore will overload the last stage of the i-f postamplifier. This results in a capability in the radar for handling a J/S of +10 to +17 db for cw jamming and a J/S of 0 db for noise-modulated jamming. Signals exceeding these J/S values can be easily generated.
3. Video amplifier - The design of the video amplifier is contemporary. The amplifier contains a pilot-selectable FTC whose major function is to break blocks of clutter into pulse packets which are consistent with the $0.5\text{-}\mu\text{sec}$ pulse width used by the system. The use of the FTC in the track mode of operation is a poor substitute for adequate system design to take care of clutter and enemy CM. A better system design having wider dynamic characteristics of the same general type as the FTC and automatic operation capability will be described later.
4. Local oscillator and AFC - In the track mode of operation the local oscillator and AFC loop represent inadequate design to the point where the previously mentioned excessive i-f bandwidth is required for system operation under expected environmental conditions. It would be desirable to optimize the AFC design so that a narrower i-f bandwidth can be employed, thus reducing the spectrum available for admittance of jamming signals.

Range Tracking Subsystem

The purpose of the range tracking subsystem is to select a target in range, so that angle tracking may be accomplished on the target of interest, and to accomplish range tracking so that a suitable quality of range information (accuracy and noise content) can be supplied to a lead angle computer. The characteristics of the range circuitry should be such that no distortion is introduced on the angle tracking signal. The following is a description of the susceptibility resulting from the design philosophy and mechanization techniques used in the range tracking subsystem of a typical system.

The mechanization of the range tracking function in pulse AI radars determines to a large extent the degree of immunity from the effects of intentional and environmental jamming. Perhaps the basic distinction between range tracking systems is between the use of gated or ungated echo signals to operate the time discriminator. When pregated video is used, the gating may be done either before or after conversion to video. Although i-f gating requires the use of an additional i-f amplifier to provide ungated signals for the indicator, it offers among other advantages the chopping of cw interference into pulses which can actuate the angle tracking system. Thus elevation and bearing information about the jamming source can be obtained, although range information may be nonexistent.

Some AI radars use video gating, but i-f gating appears to be superior. Bipolar video time discriminators are usually used in the range tracking loop. Although the original designs called for using ungated video to produce the bipolar signal, many production equipments have been redesigned to gate the video signals before applying them to the range tracking subsystem. The basic range tracking subsystem is shown in Fig. 15. For the case where ungated video is used as the range tracking information, the following discussion applies (16).

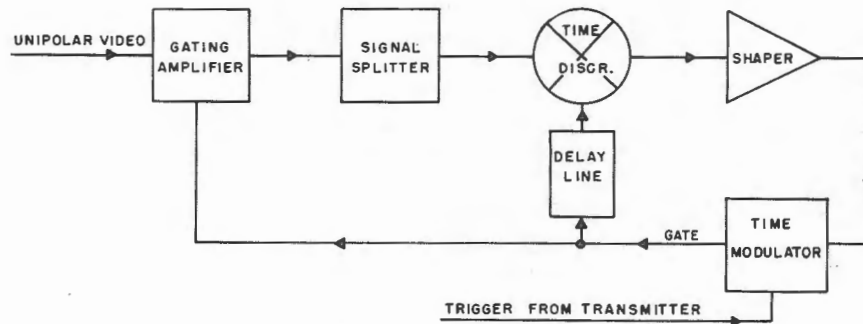


Fig. 15 - Typical range track loop

Unipolar pulses from the i-f detector are made bipolar by delaying them one pulse width, inverting and adding them to the original pulses. The resulting pulses are symmetrical if the original pulses were symmetrical, but if they were not, the composite pulse is asymmetrical as shown in Fig. 16. The time discriminator compares the degree of coincidence between the bipolar signals and the gate generated by the time modulator. The voltage or current so generated is amplified and operated on by the shaper and fed to the time modulator in such a phase as to hold the gate centered on the bipolar pulses. If the coincidence of a range gate having the same width as the unipolar video pulse is caused to vary, the output of the discriminator would have the form shown in Fig. 17, assuming the use of rectangular pulses and no interference.

The apparent aperture of the time discriminator is seen to be 3τ (pulse widths). If, however, an interfering signal of the same width and amplitude as the desired echo occurs prior in time to it, the aperture may become considerably wider. Figure 18 illustrates a condition wherein the aperture has increased to 4.75τ . This happens if such interfering signal occurs 1.75τ ahead of the echo.

For systems in which the range gate searches from short range outward, it will lock on the inward stable zero, which is to say, on the interfering signal. It can be shown that the interfering signal will be acquired if it occurs earlier than the echo by 1.25τ . At this separation, even if the desired echo is acquired, the shift in discriminator zero will cause the indicated range to be in error (Fig. 19).

To sum up, the case against using ungated video as an input to the time discriminator is that the discriminator aperture is widened, and the possibility of acquiring the interfering signal is high. This effect is, of course, dependent upon relative amplitudes and signal shapes as well as separations. The dynamic effects, i.e., the length of time the errors exist and their magnitudes, depend upon the range tracking servo bandwidth and configuration, and the velocities involved in addition to the other factors.

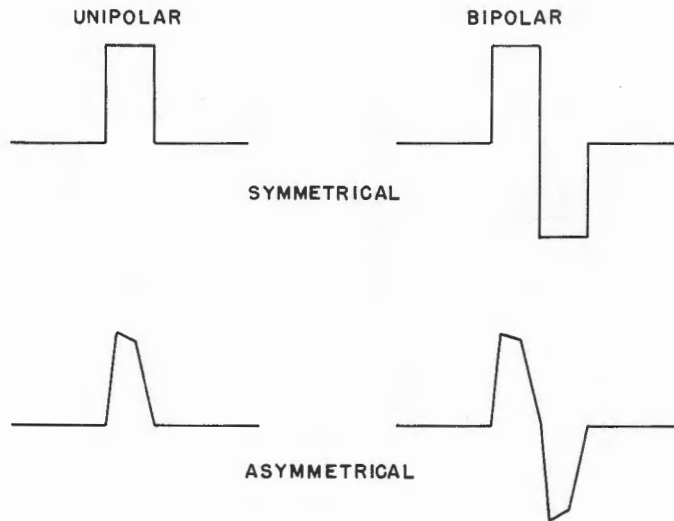


Fig. 16 - Signal splitting or bipolarization

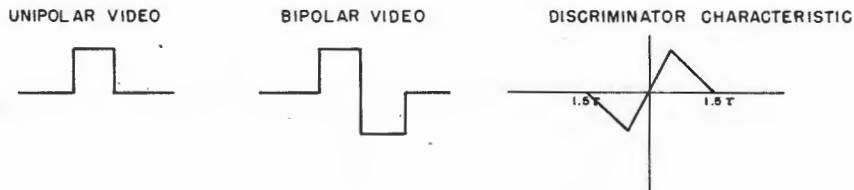


Fig. 17 - Discriminator characteristic in a system using ungated video, assuming no interference

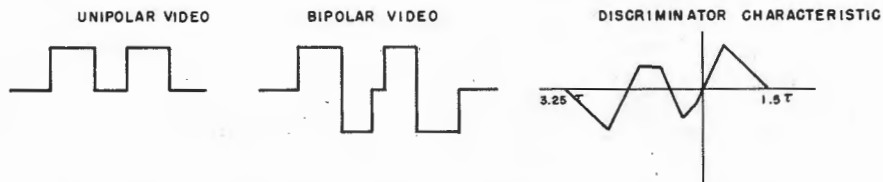


Fig. 18 - Discriminator characteristic in a system using ungated video when an interfering signal occurs

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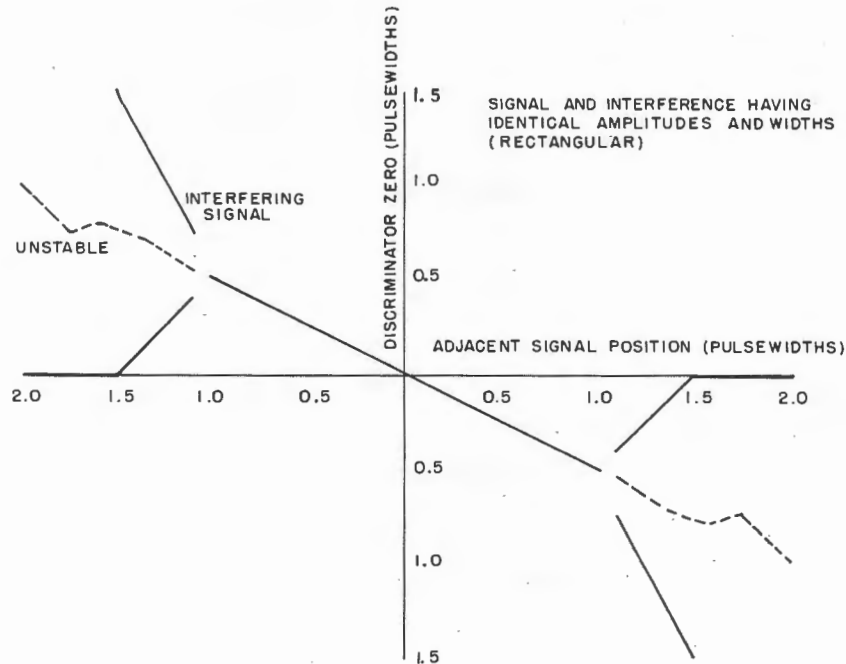


Fig. 19 - Static range tracking error when the discriminator input is ungated

If the echo is gated before the bipolar signal is produced (as is done in the current AN/APQ-50) the aperture cannot exceed two pulse widths. Figure 20 shows the effect of an adjacent signal of the same amplitude as the desired echo when gated video is used. From comparison of Figs. 19 and 20, it will be seen that for separations greater than 1.25τ the interfering signal can cause no tracking error. For separations less than 0.75τ the two methods are about equivalent, but there is a slight decrease in the maximum error from the gated system. At separations in the vicinity of 1τ , the gated system produces zero output, and as Fig. 20 shows, the error may rise to appreciable values.

It should be noted that Figs. 18, 19, and 20 are over simplified in that it is assumed that the target and interference signals add in the video circuitry. The signals actually add at $i-f$ for separations less than 1τ . Also, the results shown apply where there is no velocity difference between target and interference. Similar results occur where these assumptions are not made; the differences are in detail only.

There are disadvantages attendant upon using gated video to operate the time discriminator. The gating process, if accomplished at video frequencies, usually results in a residual gate pulse or pedestal. This may result in difficulty in keeping the discriminator in balance over wide variations in receiver output noise. A very precise time match must exist between the receiver enabling gate and the discriminator keying gate. This requires very stable, high quality delay lines, as well as adequate bandwidth in the video amplifier. Finally, and an admittedly minor item, the gated system has an error sensitivity 6 db less than the ungated arrangement. These adverse effects are not impossible to overcome, and practical testing of both types show pronounced improvement in AJ capability for the pre-gated system now being used in the AN/APQ-50.

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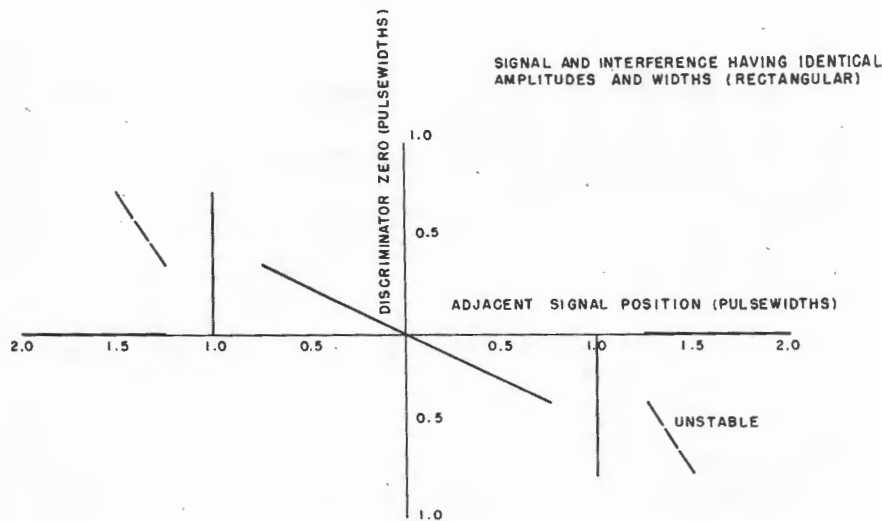


Fig. 20 - Static range tracking error when the discriminator input is gated

It is now important to look at the susceptibility of this subsystem to CM both intentional and environmental. In many cases environmental CM will have the same effect on the range tracking subsystem as forms of intentional CM. Thus the incorporation of features to reduce the effects of environmental CM will also improve the tracking performance in the presence of intentional CM. The following is a discussion of the effects of various forms of CM on the range tracking subsystem.

Altitude Line - Test results have demonstrated that the AN/APQ-50 can successfully track targets through the altitude line in all expected tactical situations. Figure 21 shows the results of tests conducted at NATC, Patuxent, with the AN/APQ-50 installed in an F3D aircraft against a F2H-2 target (17). In brief, this plot indicates that the AN/APQ-50 radar (modified synchronizer and vertically polarized antenna) never failed to track the target through the altitude line at all test altitudes between 20,000 and 1000 feet with the target opening or closing rates between 0 and 200, and 0 and 800 knots respectively. In some instances, to impose various transient range and angle rates on the tracking system, the range rate of the F3D airplane was gradually changed from a closing to an opening rate while the F3D was within the slipstream of the target airplane. Under these test conditions the radar continued to track the target airplane. At 30,000 feet altitude, the AN/APQ-50 radar tracked the target airplane through the altitude-line interference on all trials between relative rates of 100 and 800 knots. At this altitude, the system tracked the target airplane through the altitude-line interference 60% of the time at range rates below 100 knots.

The performance of the AN/APQ-50 against the altitude line is the result of several things: (1) double integrator tracking system designed to track only the expected target maneuvers, (2) antenna design to have as small a response as possible in the direction of the ground, and (3) pregated range track video. It should be noted that harp material was not used in the radome (because it destroys other characteristics of the radar) nor was its use necessary.

characteristics. The estimate is a broad one and falls between 5 and 100 g's with the most likely value being around 30 g's. In addition, the packaging and opening techniques are changing from day to day, and it is virtually impossible to bracket the reflective size and length of the chaff echo. One test indicates that a particular type of chaff (RR-12) looks like the echo from a single aircraft (1/2- μ sec transmitted pulse) and produces an echo 6 db greater than a 5-sq-meter target.

Limited bench and flight tests have been conducted which demonstrate the effects of chaff on the AI radar under particular tactical situations.

Bench tests were conducted to evaluate the effects of an isolated bundle of chaff on the range tracking performance of the AN/APQ-50 radar. Isolated bundles of chaff are analogous to the altitude-line problem. However, polarization and antenna design features which assist in tracking through the altitude line do not help in the chaff problem. Thus, pregated video and the double integrator tracking characteristic are the two essential aids in tracking through chaff. Bench tests have demonstrated that this radar will usually track through isolated bundles as long as there is a range rate differential (difference between target to interceptor and interceptor to chaff) of 110 knots for a 5-sq-meter target. Thus tracking through isolated bundles of chaff will be no problem to a properly designed radar. This performance will vary with target size and length of the interfering signal, and will be improved as the target-to-interference ratio increases.

Limited flight tests of the AN/APQ-50 have been conducted at Patuxent against a target dispensing chaff (17). Figure 22 gives a polar plot of the test results. The chart indicates that the AN/APQ-50 radar continued to track the target at bearing angles from 180 to 230 degrees and from 310 to 360 degrees. At bearing angles between 230 and 310 degrees, the radar broke lock at least once during tests and returned to automatic search. The quantity of chaff and rate of dispensing had no apparent effect upon tracking success. Rates of between one bundle and 4 bundles per second, by automatic dispenser, were employed. The target used was an AD-4N and the interceptor was an F3D. The AN/APQ-50 is susceptible to chaff while making a beam attack on a target. As yet, the area of susceptibility looks large (Fig. 22). The data sample was too small, however, to obtain statistical estimates of the problem. Theoretically the area of susceptibility should be on the beam of the target and between 10° and 20° wide.

Theoretical calculations on the zones of effectiveness of chaff are involved and depend upon many factors. To date, flight tests appear to be the best method for revealing these zones. Studies have been made, however, which outline methods for calculating zones of effectiveness for chaff (18).

Brute Force Jamming (environmental and intentional) - Any interference of time duration appreciably longer than the target signal is defined as brute force jamming. Nature provides such signals in the form of clutter (ground, weather, and atmospheric effects). The enemy can provide similar interference in the form of brute force jamming such as cw, noise-modulated cw, and frequency-modulated cw. The jammer utilized can be of the spot-frequency or swept-frequency varieties.

The effects of clutter on the AN/APQ-50 in the track mode of operation are illustrated in Fig. 23. These tests (9) were conducted using 5- μ sec unmodulated pulses to simulate clutter (10 times echo length). It can be seen from Fig. 23 that for clutter 30 db stronger than the signal, the minimum relative velocity is required to be between 300 and 350 knots for successful tracking. These tests represent an idealized situation. Normally, isolated blocks of clutter will not exist. In fact, when a 5- μ sec block of clutter occurs, it is usually

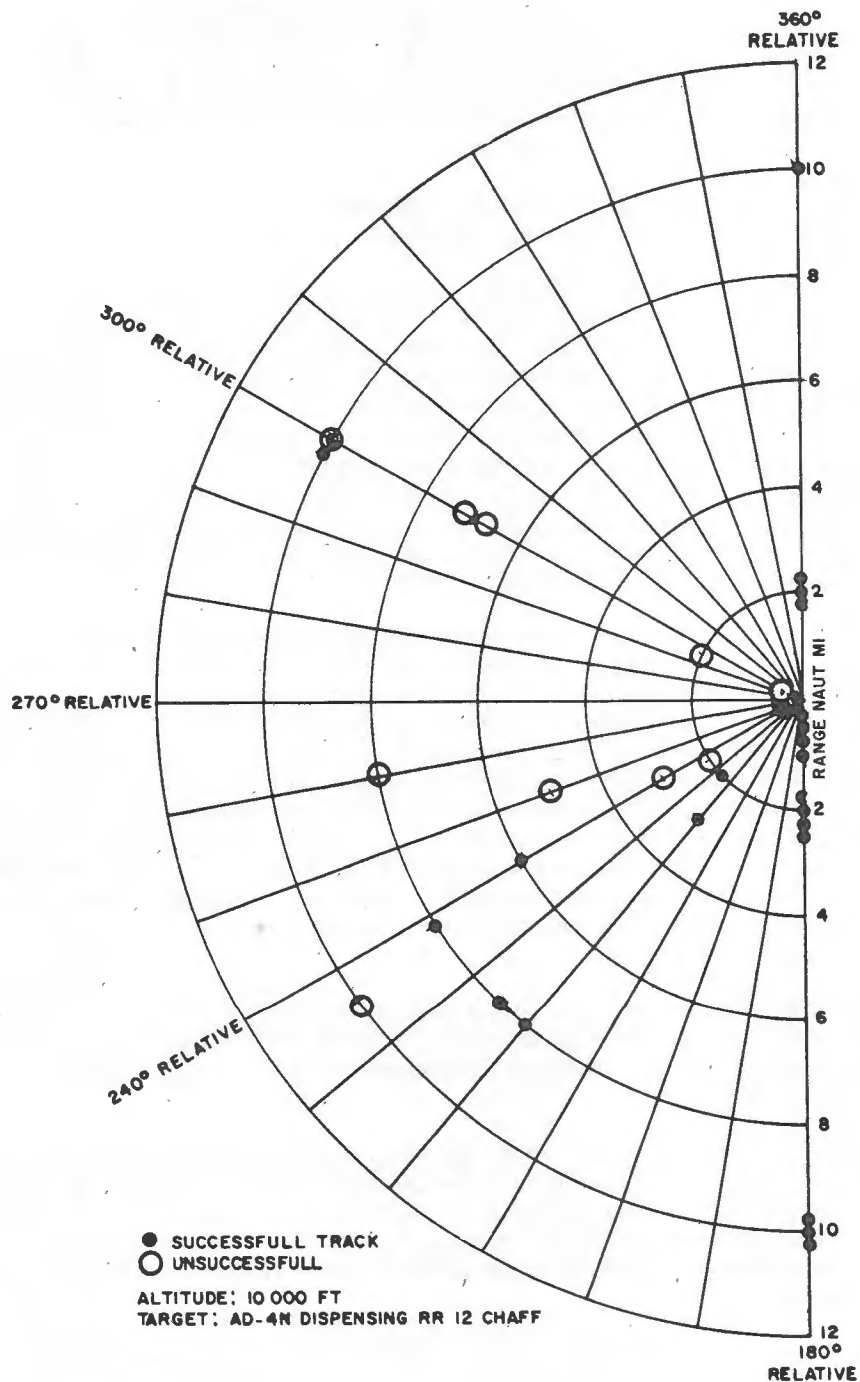


Fig. 22 - Tracking performance of the AN/APQ-50 in the presence of chaff

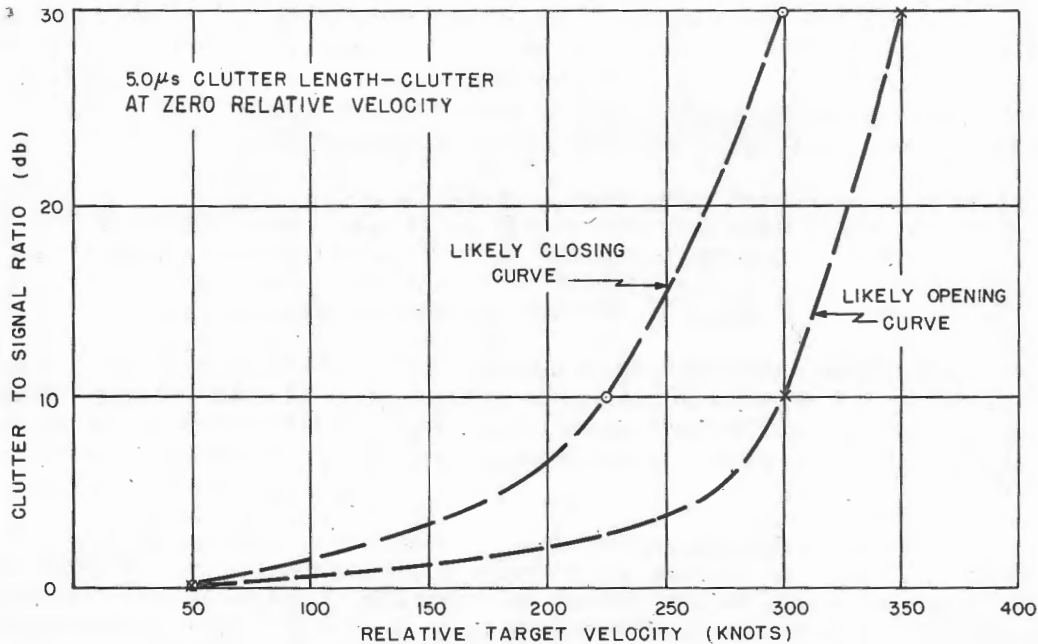


Fig. 23 - Effects of clutter on the tracking performance of the AN/APQ-50

accompanied by many others with little or no clear range between them. The performance of range track circuitry of the AN/APQ-50 for a fading target (memory time) is well known. It is well in excess of the 2.7 seconds allowed to elapse between the loss of signal and the automatic return to the search mode. Little is known, however, of the ability of the range subsystem to learn new velocities which occur as a result of clutter. It is known that the clutter performance of the AN/APQ-50 (range tracking) is marginal.

A design feature currently in use aids tracking in the presence of some types of clutter. This is the FTC circuitry which is of marginal utility in the search mode. Its usefulness in the track mode has never been measured objectively. It is known, however, that FTC is not the optimum technique for tracking through clutter. This will be discussed in more detail in the section on short-term improvements.

Intentional jamming can take the form of cw and modulated cw. With the present mechanization, the range tracking subsystem is susceptible to this type of jamming; cw jamming at a +10-db J/S level and noise-modulated cw jamming at a 0-db J/S level results in loss of range track operation. This susceptibility results from two facts: (1) jamming signals of a continuous nature contain no time reference from which range information can be obtained, and (2) jamming signals of this character cause overloading of the receiving subsystem.

Deceptive Jamming - One form of deceptive jamming which can be employed against the range tracking subsystem is range gate pull-off. This can be compared to the chaff problem in that it consists of an interfering signal suddenly appearing in the gate. The jammer has control, however, over how long the interfering signal stays in the gate and the rate at which he moves this signal away from the true signal. This is, in effect, a change in interfering signal velocity relative to true signal velocity. There are two forms of range pull-off jammers: past history jammers and pulse-to-pulse jammers.

Past history jammers are preset by the operator according to the previous pulse period of the stabilized repetition rate so that the delay between the jamming signal and the target signal is zero. He can then program the jamming in or out in range in an attempt to pull the gate off. Currently, pulse-to-pulse jitter is small. Thus it appears that such a jamming technique could be employed to place an interfering signal within the gate.

Pulse-to-pulse jammers repeat each pulse independently. The success of this technique does not depend upon a stable repetition rate at the AI radar. Inherently there will be a small delay between the jammer's reception of the AI radar pulse and the transmission of the jamming signal. This is currently 0.15 to 0.2 μ sec and is undesirable from the standpoint of the jammer because it makes the interfering signal less effective.

In the typical radar the gate width is 0.5 μ sec. With a 0.2- μ sec delay, the jammer can get into the gate with approximately 0.6 of his pulse power. If he can maintain a favorable J/S, the receiver gain will be lowered and the system will shift track to the stronger interfering signal. In this technique, the interfering signal can only be programmed outward in range.

In either of these range pull-off techniques, if the jammer is programmed in a manner such as to cause the range tracking subsystem to track the interference with errors less than the range gate width, the jamming will be successful. The time required for the jammer to pull the tracking gate off is small compared to the time which elapses during the tracking phase. For realizable J/S an optimally designed jammer delay controller can achieve range gate pull-off on the order of 1/2 second elapsed time for contemporary AI radars (18). Current laboratory-model United States jammers, however, are mechanized with an operator-adjusted control for the rate of pull-off. Maladjustment usually results since experience in general is obtained against obsolete radar equipment.

Angle Tracking Subsystem

The purpose of the angle tracking subsystem is to generate line-of-sight angles and rates of change of these angles in an azimuth-elevation coordinate system. These signals are furnished to a computer which requires a S/N dependent upon the tactical problem. In order to do this, the subsystem contains automatic tracking and space stabilization circuitry.

In current radars the angle tracking subsystem consists of two servo loops. The first of these is the "inner" loop which is concerned with stabilization. The purpose of this loop is to relieve the "outer" or tracking loop of the noise generated by own ship's motion. As previously stated, the objective of the inner loop is to reduce the line-of-sight noise to 1.0 mil and the rate of change of the line of sight noise to 0.5 mil/sec. This is to be accomplished in the absence of signal as well as during tracking. Figure 24 gives a block diagram of an angle tracking subsystem. Figure 25 gives the track mode stabilization performance of a typical radar (8). It is important to note that in the absence of a signal, antenna stabilization is still available because of the "inner" loop. In many contemporary radars a special track-mode stabilization loop is not employed; stabilization is accomplished through tracking the target. These nonstabilized systems are extremely susceptible to CM of any sort which will cause disappearance of the target signal.

The "outer" loop as shown in Fig. 24 is utilized for angle tracking the target. The closed-loop response of the "outer" loop is shown in Fig. 26 (8). This closed-loop response is a result of mechanizing toward the open-loop response curve of Fig. 27 (4).

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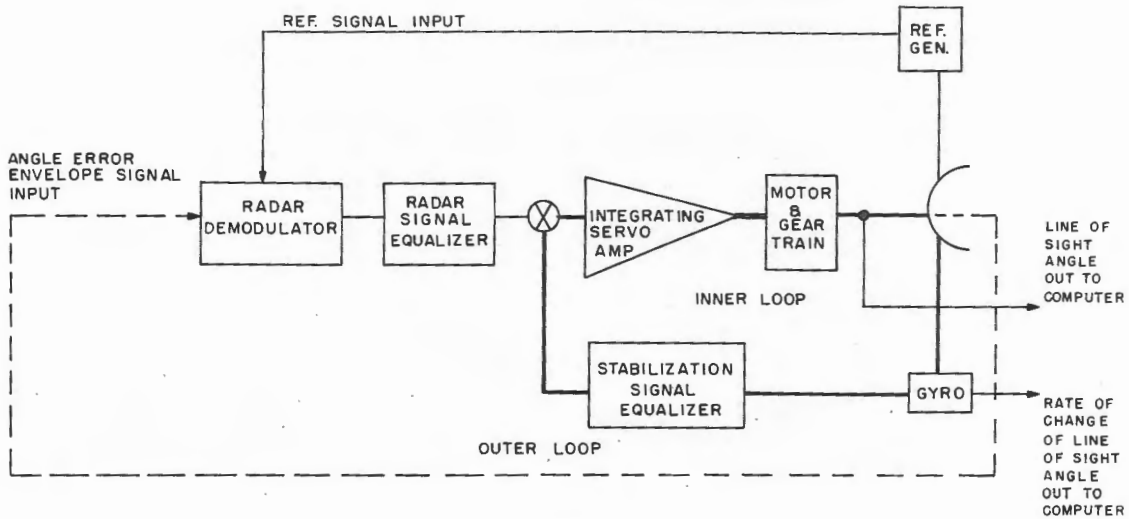


Fig. 24 - Typical angle tracking subsystem

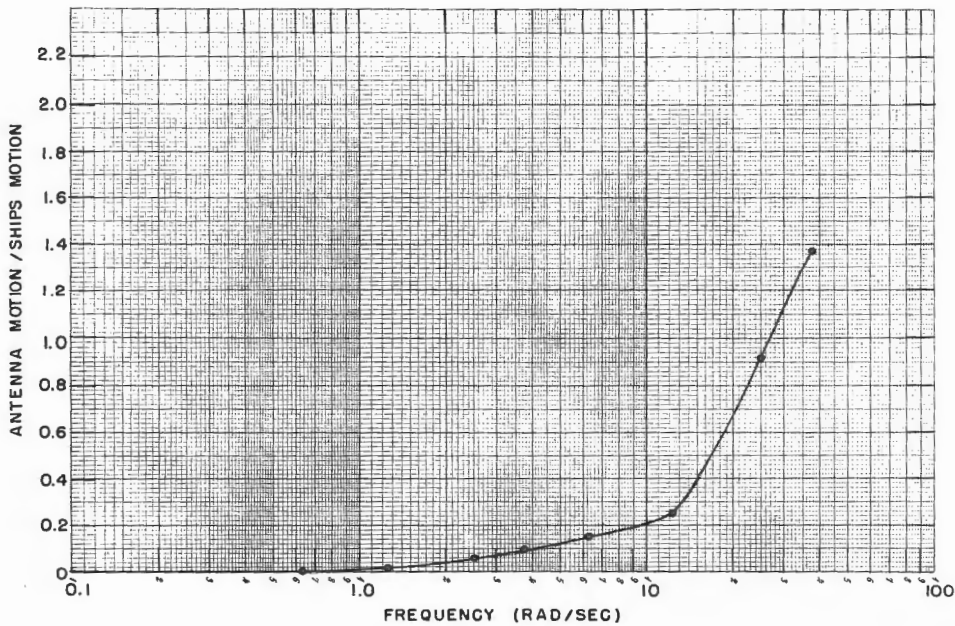


Fig. 25 - Track mode stabilization performance of a typical radar

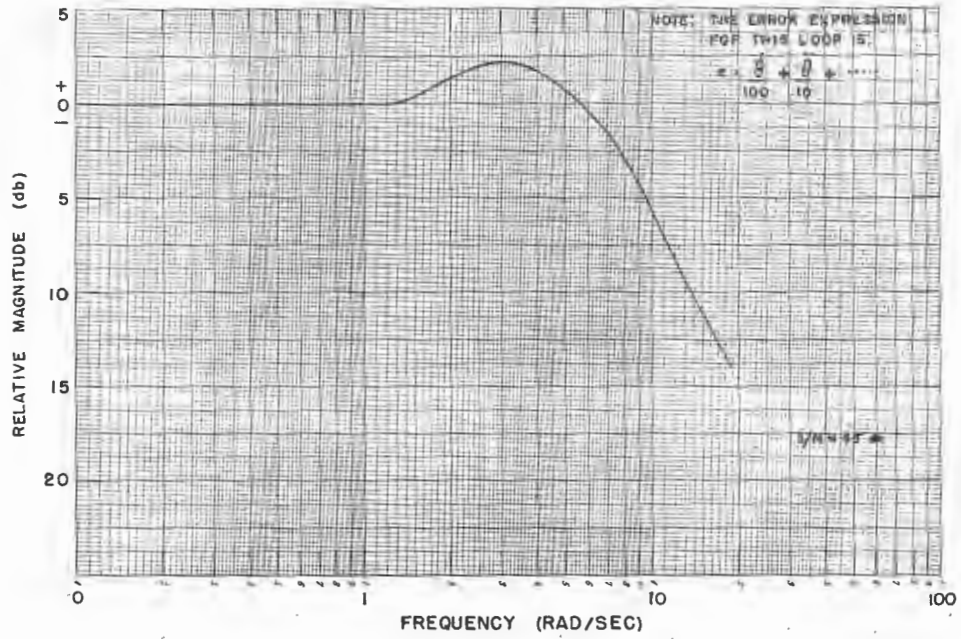


Fig. 26 - Closed loop frequency response of the elevation angle track loop

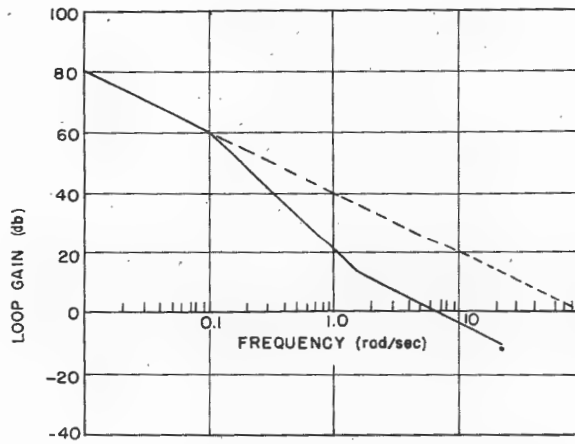


Fig. 27 - Open loop transfer characteristic in the angle track mode

Environmental Jamming - A double integrator tracking system is used which takes advantage of a knowledge of the bandwidth required to solve only the tactical problem. This reduces the susceptibility to environmental jamming, because the bandwidth employed is small enough to exclude much of the environmental noise. By reason of its design to exclude noise, the angle tracking loop is not susceptible to jamming.

The antenna beam when nutating passes the wings of the target twice in each scan cycle, resulting in a large envelope signal at the second harmonic of the scan frequency. Figure 28 shows that the angle demodulation circuit response at the second harmonic of the scan frequency has been minimized, thus reducing the susceptibility to this natural CM (9).

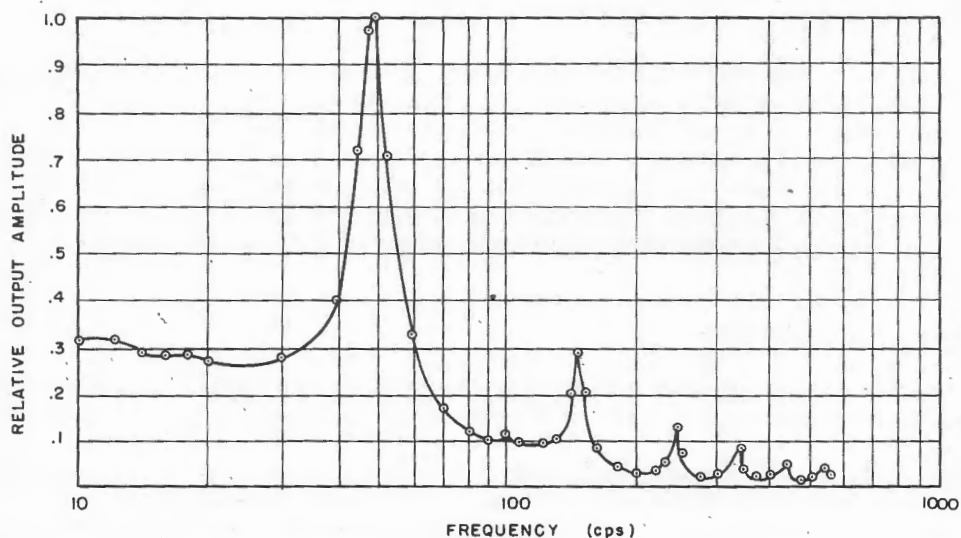


Fig. 28 - Angle demodulator frequency response

Brute Force Jamming - Gating the target in the angle tracking subsystem is accomplished by (1) antenna beamwidth, and (2) gating employed to select the target in range. In addition, range and angle tracking transfer characteristics designed to handle only the tactical problem are a great aid in reducing susceptibility to chaff. There are areas on the beam of a target where both gating methods and the favorable transfer characteristic will fail. Then the angle tracking subsystem becomes susceptible to chaff.

The angle tracking subsystem by itself is not susceptible to brute force jamming. Given the proper input signals from the rest of the system (which is susceptible) it is capable of angle-tracking either the target or the jamming signal.

Deceptive Jamming - Several forms of deceptive jamming will be employed against AI radars. The types and their effects on the angle tracking subsystem are as follows:

1. Modulation at the Scan Frequency - In this method the jamming signal is modulated at or near the conical scan frequency of the radar. The conical scan signal is generated within the jammer utilizing intelligence information relating to the scan characteristics of the radar to be jammed. Because of the close tolerance maintained in the scan frequency, the radar is susceptible to this type of modulation. AJ modifications will be discussed later.

2. Inverse Gain - In this method the jammer will receive the modulated signal as transmitted by the AI radar. He will change the angle sense (phase of scan signal) of the radar signal, amplify it, and retransmit the signal. The susceptibility of the radar to this type of jamming is heavily dependent upon the tactical situation. If the jammer is working against one isolated AI radar, he can jam this radar. If he has to jam several radars he will fail. Verification for these conclusions is given in a report which describes the results of tests conducted at NRL (19).

3. Crosseye - This form of jamming employs a method of distorting the phase front of the reflected signal from the target. The effect is an indirect one on the angle tracking subsystem. As a result of the jamming, the rest of the radar will supply the angle circuitry with false data. The angle tracking subsystem will perform according to its design specification. The radar as a whole is vulnerable to this jamming technique. As a side note of interest, according to the design concepts of Crosseye, monopulse systems are believed to be even more vulnerable to this type of jamming than conical scanning systems.

Cockpit Display and Controls

The purpose of this subsystem is to provide the pilot with suitable display and controls so that he can zero the lead angle error in order to successfully launch the weapon.

Display - The display in the track mode is subjected to the same sort of environmental jamming as was described in the search mode. There is less effect due to ambient light in the track mode of operation because the signals displayed can be at a higher intensity and are of characteristics well known to the pilot. By comparison with the search mode, degradation of the track mode is less, but the situation is poor at best.

In addition to the environmental CM described above, there are currently several man-made features which serve as effective CM. For example, a number of markers and lines engraved on the scope face are not necessary in any of the modes of operation. They cause confusion and result in self-made jamming.

The location of the display introduces another self-made CM into the track mode of operation. During the tracking the pilot must look up from the scope to observe the target optically (if he wishes to resort to optical tracking or an optical check). This results in a reorientation and accommodation problem. The lost motion resulting is obvious.

Controls - During the track mode of operation, a multiplicity of controls and control locations can represent a self-made CM. For example, if the pilot wishes to switch from missiles to a back-up weapon such as rockets he has to remove his eyes from the scope, locate the control, set the control, and return his eyes to the scope. In addition, he may have to switch hands on the joystick in order to select the desired weapon.

As described previously, a second example of the self-made CM imposed by controls is the location of the indicator relative to the joystick. In one current fire control system (F4D) the joystick obscures part of the scope.

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PROGRAMS TO REDUCE VULNERABILITY

SHORT-TERM IMPROVEMENT PROGRAM
(2 TO 3 YEARS)

The preceding sections have described the current status of the AI radar and the susceptibility of its subsystems to environmental and intentional CM. It is now of interest to investigate what can be done to improve the performance of the radar on a short-term basis (2 to 3 years). In many cases the AJ modifications proposed for the short-term program result in improvement which can be demonstrated only under special tactical conditions. They do not represent the optimum solution to the problem nor are they likely to result in tactical improvement. In the long-term program, to be described later, these modifications will be discarded and others which represent system improvements of tactical utility will be substituted.

The basic purpose of any AI radar is to provide range, line of sight, and rate of change of line of sight information to the fire control computer. It has been shown that in the presence of environmental and intentional jamming these radar outputs can be denied the fire control system as it is currently configured. Figure 29 gives a block diagram for a proposed short-term system which could re-establish the radar outputs in the presence of some forms of jamming. Basically, the changes consist of the following:

1. An improved modulator and transmitter designed to reduce friendly interference and enemy jamming.
2. A receiving system designed to have improved performance in the presence of clutter and brute force jamming through the incorporation of a limited amount of i-f fast time constant (backbias) and a gated i-f amplifier to allow angle tracking on a brute force jammer. Jamming will still deny direct range output. Utilization of velocity memory and automatic reacquisition circuitry, however, should furnish the computer with sufficiently accurate range information to solve the problem.
3. An improved indicator and cockpit layout to relieve self-jamming.

The following is a discussion of the improvement features to be incorporated in the short-term interval. Details of the degree of resulting improvement are given.

Tuneability

Currently most AI radars operate on one frequency; 9375 ± 40 Mc is the specified frequency band, but in practice most magnetrons fall within ± 5 Mc of the design center frequency. As was shown in the preceding sections, operating on one frequency is an aid to the jammer and also increases friendly interference.

Navy planning currently calls for future AI radars to have in-the-air tuning capability. The tuning range is to be ± 400 Mc. The benefits to be gained by in-the-air tuneability are questioned. It is true that in-the-air tuneability would defeat current slow tuning jammers; but by the time this in-the-air tuneability feature is available in the Navy, AI radar jammers having the same tuning capability will also be available.

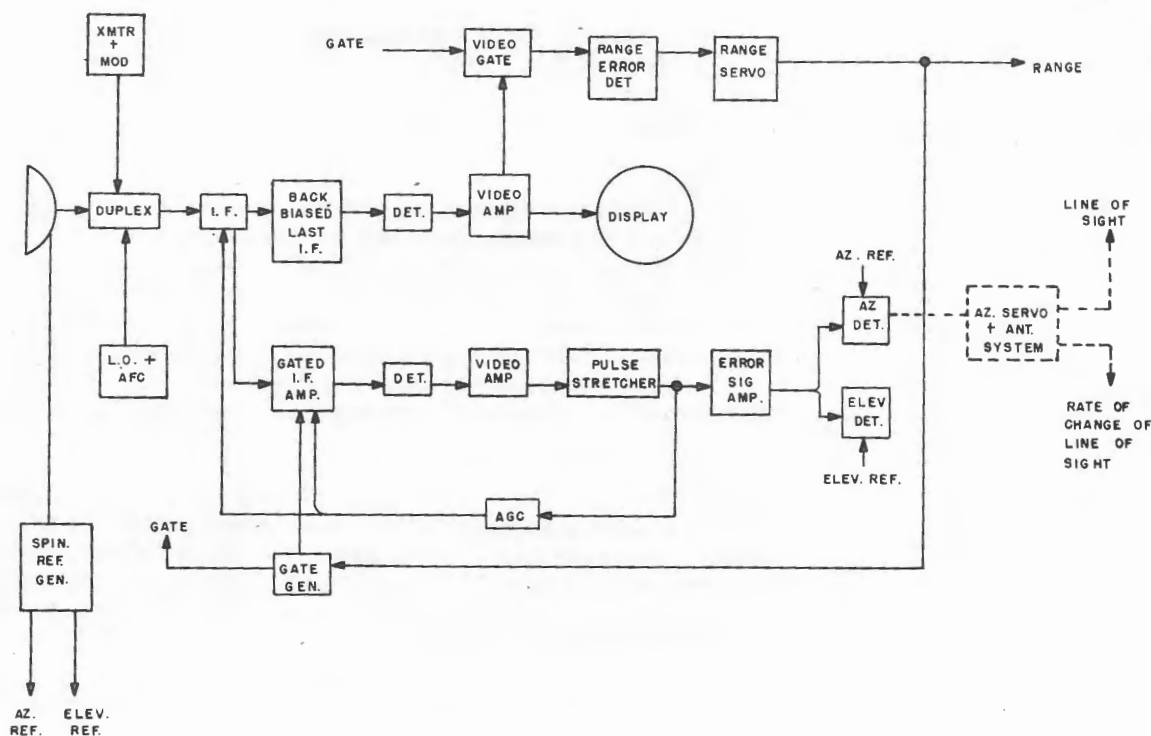


Fig. 29 - Proposed short-term AJ improvement

Incorporation of in-the-air tuning capability results in penalties in the normal performance of the AI radar and in any accessories which must be added to the radar for missile launching capability. One area of concern is the performance of the antenna and radome. Even under fixed frequency operation it is difficult to obtain satisfactory performance of these elements. For instance, as shown earlier, there are current AN/APQ-50 specifications for antenna crossover, beamwidth, sidelobes, percentage modulation as a function of angle, second-harmonic distortion, boresight shift, etc. These specifications call for tolerances which are governed by the state of the art. It will be impossible to achieve these specifications in the short-term era if the frequency is allowed to vary continuously over wide ranges unless the state of the art advances much faster than in the past.

In addition, one of the current missile systems (Sparrow III) requires cw injection into the AI radar. If in-the-air tuneability of the AI radar results in less jamming vulnerability, then it seems reasonable to assume that the fixed-frequency cw link used for the Sparrow III missile system is very susceptible. Therefore, to be consistent with in-the-air tuneability concepts, this cw injection frequency should also be made capable of wide-band continuous tuning. The missile equipment, to be compatible, will then require automatic tuning capability. It is currently impossible to mechanize a doppler system using a continuously tuning magnetron, because the time intervals involved between transmission of the signal and reception of the echo results in an error in the doppler signal received. It is difficult to separate the AI radar frequency and the cw injected frequency. Spot frequency filters are used. It will be extremely difficult, if not impossible, to separate these signals if continuous tuning of either the radar or the cw transmitter is employed. Filters which can be automatically tuned are not available now or in the foreseeable future.

Other problems of a major nature are AFC and receiver tracking problems, changes in tracking loop gains, and loss of power as a result of tuning. All of the changes in system characteristics occur at a frequency which will fall within the frequency response band of the angle tracking loop. In addition, penalties in size, weight, complexity, and ease of maintenance must be paid.

As previously shown, the pilot now has available too many controls. The addition, as planned, of in-the-air tuneability will result in even more controls, plus the fact that the pilot must make the decision as to when this tuneability feature is to be used and whether he will be any better off having tuned.

It appears more feasible to design the tuneability feature on the basis of a number of preselected spot frequencies to which the equipment can be preset while on the ground. The changes in system operation as a result of changes in frequency, can be compensated for at the same time that the frequency adjustment occurs. Properly engineered, these compensations, if even necessary, can take very simple forms such as the connecting of links between terminal points or the use of plug-in jumpers.

The most frequent form of jamming which the AI radar encounters is friendly jamming from other radars. It has long been fleet practice to select magnetrons to avoid this problem. The fleet is thus well prepared to use the spot-frequency approach to tuneability. Obviously, the use of spot-frequency tuneability will greatly relieve the susceptibility presently existing, because enemy jammers will not be able to jam so easily over a widely spread band of frequencies.

Scan Frequency and PRF Stability

As shown previously, the use of stable scan frequency and prf as currently employed represent areas of susceptibility to jamming. Currently, the scan frequency tolerance band is approximately $\pm 5\%$, but individual equipments will have a fixed scan frequency somewhere within this band. It is recommended that the prf be jittered $\pm 10\%$ and the scan frequency be allowed to drift in a random fashion over ± 5 cps. The proposal to allow this scan frequency to randomly drift over ± 5 cps will actually result in a weight and complexity reduction in current equipments. Design engineering may be required, however, to assure that the system subcarrier circuitry is flat in amplitude and phase over the proposed band. No increase in hardware should be necessary.

I-F Gating

The brute force jammer potentially represents a very large signal at the location of the target if the AI radar could use it. Current AI radars, however, as was shown previously, are not capable of tracking such a jammer. The block diagram of Fig. 29 illustrates a technique for allowing angle tracking on the jamming in the presence of brute force jamming. This technique consists of gating in the i-f section of the receiver to convert (chop) jamming to a pulse form for which the radar was designed. Once the signal has been converted to pulses, the AGC and angle track portions of the AI radar perform in a normal fashion. The tracking capability will be enhanced by the stronger jamming signal.

Experience and analysis have shown that any form of modulated cw, except where the modulation frequency is very close to the scan frequency, can be tracked with little or no increase in tracking noise. Transition between angle-tracking the echo and the jammer is

automatic without the use of switches. It is obvious that range tracking information will not be available during heavy jamming ($J/S > 10$ db) with this system alone. The "velocity memory" feature of the range tracking circuitry, however, will allow range information to be extracted on the basis of extrapolation of the last known target velocity for a limited period of time. The regenerated or "velocity memory" range information can be mechanized to have utility for a period of time varying between about ten and several hundred seconds depending upon the nature of the jamming.

When the gated i-f system is used, with $J/S > 10$ db, if the jammer is turned off when the echo is not in the range gate, steps must be taken to reacquire the echo. This should be accomplished automatically. The additional hardware for accomplishing i-f gating is small, simple, and well known. A maximum of four additional vacuum tube stages would be required. Because of the use of a one-way propagation path, the gain of the angle tracking loop is halved. This change in performance in a well-designed system is a minor one which can be tolerated with little loss in weapon system effectiveness.

Range Tracking Subsystem

It was shown previously that a J/S of 10 db for cw jamming and 0 db for noise-modulated cw jamming limits the performance of the AN/APQ-50. It is proposed that the FTC of the current radars be replaced by a backbiased last stage in the main i-f amplifier. Further, it is proposed that automatic reacquisition features be added to the range tracking subsystem.

Backbiased I-F Stage - Figure 30 is a schematic of a typical backbiased last i-f stage. The performance of this stage in the presence of cw jamming is shown by Fig. 31. This figure shows that an improvement of 10 db in J/S capability is realized by using this backbiased stage (20). Thus the range tracking performance of the system will be essentially unimpaired for a J/S up to 20 db per stage of backbias amplification. Since the backbiased stage has been designed to take advantage of the spectral difference between the jamming and the signal, the improvement approaches zero as the spectral difference approaches zero. Thus, the improvement will approach zero when pure noise is used.

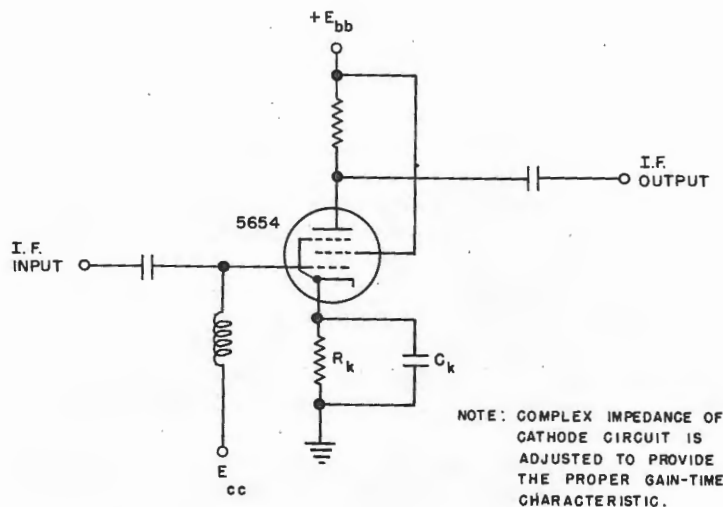


Fig. 30 - Typical backbiased i-f amplifier stage

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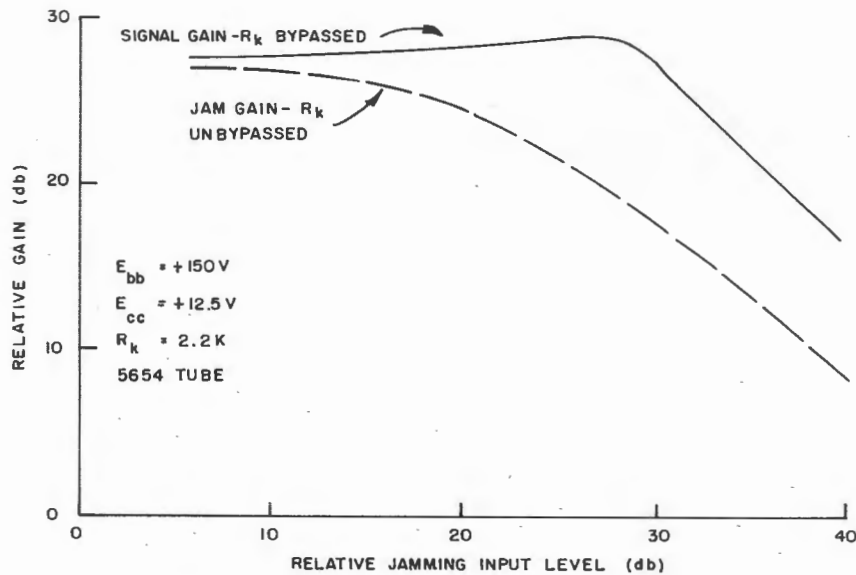


Fig. 31 - Performance of a typical backbiased i-f amplifier stage.

Practically, the jammer cannot afford to carry the power necessary to modulate a carrier 100% (rms) with wide-band noise. Thus, in general, the carrier is much less than 100% modulated (large cw jamming content still available) and the spectrum of the jamming is much less than wide-band. Since this is true, some improvement in J/S will always be available in tactical use. In addition, the performance of the system in the presence of clutter will be improved, because the backbias technique gives better FTC performance than the video differentiating circuits now in common use.

Range Tracking Improvements - It was stated in the section on i-f gating that if the jamming signal is turned off, the possibility of having to go completely through the search and acquisition phases exists. The techniques described here for automatic reacquisition will serve as an aid during this type of tactical situation. If the system is homing on jamming and the jammer turns off his signal, automatic range search will be initiated to reacquire the actual target. The methods used are simple and require no additional switches or relays over those now employed.

Typical range tracking circuitry is overly complex for the rather simple tasks it is called upon to perform. Earlier work has shown that a simpler circuit having automatic reacquisition features is possible of attainment (21). Part of the earlier work relating to automatic reacquisition will be repeated here.

Figure 32 shows the sequence of events which occur in the proposed reacquisition sub-system. Until time t_1 the radar is range- and angle-tracking the target. The indicated and actual range are equal within the accuracy of the system. At time t_1 the signal is denied the range tracking circuitry either through a fade or the encountering of enemy jamming. The double integrator tracking circuit required to adequately solve the tactical problem fortunately provides a "coasting" feature in the absence of a signal. The range output voltage during the jamming or target-fade period is a result of the coasting feature and is in error

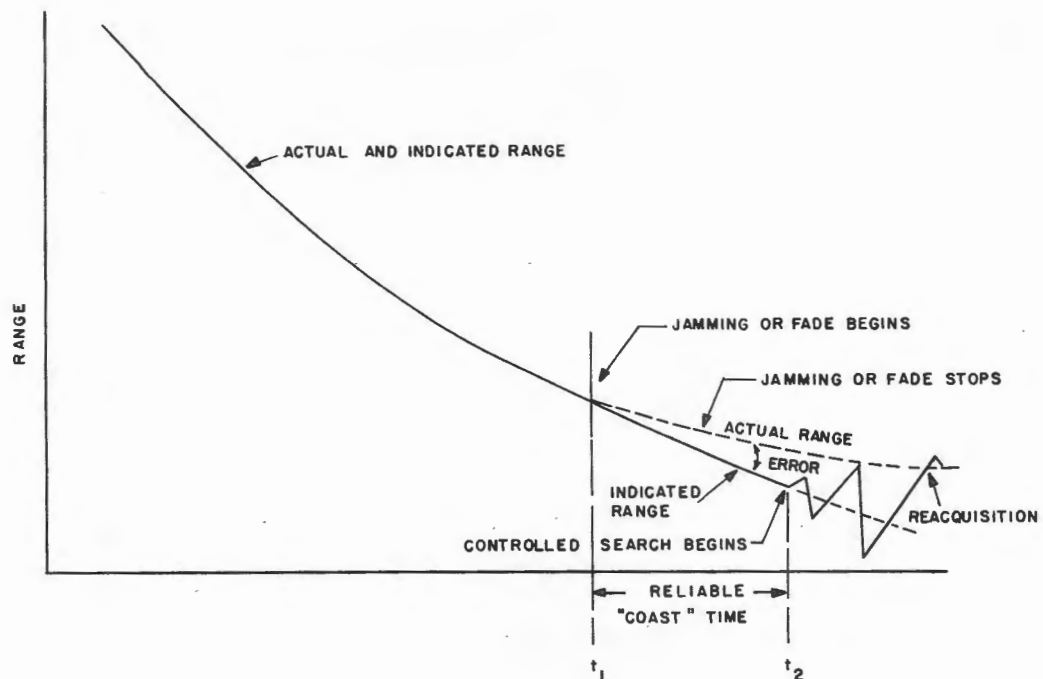


Fig. 32 - Recommended reacquisition program

from the actual range by an amount depending on target maneuver and radar circuit design. For a given target maneuver and a given circuit design, the error as a function of time after t_1 has a calculable and measurable maximum value (under laboratory conditions). Comparison of this maximum error under all practical conditions with the allowable error which the tracking system can accept and just re-lock results in the development of a "reliable coast time" which can be mechanized into the system to initiate search for reacquisition. Since at time t_2 the target is not expected to be far from the indicated range (gate position), the first few cycles of search should be at small amplitude with a gradual increase in the search amplitude to the normal maximum value of one mile. Figure 33 gives a signal flow block diagram of the suggested mechanization for automatic reacquisition.

Indicator and Cockpit Layout

In the section on jamming vulnerability of current AI radars it was shown that the pilot's indicator and cockpit layout constitute a source of CM susceptibility (environmental and self-made). The following is a discussion of recommended short-term improvements for the indicator-cockpit arrangement.

In the short-term program three important characteristics of the cockpit should be considered in connection with the vulnerability of the AI radar to environmental and self-made CM. These characteristics concern the indicator display itself, the number and operational use of presentation adjustments, and the ability of the pilot to extract tactical utility from this complex equipment.

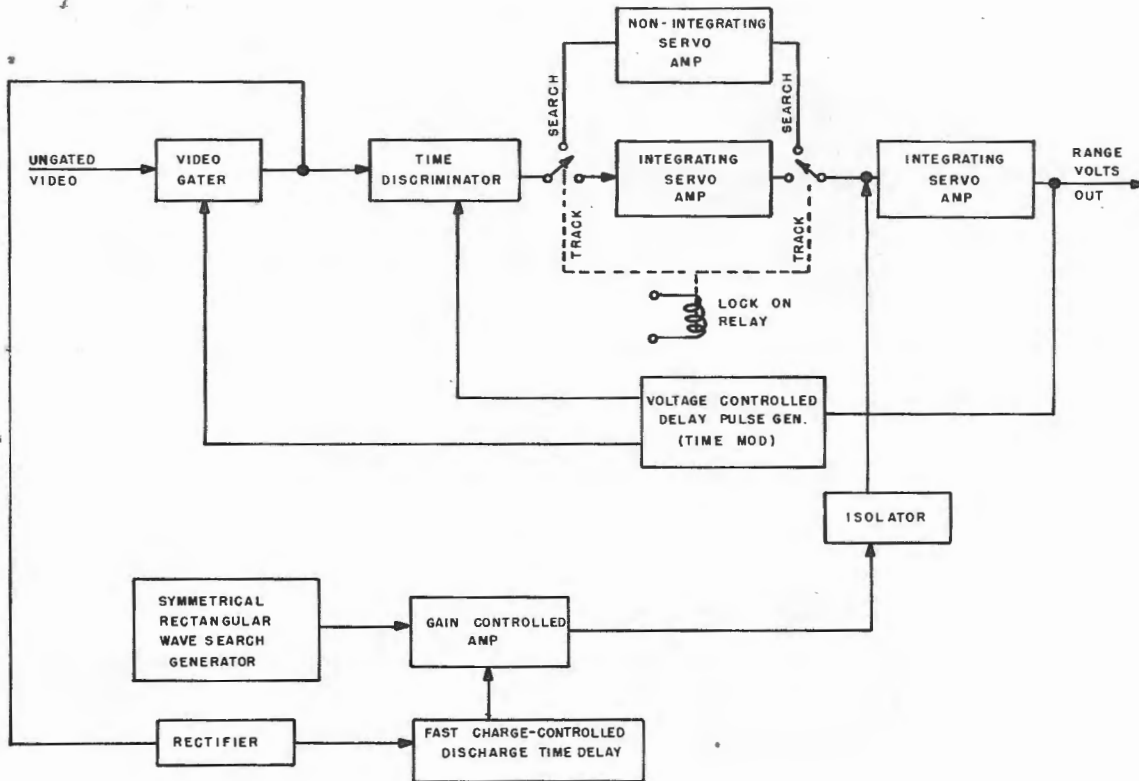


Fig. 33 - Automatic requisition system

For the short-term improvement program, it is recommended that the following steps be taken to improve the operational deficiencies related to these characteristics:

1. In current installations (F4D) the placement of the indicator introduces high-level ambient light and interferes with the aircraft control stick. Only the deficiency due to ambient light can be alleviated in the short-term period. Various agencies have partially designed and tested hoods to restrict the ambient light reaching the indicator tube. This has resulted in a number of incomplete quick fixes. It is recommended that a panel be appointed to examine the hoods and the test data concerning them with the objective of establishing an optimum design and immediately introducing it into operational squadrons.

2. Nonreflective coatings should be added to the indicator tube and the faces of other cockpit instruments to eliminate spectral reflections.

3. A number of studies (22) have been conducted which indicate the necessity of painting the instrument scales, and other surroundings with light paint to increase the contrast between operational instruments and the background. Presently dark paints are used. It is recommended that the results of the above studies be applied.

4. In the F4D installation, the accessibility and complexity of the radar set control is such that operational usage of the system is marginal. This control was designed to be used in a readily accessible location. Since it will be impossible in the short-term program to relocate the control it is necessary to optimize the mechanization of the set control to compensate for the poor location. The type of set control used in this installation results in crosstalk between azimuth and elevation channels when acquisition is attempted. In addition, all of the controls which are used by the pilot during the operation of the equipment are poorly placed on the set control. It is recommended that the set control be optimized for the poorly designed cockpit layout of the F4D and that the mistakes made in the F4D be avoided in other installations.

5. Current search-scan patterns represent a source of self-made CM. These search patterns are not optimum and result in reduced detection and lock-on ranges. The search pattern can be changed in the short-term period to one which is consistent with tactical requirements. The present search pattern is inconsistent with the requirements for vectored intercepts. The design of a search pattern should be accomplished so that it puts a maximum of average power into the region where the target is most likely to appear. If the search volume is too large, the average detection range is decreased because the average power per unit volume decreases. If the volume is too small, the target may be lost because the volume does not cover the actual target position. Thus the design of a search pattern must be a compromise between these two factors.

A further factor which tends to penalize the user of an extra large search volume is that it increases the probability of mutual interference and, at the same time, allows a jammer located away from the target to jam the AI radar. Thus fewer barrage jammers would be required to cover an attacking force.

The search volume which an AI radar must cover is dependent upon the accuracy of the vectoring system. The vectoring system informs the pilot of the expected position of the target with respect to the interceptor. This information is extracted from search radars and height-finding radars. At 80 miles range (search radar to target) the search radar azimuth information will have an error with a standard deviation of 0.8 naut mi. The search radar information pertaining to the interceptor will have a similar error. The information will be processed and eventually transmitted to the interceptor. The accumulative error of the entire system, target position relative to interceptor, is likely to reach a standard deviation of 2.0 naut mi. The errors in height-finding are likely to be approximately 1 naut mi standard deviation from the designated altitude (99% lie within 15,000 ft of the designated altitude). This rather large error in altitude comes about from two factors. The first is equipment errors and the second is the fact that a single piece of height-finding equipment is to be shared to obtain height information on a number of enemy and friendly targets. This often makes the data obsolete under saturation conditions.

To cover the volume of expected target positions and have no appreciable number of targets outside the search volume requires an azimuth search of about 24° and an elevation search of 12° when the designated range is greater than about 25 naut mi. This search should be centered on the designated azimuth and elevation angles to the target.

When the range decreases, the search angles required to cover a volume in space increases. A search pattern 40° in azimuth and 20° in elevation will adequately cover the volume of expected target position within about 10 naut mi. At ranges closer than this, an increasing number of targets will be lost because they would fall outside the search volume. By the time that the target has closed to 10 naut mi, however, most targets must have been detected to provide for high system effectivity. Many of those targets that remain will not be detected in time to consummate an attack. The only true measure of the success of a

fire control system is the number of attempted intercepts which result in a kill. To kill a target from the rear hemisphere with conventional weapons may call for a detection range of only 2 to 4 naut mi, while a kill with a special weapon in the forward hemisphere may require nearly 20 naut mi.

A measure of detection system adequacy is the number of detections which occur at an adequate range for the particular tactical situation. Figure 34 shows the computed cumulative probability of detection of a target as a function of range for two hypothetical radar systems. The only difference in these two systems is the search volume coverage. One system has a search coverage of 10° in elevation and 100° in azimuth. The other uses a $12^\circ \times 24^\circ$ search volume for ranges about 25 naut mi, and a $20^\circ \times 40^\circ$ volume of coverage inside 25 naut mi. The $10^\circ \times 100^\circ$ radar shows poorer probabilities at all ranges. It suffers by having so large an azimuth coverage as to reduce the average power on the target, while having so small an elevation coverage as to lose targets in the elevation coordinate. The use of different search patterns for different ranges more nearly fits the required conditions.

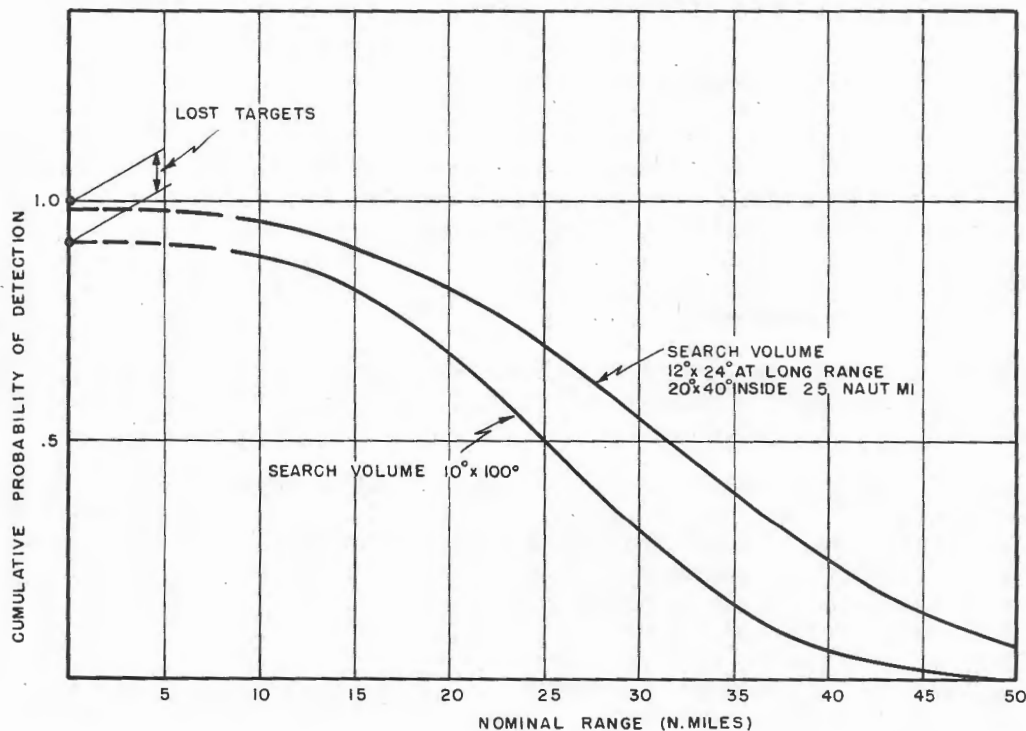


Fig. 34 - Search ranges for optimum and nonoptimum scans of a hypothetical AI radar

If the tactical situation were such that a detection range of 20 naut mi was required to convert the attack into a kill, the $10^\circ \times 100^\circ$ search system would allow only 68% of all intercepts to proceed from the detection phase to the tracking phase, while the optimum multiple search volume system would allow 82% to proceed to the tracking phase. Table 1 summarizes these results for various required detection ranges. The required search coverage for AI radars is shown by Fig. 8. The theory from which the optimum search coverage was developed is given in an NRL Report now in preparation (10).

TABLE 1
Percent of Aborts due to Insufficient Detection
Capability of the Radar System

Detection Range Required for a Successful Kill (naut mi)	$10^0 \times 100^0$ Search (%)	Multiple Search (%)
20	32.0	18.0
15	18.6	9.5
10	11.5	4.4
5	9.0	2.0
2	8.5	2.0

Research Directed Toward a Long-Term Improvement Program

The previous sections have described techniques for modifying AI radars to improve their performance against limited types of CM and tactical situations. These techniques can be easily incorporated in the system without disrupting an entire production program. It is recognized, however, that these AJ improvements are not the ultimate. They represent a compromise consistent with the time schedule and may not result in any tactical utility. The following discussion cites the deficiencies of the short-term improved system as related to the tactical sequence of operation.

In a typical tactical situation the radar has three modes of operation: search, acquisition, and track. It is necessary to examine each of these modes to establish the remaining susceptibility to environmental and intentional CM.

There are four basic improvements recommended for the short-term program which reduce susceptibility in the search mode of operation. These are on-the-ground tuneability, scan pattern optimization, backbiased last i-f stage, and display and cockpit improvement. All of these improvements help in the presence of environmental CM, and thus also in the presence of intentional CM, by the simple process of increasing the available signal-to-noise ratio. Insufficient improvements have been incorporated, as a result of the short-term program, to counter all expected magnitudes and types of jamming. A remaining susceptibility is the loss of range information. It is possible to achieve range information under all conditions of expected jamming. Improvements to effect this are discussed in the section on long-term improvements.

The recommended short-term improvements which aid during acquisition in the presence of jamming are basically the same as those stated in the preceding paragraph for the search mode. Jamming which is initiated during search will in all probability continue during acquisition. Thus the basic remaining problem during acquisition is one of obtaining range information in the presence of an interfering signal. If the recommended short-term program is followed, the system would lock-on and track the jamming signal in angle. No range information would be available.

In the track mode of operation all of the improvements recommended will reduce the susceptibility to CM and hence system vulnerability. There are areas of susceptibility, however, that still remain. If the jamming begins prior to acquisition and continues into the tracking phase, it will not be possible to get range information through the use of the normal range tracking circuitry of the radar. It may be possible to have a tactically useful missile system which utilizes the recommended homing-on-jamming feature (gating in the i-f) and an estimated launching range based on signal strength measurements or other methods. It will not be possible to have a tactically useful rocket and gun system without further AJ modifications.

LONG-TERM IMPROVEMENT PROGRAM (3 TO 5 YEARS)

In the preceding section a short-term AJ improvement program was described. The improvements and remaining deficiencies were detailed. In this section a long-term AJ improvement program which attempts to reduce some of these deficiencies will be described. The basic premise that design based upon optimum AI radar performance in the presence of environmental CM will also give improved performance in the presence of intentional CM will be followed throughout. It is believed that if a research and development effort is started in the near future on the long-term improvement program, operational equipment can be made available in this period of 3 to 5 years. All the improvements recommended for this period will require research and development.

Figure 35 gives a block diagram of the basic AI radar proposed for the long-term period. Basically the changes consist of (1) an AFC design compatible with the bandwidth of the i-f amplifiers to be described later, (2) a narrow-band gated i-f system for angle tracking, (3) wide-band backbiased i-f amplifiers for range tracking and display (using video gating for range), and (4) improved display and improved cockpit installation.

In addition to these basic changes the following improvements recommended to the short-term program will be retained: (1) on-the-ground tuneability, (2) ungoverned scan frequency, (3) ungoverned prf, (4) jittered prf, (5) improved search scan, and (6) gating in the i-f. In addition shortening the pulse width and gate width to counter pulse-to-pulse repeaters should be considered contingent upon the state of the art. The improvements realized from the AJ features recommended for the short-term program have been discussed previously. The following sections discuss the AJ features recommended for the long-term program along with the resulting improvements.

Separate I-F Channels for Angle-Tracking and for Range-Tracking

The main outputs of the radar system are line-of-sight angle, rate of change of line-of-sight angle, and range. Because of the differences in the nature of the signals, range being wide-band and angle being narrow-band, the transmission path through which the signals must pass should be compatible. It is proposed that a narrow-band gated i-f amplifier be the first system element through which a separate angle signal is passed and that a wide-band backbiased i-f amplifier be the first circuit element through which a separate range signal is passed. This approach has the advantage of narrowing the aperture to that actually required by the signal. In addition, the wide-band backbiased i-f amplifier is used to pass the display signal through a minimum aperture actually required by the nature of the signal.

Wide-Band Backbiased I-F Amplifiers for Range-Tracking and Display

In the section on short-term improvements a last-stage backbiased i-f amplifier was recommended. Figure 30 gave the basic diagram of a backbiased stage. The performance of this backbiased stage was shown in Fig. 31. For large cw jamming signals (clutter and intentional jamming) a 10-db J/S improvement is obtained. On the basis of a J/S of 60 db being required and the fact that the current system already has a 10-db J/S, five stages are required to accomplish the desired J/S (20). This improvement will be realized in both search and range tracking modes.

The passband of the range track-display i-f amplifiers is a function of the pulse length used. In the track mode of operation (using a 0.5- μ sec pulse) the passband required is 2 Mc, and in the search mode it is 0.57 Mc. In the current AN/APQ-50, the bandwidth used is 4.0 ± 0.5 Mc. It is recommended that this bandwidth be reduced to a compromise value of 2 Mc for both search and range tracking. This results in two improvements. First, it narrows the aperture through which jamming can enter, and second, it results in an improvement in detection range.

The bandpass should be designed with steep skirts to minimize the effect of sweep frequency jammers. The amount of energy which gets through this passband is dependent upon the steepness of the sides of the i-f passband, the frequency of jammer sweep, and the jammer frequency sweep excursion. In general, the steeper the sides, the higher the sweep frequency; the higher the center frequency of the jammer, the lower the entering jamming energy will be.

The range track and display filters shown in Fig. 35 are the result of the need for equalizing the range-track and display signals which have been passed through a compromise i-f amplifier chain. The nature of this compromise is slight because of the slight difference between the required bandwidths (2 Mc and 0.57 Mc). The design of these filters should be such as to optimize both display and range tracking.

The remaining circuitry in the range tracking loop will be essentially the same as in modern AI radars. Current design, however, is believed to be overly complex. The design to reduce complexity and thus increase reliability should also incorporate the automatic reacquisition described in the short-term program, because this circuitry represents an improvement in the absence of jamming.

The 50-db improvement in J/S capability realized by using five stages of backbias is based on cw jamming. As the jamming signal spectrum approaches the spectrum of the reflected signal and as the jamming modulation factor increases, the J/S improvement will progressively decrease. In the tactical situation, the power required to generate wide-band, highly modulated jamming is such that the expected jamming signal will be narrow-band noise with a large cw content (low modulation percentage).

Narrow-Band Gated I-F System for Angle Tracking

The block diagram of Fig. 35 shows that a narrow-band gated i-f amplifier is the first element in the separate angle tracking channel. Except for narrow-banding, these stages will be the same as the gated i-f stage described in the short-term program. The

improvement realized by narrow-banding is due to the smaller aperture through which jamming energy can enter. If jamming does succeed in entering the angle track channel, the system will automatically angle-track the jammer.

Automatic Frequency Control

The i-f bandwidths used in the system should be decreased to a value required to pass only the target information. This causes the AFC requirements to become more stringent. It will be necessary, using design techniques presently available to design an AFC (servo system) to reduce tuning errors to the required minimum. It does not appear that this is a difficult problem.

Cockpit and Indicator

The display system for the long-term program should be one which is integrated into the rest of the system. The current trend is essentially one where the indicator is placed in the aircraft as an afterthought. This approach should be avoided in the long-term program. The indicator proposed for the long-term AI radar uses a separate i-f and video channel optimized to provide the best display. All of the improvements recommended for the short-term period apply to the long-term program. In addition, it is recommended that the display be projected into an optical system that will allow it to be viewed simultaneously with the optical image of the target. The placement of this simultaneous display should be at a position in the direction in which the pilot will normally be looking; namely at or near the windshield. This will relieve the current problem of the pilot having to change his field of view from a hooded indicator to outside observation. The eye accommodation problem will be lessened as a result. An extension of the current color separation technique appears to be the most feasible method of displaying radar and optical data simultaneously (23).

In the type of display proposed, it is recommended that a bright radar presentation be utilized. This will probably involve the use of storage-tube techniques. The use of storage tubes is currently being investigated (11). Use of a bright display properly located with additional simplification of controls (as discussed in the short-term program) will result in attaining a total system noise figure under tactical conditions nearer to the 11 db measured in the laboratory than the 25-db currently available.

There is almost unanimous agreement among the pilots using current AI radars that too much extraneous information is presented on the indicator. It is recommended that a study program be started immediately in order that an optimized presentation can be incorporated in the AI radar of the long-term period. This will have the effect of reducing the system noise figure and thus improve its performance in the face of CM (environmental and intentional). In addition, it will result in a system designed to solve only the required tactical problem instead of the present system which partially solves a multitude of irrelevant problems.

The current trend for autopilot tie-ins is partially engendered by the deficiencies of current cockpit layouts. Properly designed autopilot tie-ins will result in further simplification, because the display will be of the monitoring type rather than the type requiring action functions.

Pulse and Gate Shaping

It was stated in the section on the CM threat that pulse-to-pulse repeater jammers will be available in the long-term period. These jammers will have an inherent delay between the reception of a radar signal and the transmission of the jamming. This delay is currently between 0.15 and 0.2 μsec . There is a minimum delay which cannot be improved upon. This is estimated to be 0.1 μsec . Thus a radar with a 0.1- μsec pulse would be useful. The short-term and long-term programs both describe backbias techniques which operate on the spectral differences between the signal and the jamming. Presently used pulse widths result in a spectrum which is not widely different from that capable of being generated by a brute force jammer (but not presently being used). With the above considerations in mind, it is desirable to shorten the pulse and gate widths for the following AJ reasons.

Shortening the pulse and gate widths to 0.1 μsec or less will reduce to essentially zero the probability of a pulse-to-pulse repeater entering the system. Figure 36 illustrates the placement of a jamming signal, having a 0.1- μsec delay, relative to the target signal and gate in the current radar. It is obvious that a jammer would have no trouble getting into the current gate. Figure 36 shows the gate and the target pulse along with the 0.1- μsec delayed repeater jamming signal for the proposed radar. This illustrates that the jammer will not get into the gate. In addition, since the pulse is over before the jammer can start transmission, the pulse repeater signal will not actually be present.

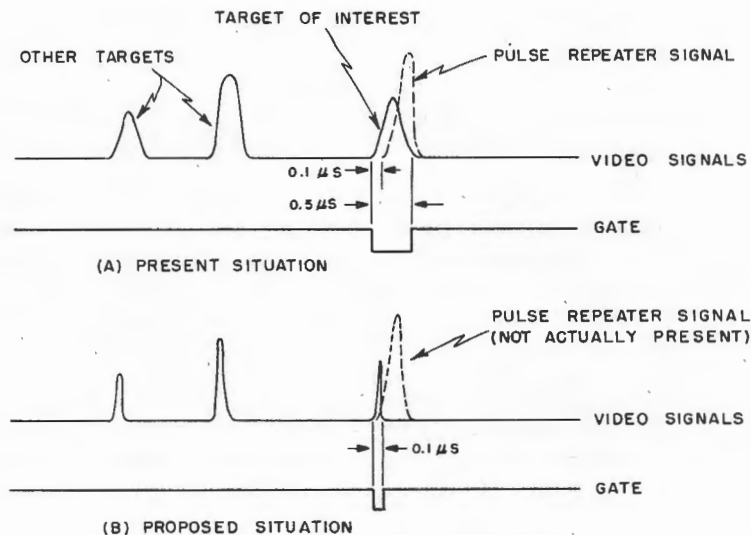


Fig. 36 - Effects of pulse-to-pulse repeaters

Shortening the pulse width will widen the spectrum and thus place more stringent power and weight requirements on the brute force jammer. Figure 37 shows the present spectra of the signal and the jammer. It should be noted that present brute force jammers, if properly tuned, do not adequately cover the pulse spectrum. If the jammer is improperly tuned, the pulse spectrum is sufficiently narrow that it will be extremely difficult to get even partially effective jamming. It is economically possible to develop a jamming system

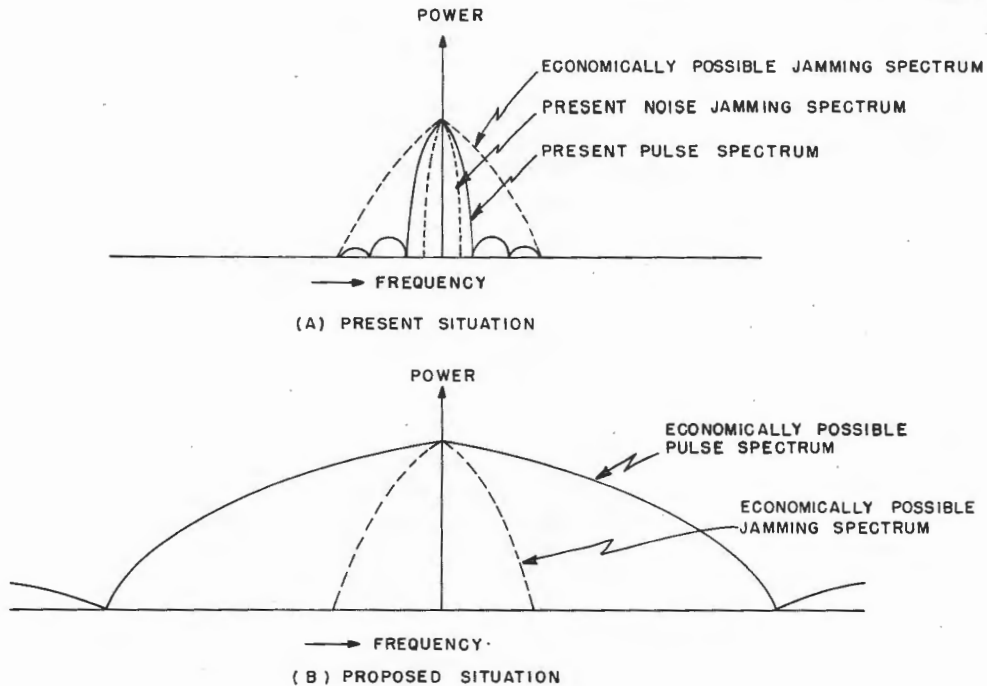


Fig. 37 - Jamming vs signal power spectra

having a large enough spectrum to completely cover the signal spectrum even in the presence of tuning errors. This, however, costs the jammer in terms of weight and size.

Figure 37 illustrates the proposed situation. It shows that the signal spectrum can be made so wide that it is economically impractical for the jammer to match or approach full coverage. The technique of widening the transmitted radar spectrum will make it easier for the jammer to find the radar signal but will leave him some doubts as to which part of it to jam. Additionally, if he does jam, the backbias technique for extracting range and display information will be highly successful in the AI radar. If a transmitting tube is made available for the AI radar with the capability of operating with this short pulse length and with the same average power as currently available, there will be essentially no increase in weight and size anywhere in the system. Except for the transmitting tube availability, the proposed modification can be accomplished using currently known techniques.

Strictly from the AJ standpoint the preceding recommendations to shorten the gate and pulse widths are desirable. However, there are side aspects which need consideration. First, if it is desired to maintain the same average power currently available (detection range is proportional to average power), it will obviously be necessary to raise the peak power of the transmitting tube or raise the prf or a combination of both. There is a practical limit to which the prf can be raised (maximum range limit) and there is a limit to which the state of the art allows peak power to be raised. Additionally, the waveguide and antenna will need redesign to handle greater peak power

At the present time there is a strong desire by many people in the AI radar field to increase the detection performance of the radar via the brute force approach of increasing

average power. It is believed that this is a costly and unnecessary approach because the current AN/APQ-50 has a field noise figure (NF) performance of approximately 25 db. This means that the AN/APQ-50, which radiates approximately 200 watts of average power, is making effective use of approximately 20 watts. The radar is capable of performing with a field NF of approximately 11 to 15 db. Many of the recommendations already made have the objective of regaining the lost average power. Among these are optimized search pattern, optimized display, and reduction of the deficiencies of cockpit layout. Thus it is strongly recommended that since we have sufficient average power we work first toward its full utilization.

If after the full system power capability is realized the need for increased detection performance arises, an increase in average power can then be considered. However, space and weight penalties must then be accepted.

It is recommended that a transmitting tube development program be started immediately with the objective of developing a short-pulse, high-average-power tube.

Low-Noise Figure TWT RF Preamplifiers

The development of low-noise-figure traveling-wave tubes has introduced the possibility of the tactical use of these tubes as rf preamplifiers for search and automatic track radars. It is true that laboratory tests have indicated that receivers with noise figures as low as 6 to 8 db can be designed for X-band operation. The noise figure of the current AI receiver is approximately 11 db. From the standpoint of detection capability the use of the TWT technique appears to be justified. The range improvement realized for a 4-db improvement in NF is 26 percent.

Considering the state of the art in TWT's, however, other factors are believed to be more important than range improvement alone. Reference 19 gives the results of tests which demonstrate that a system using a TWT preamplifier is more susceptible to CM and does not have the dynamic capability required for tracking in the tactical situation. The basic problem is that the TWT saturates on signal levels which can be expected in normal operation of AI radars. For example, the maximum signal strength that the typical radar can expect on a normal tactical problem is 0 dbm. The TWT tested (S-band) saturated at -25 dbm.

Application of the TWT technique introduces several other important considerations. An rf filter will be necessary to reduce the effects of jamming and noise which would be received in the wide bandwidth of the TWT. This rf filter becomes very complex if in-the-air tuneability is to be used. If on-the-ground tuneability is employed, narrow-band TR tubes can also be employed. This will not represent nearly as large a design problem as the filter required for in-the-air tuning. The use of filters will cause an insertion loss and will increase the NF of 6 db to 8 db.

With the preceding considerations in mind, the use of a TWT preamplifier does not appear to be justified in the next 3 to 5 years. The use of a TWT for increased detection range is accompanied by more important detrimental effects. Contractor laboratory demonstrations of advanced crystal mixer techniques have shown a capability comparable to that possible with a TWT, thus relieving the need for TWT rf preamplifier.

Remaining Vulnerability

The vulnerability of any system is a relative thing. It is believed that if the recommendations outlined in the long-term program are followed, the AI radar will not be vulnerable to the types of CM to be expected in most tactical situations. The intentional jammer will have a very low probability of being successful against the AI radar. As will always be the case, however, specific situations can be selected where the radar will be susceptible. Some of these particular situations are angle deception by pulse repeaters, angle deception by Crosseye, very low altitude attacks (considerable improvement to clutter will be realized by the long-term program), and chaff in beam attacks. Of these susceptible areas the principal remaining area is clutter at low altitudes. As stated previously the improved AI radar resulting from the long-term program should be a tactically useful element in a large percentage of expected engagements. If it is desired to reduce the small remaining susceptibilities of the equipment, however, the following section lists some techniques which constitute greater improvement.

LONG-RANGE RESEARCH PROGRAM TO REDUCE VULNERABILITY

As stated above, the remaining principal CM is an environmental one: clutter at low altitude. There are techniques which show promise of reducing the clutter susceptibility below that which will be realized from the above AJ programs. These are pulse doppler and airborne moving target indicator (AMTI). Each of these techniques represent long-range research programs. Accompanying the development of such techniques will be additional susceptibilities both environmental and intentional. The research program should insure that a system having increased performance evolves.

Angle deception techniques (although not currently believed to be a tactical threat to the AI radar) will be successful against the radar evolving from the long-term program. A long-range research program which can counter one form of angle deception (inverse gain) is conical scan on reception only. It is recommended that an antenna research program be started to develop an antenna scanning on reception only.

Unfortunately, some of the recommendations made in past studies for AJ modifications have not been based upon a thorough knowledge of the reason for the susceptibility and resulting vulnerability. For example, leading and trailing edge tracking along with feeler gate techniques have been applied to several service radars without a thorough knowledge as to why the equipment was deficient to begin with. These techniques represent quick fixes which remedy one situation but which may introduce other more harmful effects. Other techniques in this category are in-the-air tuneability and rapid tuning systems.

CONCLUSIONS AND RECOMMENDATIONS

SYSTEM CONSIDERATIONS

The overall weapon system study has indicated that the AI radar is not the most susceptible of the several links in the system loop. However, current AI radars leave much to be desired in regard to performance in their natural environment as well as in an environment of deliberate jamming.

The normal environment of a weapon system is inherently noisy. This natural noise is similar to (and in many cases identical to) various forms of enemy CM.

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AJ features should be incorporated in the equipment to reduce its susceptibility to normal environmental noise. AJ features incorporated to improve system performance in the presence of environmental noise will also defeat many forms of intentional CM.

AJ features which do not improve performance in the normal environment should not be utilized unless a clear understanding of the penalties in weight, size, performance, and reliability can be had and justified in terms of the AJ advantage gained.

COUNTERMEASURES THREAT

The potential enemy is assumed to have a CM potential equivalent to that of the United States.

Jamming techniques to be available for large-scale operational use during the short-term period (2 to 3 years) are of the brute force variety: chaff, spot frequency jammers, barrage jammers, and sweep frequency jammers.

Major advances in jamming techniques will be operationally available during the long-term period (3 to 5 years). The traveling-wave and carcinotron tubes have made practical deceptive repeat-back and rapid-tune jamming systems.

SUSCEPTIBILITIES OF CURRENT AI RADARS

The text shows many detailed susceptibilities of current AI radars. Of these, only the ones listed below are of great importance.

1. The antenna design of contemporary AI radars results in susceptibility to environmental and intentional CM because (a) the search pattern is not optimum, and (b) the conical scan frequency employed is out of the optimum band.
2. The current AI radar transmitter causes susceptibility to jamming because (a) all AI radars of the era operate within a very narrow frequency band, (b) the prf is too stable, and (c) the 0.5- μ sec pulse width is too long to exclude pulse repeaters.
3. The receiver design results in susceptibility because (a) the i-f bandwidth is greater than necessary because of an inadequate AFC, (b) the receiver will not pass other than pulsed signals (lack of i-f gating), (c) the receiver is easily overloaded by any form of interference, and (d) the AGC is not capable of handling very strong signals.
4. The cockpit layout results in a degradation of system performance because (a) the radar set control is improperly located and overly complex, (b) the indicator is poorly located and difficult to interpret, and (c) the indicator is difficult to read because of improper background treatment and because of the high-intensity ambient lighting conditions.

SHORT-TERM AJ IMPROVEMENT PROGRAM

The short-term improvement program detailed in the text is, in general, intended for contractor education and hardware demonstration rather than for system tactical utility. Areas of interest in the AI radar are as follows.

1. The susceptibility of the radar may in part be reduced by antenna redesign to (a) optimize the search scan coverage, and (b) allow the conical scan frequency to wander over a wide band.
2. The modulator and transmitter of the radar may be designed to reduce susceptibility by (a) dispersing the radar frequency through on-the-ground selection, and (b) allowing the prf to have a wandering mean value and jittering it.
3. The receiving system may be modified to reduce susceptibility by (a) using a back-biased last i-f amplifier stage to improve clutter and jamming rejection, (b) using a gated i-f channel to allow homing on jamming, and (c) simplifying the range tracking circuitry and providing for automatic reacquisition.
4. Improved cockpit layout can improve system performance. To effect improvement (a) a simple stop-gap hood must be decided upon, (b) nonreflective coatings should be applied to the face of the indicator and to other instruments, (c) the human engineering approach to background painting described in several recent studies should be used, and (d) the radar set control should be optimized for the current poorly designed cockpit layout.

LONG-TERM AJ IMPROVEMENT PROGRAM

The long-term AJ improvement program is intended to supply the long-term tactical need of the Navy by utilizing adequate system engineering. The largest single susceptible area in our current weapon systems results from a lack of complete compatible system integration. A weapon system consists of an aircraft, a pilot, a radar, a display device, a computer, and a weapon. Current systems are not integrated in compatible fashion but are, rather, a forced-together conglomeration of units. Some of the short-term techniques should be engineered into the long-term program. These techniques are as follows.

1. The antenna should be redesigned to (a) optimize the search pattern, (b) allow the conical scan frequency to wander over a wide band, and (c) utilize the principles of system engineering to properly integrate the system.
2. The modulator and transmitter should be redesigned so that (a) the radar frequency can be dispersed by means of on-the-ground selection, (b) the prf will have a wandering mean value and will be jittered. In addition, consideration, contingent upon the state of the art, should be given to shortening the pulse and gate width to counter pulse-to-pulse repeaters, and principles of system engineering should be utilized to properly integrate the system.
3. The receiving system should be completely redesigned to (a) provide a noise figure consistent with the state of the art, (b) utilize separate, optimum-bandwidth range, display, and angle tracking i-f channels, (c) provide for a backbiased range-display i-f channel, (d) gate the angle tracking i-f amplifier, (e) provide an adequate AFC to permit the use of narrow i-f channels, (f) allow automatic reacquisition in simplified range tracking circuitry, and (g) utilize the principles of system engineering to properly integrate the system.
4. The cockpit layout and display components can be improved if (a) a nonreflective coating is used on all displays and instruments, and proper background painting is provided, (b) the radar-optical display is integrated into the cockpit, (c) separate i-f and video channels

are used which are optimized to improve the display, (d) bright indicator displays are exploited, (e) the quantity and type of information displayed is reduced to that which is necessary, (f) the complexity of controls and the amount of judgment required of the operator is reduced, (g) a combined optical and radar display is provided for, and (h) the principles of system engineering are utilized to properly integrate the system.

LONG-RANGE RESEARCH PROGRAM

Radars evolving from the long-term AJ improvement program recommended herein will be greatly improved in capability in the presence of both environmental and intentional CM. However, there are remaining areas of susceptibility; chaff in beam attacks, clutter at very low altitudes, and electronic angle deception. A long-range research program directed toward such new techniques as pulsed doppler, AMTI, and scan only on reception should be instituted to resolve these susceptibilities.

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APPENDIX
Countermeasures Threat

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What is the nature of the electronic CM threat faced by the designer of AI radar equipment within the next five years? First, it must be recognized that the question as just stated is only one phase of the more general question, "What is the probable nature of the electronic CM threat against our air defense system within the next five years?" Since our air defense system consists of a number of elements, the nature of CM will be determined by considering the overall picture and not the AI problem alone, although that will be one of the important factors. It is obvious that no country possesses the equipment, talent, and resources capable of tailoring a CM to each particular situation. Even if such a variety of CM existed at the outbreak of major hostilities, it would be a formidable task to have them at the right place at the right time and it would not be possible to know which one to use nor would it be possible to use all of them.

From a technical point of view many of these problems can be solved in a single instance, under favorable conditions, when all factors are known, when all factors are under control, and plenty of trained manpower is available; but under conditions of modern warfare these strictly technical solutions would be so unworkable that they would contribute little or nothing to the final result. It is quite startling to contrast the literature on the subject of CM for the past ten years as to the many technical possibilities with the small number of equipments that are installed in tactical fighting units ready for service right now. This leads to the conclusion that technical feasibility is only a small factor in determining the tactical usefulness of a CM. These same problems will be faced by a potential enemy and will have a direct bearing on the nature of the CM threat to be faced by our forces.

PRESENT STATUS OF OUR COUNTERMEASURES

One extremely important factor in assessing the CM threat for the next five years is to examine our own present CM capability at this particular moment. This is done in very general terms for both the Air Force and the Navy.

If major hostilities were to begin today, the Navy would have ready for service in their tactical aircraft exactly two types of electronic jammers. The only other production equipment presently installed is a modest window (chaff) dispenser in their propeller aircraft. There is no operational jammer aboard ship.

Major effort in the Air Force lies in two directions: unattended sweep jamming in the S-band, and generous quantities of chaff capable of producing echoes throughout the frequency spectrum. Methods employed are brute force techniques requiring no electronic analyses equipment and no trained CM operators. This type of thinking is worth careful consideration from the point of view of the radar designer.

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BASIC QUALITIES OF A GOOD COUNTERMEASURE

A consideration of the basic qualities which would make a CM device worth building and using should give a reasonably good insight as to what a potential enemy would do. Some of these qualities are listed below.

1. A good CM design in aircraft should be such that it can be preset for operation with the exception of the start-stop switch. It should not require the services of a trained operator or a complex electronic analysis and frequency set-on mechanism.

2. The CM design should be effective against a class of equipment which is in reasonably wide service. For example, a package of window properly used would have some degree of effectiveness against a considerable number and variety of radars. The objective of airborne CM designs, however, must be carefully limited to prevent the equipment from having such complexity, size, and weight that it becomes impossible to install and carry it in a tactical aircraft. The most impractical of CM devices in a tactical aircraft would be a universal jammer with a special mode of operation suitable for each particular set of circumstances. This type of thinking always has a certain appeal when the attendant difficulties are not realized. No universal device of this type is now in service.

3. The proper purpose of a CM device is to make warfare expensive for the enemy. It is not to load down every airplane with equipment which theoretically can cope with every situation but which in fact ends up by doing no job well, so that the net result is that CM does more harm than good.

4. A good CM should not seriously interfere with the primary mission of the aircraft (or ship) on which it is installed. The Navy's under-the-wing window dispenser can be fitted to a jet aircraft, but it reduces the speed of the jet to such an extent that pilots prefer no CM to this one. Likewise, a policy of installing CM equipment in the bomb bay seems to indicate too high an opinion of the present or near future capabilities of radar.

5. A good CM should avoid giving the enemy advance warning as to the importance of a raid. Thus a small number of planes with a lethal bomb load should not carry jammers directed at the warning radar unless they carry enough jammers to destroy the usefulness of the warning radar net. This appears impossible for a small number of airplanes to accomplish; thus the Air Force's sweep jamming tactics appear to have a poor future in the Navy.

6. A good CM should not seriously interfere with the performance of electronic equipment in its own forces. It is for this reason that the Air Force philosophy of saturated sweep or barrage jamming will face real difficulty when extended above and below S-band and thus cause interference with operation of friendly radar, communication, and navigation. It is for the same reason that our radar network, if properly distributed throughout the frequency spectrum, will never face an all out jamming effort. Just as the function of CM is to make enemy electronic design expensive, likewise radars should be designed and used in a manner that makes CM expensive.

MOST PROBABLE ENEMY COUNTERMEASURES

The following are considered the electronic countermeasures most likely to be used by a potential enemy against U. S. Armed Forces.

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Window (chaff), a World War II CM, still heads the list. It is well known, can be produced cheaply, covers a wide frequency spectrum, needs very little in the line of trained personnel, and is still effective against all but the very best domestic radars. Even against the best radars, window provides an element of confusion which tends to saturate the defense system.

Second in importance is a CM which has not received the emphasis in our program that it deserves. This is jamming of communication circuits. The potential enemy has demonstrated a surprising ability along these lines and could very probably employ it to his advantage, particularly where airborne interceptors or fleet operations were involved.

Noise-modulated radar jammers are considered to be third in importance. These are always extremely effective in a controlled demonstration. If the radar designers are sufficiently cooperative to use a single carrier frequency for a certain type of operation, the CM problem becomes quite reasonable. If, on the other hand, radar frequencies are well distributed the CM problem becomes most formidable.

Beyond these three CM, no major designs are expected to appear in large quantities within five years. Pulse repeaters are beginning to show considerable promise and may well develop into a series of useful decoys and devices capable of degrading tracking. Unmanned electronic decoys in quantity appear to be more than five years away. There are literally hundreds of other CM which can be demonstrated under peace-time conditions but none at the moment appear to be important enough to influence the design of radars.

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