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NRL Report 4720

COUNTERMEASURES AND ANTIJAM CONSIDERATIONS FOR AIR-TO-AIR MISSILE GUIDANCE SYSTEMS

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ABSTRACT

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An investigation is being conducted at NRL to determine the susceptibility and vulnerability of the various links of the over-all air-to-air weapons system loop to countermeasures both intentional and environmental. Information space links of the over-all system loop include CIC search radar, communications, IFF, AI radar, missile guidance, and warhead fuze. The study program has been divided into three phases: (1) countermeasures and antijam considerations for air-to-air weapons systems, (2) countermeasures and antijam considerations for airborne intercept radars, and (3) countermeasures and antijam considerations for air-to-air missile guidance systems.

This is a report on Phase 3. The system study has indicated that missile guidance elements are not the most vulnerable of the several links in the over-all system loop. However, current guidance equipments leave much to be desired in regard to performance in their natural environment, as well as in an environment of deliberate jamming. Primary emphasis has been placed upon analyses to disclose these weaknesses. Most action recommendations, when applied, should result in improvement of guidance equipment 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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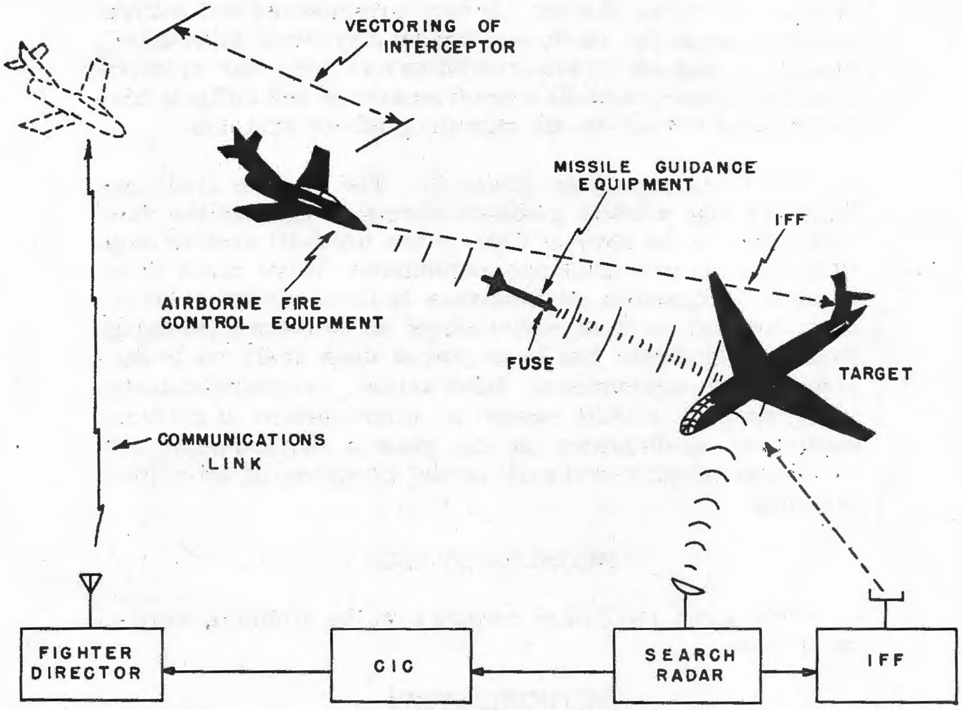

Fig. 1 - Generalized air-to-air guided missile weapons control loop

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COUNTERMEASURES AND ANTIJAM CONSIDERATIONS FOR AIR-TO-AIR MISSILE GUIDANCE SYSTEMS

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BRIEF OF INVESTIGATION

This report details an investigation conducted to determine the countermeasures vulnerability of current Navy air-to-air missile guidance equipments. There are four primary missile guidance techniques: (1) Sparrow I Beamrider, (2) Sparrow II Active Guidance, (3) Sparrow III Semiactive Guidance, and (4) Sidewinder Passive Guidance. It is realized that these missiles are still undergoing design changes. The system parameters considered in this report represent the status of development that the Bureau of Aeronautics believed most valid for current study.

The principal system elements which constitute the over-all system loop include the CIC search radar, communications, IFF, AI radar, missile guidance equipment, and warhead fuze. Rigorous analysis of all system links is required to establish relative vulnerability of the various elements. Each of these elements employ external transmission paths for data gathering or transmission. Therefore each element is susceptible to countermeasures, either intentional or environmental. However, the relative vulnerability of each element is dependent upon many factors. Significant factors include time available for the jammer to employ countermeasures effectively, relative cost in terms of equipment to jam the element, how much the basic mission of the jammer is degraded by such countermeasures action, and what will be accomplished in weapons system degradation by jamming a particular element relative to the gain realized from jamming some other element in the loop.

This report is limited to a study of the missile guidance equipments. A separate report (1) describes the relative vulnerability of the various elements of the over-all system loop. From this phase of the study it was concluded that the search radar and communications links are the system elements most vulnerable to intentional countermeasures. A corollary conclusion is that the missile guidance equipments are relatively safe from intentional jamming. However, the present study has indicated that current guidance equipments are excessively vulnerable to jamming in their natural environmental state (altitude line, clutter, target noise, etc.). This study places primary emphasis on the revelation of reasons for degradation of guidance equipment performance as a result of jamming in the normal environment. Antijam recommendations are based upon three closely related premises: (1) antijam features of any complexity should be incorporated only if they improve performance of the equipment in its natural environment, (2) in general if antijam modifications degrade equipment performance (including reliability) in the absence of intentional jamming they should not go into the equipment, (3) if it becomes apparent that the enemy will employ particular jamming techniques which require special antijam circuitry (other than those considered for improving system performance in its natural environment), before this circuitry is incorporated the resulting improvement in system performance in the presence of this jamming should be carefully weighed against the resulting decrease in performance in the absence of this jamming.

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INTRODUCTION

This report will discuss missile guidance system vulnerability to countermeasures with the object of establishing design criteria and/or specific modification leading to more secure systems. Missile guidance systems considered include Sparrow I, Sparrow IA, Sparrow II, Sparrow III, and Sidewinder. It is realized that these missile systems have been undergoing rapid changes. The missile contractors have had a difficult task to design systems which will work even under ideal conditions. However, each of these systems now appears to be approaching the point where it is of extreme importance to optimize them in terms of performance in their natural environment. This report is the result of a cooperative effort between BuAer, the contractors, and NRL. The contractors have been kept informed of the procedures 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 antijam modifications could be started in advance of the published report.

The air-to-air missile, when applied 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 antijam features. The terms susceptibility and vulnerability used in jam-antijam discussion are defined for the purposes of this report as follows. By susceptibility it is meant that the possibility exists for entry of jamming signals into an element of a weapons control system with resultant degradation of system performance. The term vulnerability is used where the ease and hence probability of jamming is sufficiently high to be of concern. Entry of countermeasures into airborne missile systems is made through the 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 the tailoring of this energy so as to maximize the error of system-generated guidance information. The objectives of antijam design are thus to make entry difficult and the system as insensitive to extraneous signals as is practicable. Since it is possible to jam any electronic space-intelligence link, these objectives cannot be completely reached and become less important as effort towards their attainment results in increased complexity.

Technological advance is resulting in weapons systems which are increasingly dependent upon electromagnetic information links. As this dependence grows, and as jamming techniques improve, the potential of countermeasures to degrade or destroy air-to-air weapons systems effectiveness is correspondingly increased. Department of Defense activity in the jam and antijam fields has recently been stimulated for this reason. Certain new techniques and devices appear to permit fundamental advances in jamming effectiveness. Traveling wave, carcinotron, and backward-wave oscillator tube types have, for example, 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 weapons control systems and constitute an important challenge to designers of such systems to make equivalent advances toward improvement in security.

Contemporary jamming equipments available in quantity are of the "brute force" type. Methods currently available for fleet usage are chaff, spot frequency jamming, barrage jamming, and slow sweep jamming. However, the advent of new techniques and devices, including the traveling wave tube, have made predictable the development of wide open repeat back systems, fast tune 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

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with contemporary chaff, barrage, sweep, and spot jammers make the antijam problem a difficult one.

Techniques employed for air-to-air missile guidance are beamrider, active, semiactive, and passive homing. Since jammer entry is made through space intelligence links, the characteristics of these are of primary concern to both the jammer and the antijam designer. In the beamrider case, electromagnetic links between the target and the interceptor, and between the interceptor and the missile are required. For active and semiactive systems, intelligence links exist between the interceptor and target, interceptor and missile, and/or missile and target. A link between target and missile is required for the passive homing system. Figure 2 illustrates typical cases of the above guidance links.

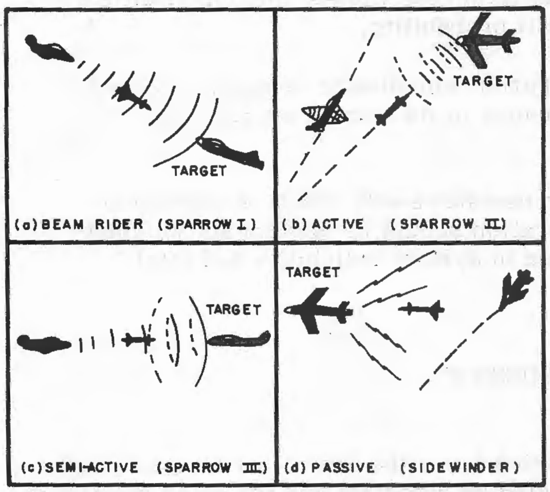

Fig. 2 - Space intelligence links of air-to-air missile systems

If the jammer can interrupt or confuse any of these links sufficiently to degrade missile guidance system performance he has successfully countered the missile weapons system. Although only the missile guidance system is considered here in detail, it is stressed again that numerous other links exist in the system as a whole which are susceptible to jamming.

The countermeasures proponent considers that he is involved in a tactical game. His strategy calls for continuous analysis of weapons systems vulnerability as the premise for specifying requirements for effective jamming devices. Thus, countermeasures equipment development will be guided by weapons system characteristics and trends. The expression "for every measure there is a countermeasure" is valid.

The task of devising effective countermeasures varies inversely in difficulty with the quality and quantity of intelligence detail defining the system to be jammed. The concentration of effort in countermeasures equipment development and application will be necessarily selective. It will vary with evaluation of the threat of particular weapons systems, and with system and component vulnerability, as these are interpreted from intelligence information. We are therefore concerned not only with vulnerability of the missile guidance system, but also with relative vulnerability of the several other elements in the weapons system loop.

Missile guidance systems, considered apart from the weapons system loop as a whole, have certain characteristics which are distasteful to the jammer. Of major concern is the existence of so many varieties of system types, and the capability of varying such parameters as frequency, coding, PRR, etc., within individual systems. It will not be practical to develop and transport in aircraft, jamming equipment which can effectively jam all of these variables. Diversity in missile guidance techniques used, and of parameters within systems, is thus a potent and expensive antijam measure.

Missile time-of-flight to target for most tactical situations will be less than 10 seconds. This feature complicates the jamming problem, particularly where the possible existence

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of homing-on-jamming missiles discourages continuous radiation of jam signals. Moreover, several missile guidance systems are inherently difficult to jam. The "passive" Sidewinder, for example, though susceptible to heat decoy jamming, poses a problem of such complexity to the jammer that he will search diligently for a more vulnerable weapons system element to operate against.

The above discussion is intended not to minimize the jamming threat to missile guidance, but rather to preface the point of view which has been accepted as a result of this study. This view dictates in essence:

a. That counter-countermeasures remedies be applied energetically to those elements of missile guidance systems which are determined to be most vulnerable to jamming. Vulnerability here is a measure of the ease with which jamming can be accomplished, and the resultant degree of degradation of system kill probability,

b. That specific counter-countermeasures remedies to be applied should generally improve system performance in its normal operational environment, and

c. Where an effective counter-countermeasures will result in additional equipment complexity, its incorporation should be judiciously weighed against resultant probable reduction in system reliability and total target kill potential.

GENERAL JAMMING CONSIDERATIONS FOR MISSILE GUIDANCE EQUIPMENTS

In the preceding summation, two factors which favor the air-to-air missile guidance equipments in the presence of jamming were listed as diversity and the short missile on-time.

Diversity

This factor may be considered from two aspects, diversity of missile guidance systems, and diversity within systems. System type diversity is being presently exploited in the development of four different missile guidance techniques (Sparrows I, II, III, and Sidewinder). From the jammers viewpoint, it is improbable that during an engagement the jammer will be able to determine which type of missile is being used against him in time to utilize specialized jamming techniques designed to work against a specific vulnerable characteristic of a particular missile guidance technique. This study does not consider the relative importance of diversity versus logistic practicability of employing several missile types in the fleet. Strictly from the antijam viewpoint, diversity is an important feature. It is realized that, currently, equipment packaging and placement on the aircraft prohibits free interchange of missile systems on specific aircraft. Because of the antijam potential resulting from diversity in missile systems, however, it is considered important that future development should, where practicable, stress design which will allow interchanging of missile systems.

The second diversity aspect to be examined is that within each specific missile system. Here the situation is not as favorable in current design practice as is the diversity among

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missile systems. Diversity within a system can be accomplished by means such as variation in frequency, scan rate, and pulse repetition frequency. It is stressed that high antijam potential is available through diversity within a system and therefore design thinking should be directed along this line.

Time

This is the second factor which favors the current air-to-air missile guidance equipments in a jamming situation. The average time of flight of the missile is 10 seconds. For those missiles which are activated at AI radar lock-on, the total active time which the jammer can utilize for countermeasures against the guidance equipment is in the order of 30 seconds (20 seconds from AI radar lock-on to launch). This is an extremely short time for jamming action to occur and eliminates the practicability of using a slow reacting human operator in the jamming loop. One exception exists for the situation where jamming action against other portions of the over-all system loop could also jam the guidance system. For example, chaff dispersed against the AI radar might also be effective against a missile guidance link. In general, however, it is reasonably safe to assume that the jammer will need automatic equipment to jam the missile guidance equipments effectively.

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SPARROW I MISSILE GUIDANCE EQUIPMENT

Status of Sparrow I

The Sparrow I is a beamrider missile which obtains its guidance information from the beam of an X-band AI radar. There are two versions of this missile. One is the Sparrow I (optical) which utilizes the beam of the AN/APQ-51 radar. In this configuration the radar antenna is slaved to the optical sight. The other version is the Sparrow IA (all-weather) which will use the AN/APQ-36 or AN/APQ-50 radars. In the Sparrow IA, the radar performs all of the normal AI functions as well as the provision of a guidance beam for the missile.

Figure 3, an illustration of the beamrider guidance technique, shows a tactical situation in which Sparrow I might be employed. The interceptor is vectored by CIC to a position from which either optical or AI radar target acquisition can occur. In the optical mode the equipment does not provide course computation, and the beam is either fixed relative to the aircraft or tracks the target within small angles off the nose of the interceptor. Effective attack courses are limited to the target's tail cone. Range tracking is performed by the AN/APQ-51 radar. An in-range signal is supplied to the pilot to indicate arrival at a suitable launching range for the missile. For interceptors equipped with the all-weather system, after the target appears on the AI radar presentation, automatic tracking is initiated, and a proper attack course is computed and displayed to the pilot. A continuous release course is flown permitting multiple missile launchings at the same target. The course to be flown, after the missile propulsion interval, approaches a constant bearing course with respect to the target in order to reduce the lateral acceleration required of the missile to ride the beam. In both optical or all-weather cases, the radar must continue to track the target until missile impact.

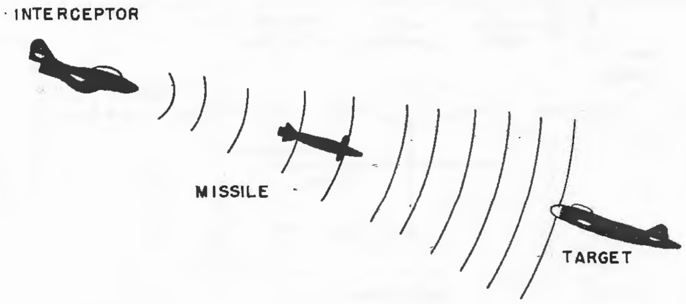

Fig. 3 - Beamrider missile guidance technique (Sparrow I)

A proposed version of the Sparrow IA separately provides phase (angle) and amplitude (lateral displacement) guidance intelligence to the missile via two space links. The links are, respectively, a phase reference transmitter and the AI radar beam. Both are physically located in the interceptor aircraft. Figure 4 is a block diagram of the phase reference transmitter (2). Figure 5 is a block diagram of the Sparrow I lateral guidance receiver and the separate phase reference receiver (3). The AI radar generates a conically scanned beam within which the missile is constrained to fly to target impact. The error magnitude in lateral displacement is derived by demodulation of the radar beam amplitude variation.

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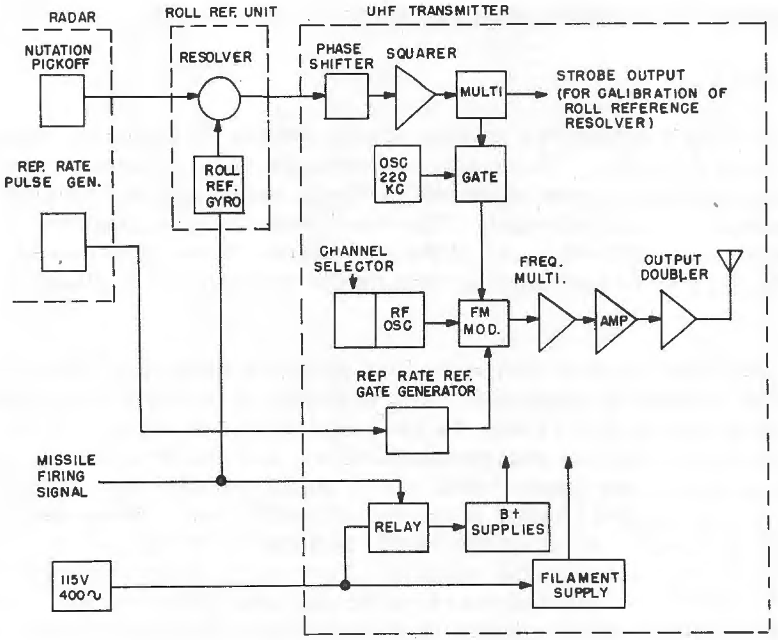

Fig. 4 - Separate phase reference (SPR) proposed for Sparrow I, uhf transmitter and associated circuits

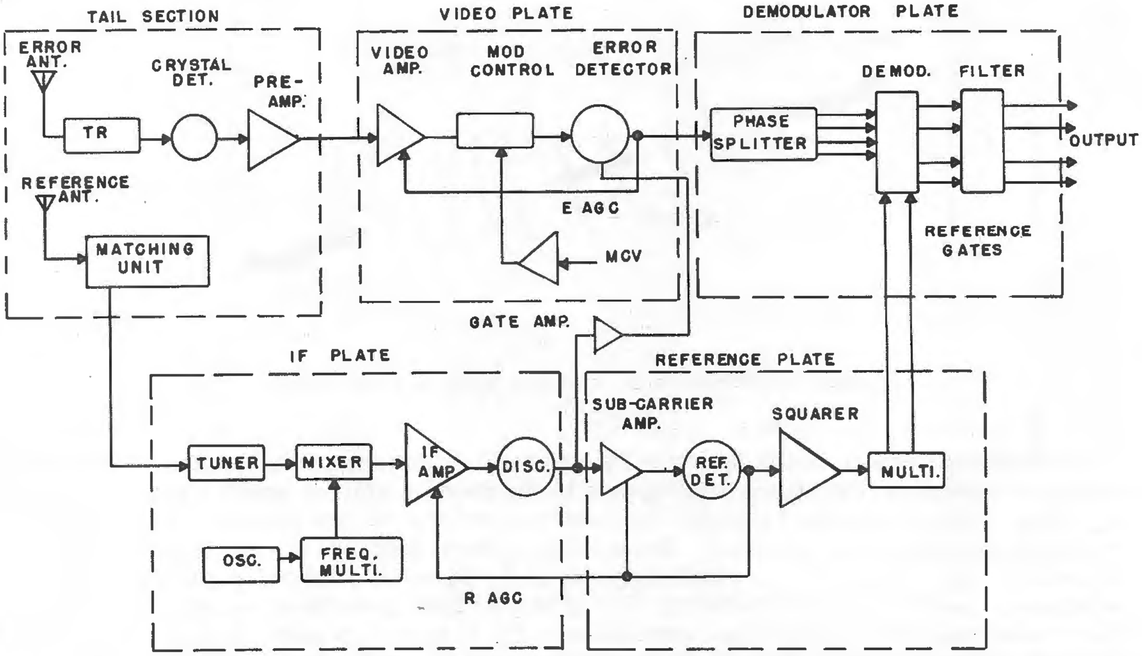

Fig. 5 - Separate phase reference (SPR) receiver proposed for Sparrow I

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The error direction is derived by phase comparison of the error magnitude signal with a uhf reference signal originally derived from the AI radar and transmitted through the separate FM-CW phase reference transmitter. It should be noted that the separate phase reference transmitter performs a function, via a second link, which a previous system, called FM-PRR, accomplished via the tracking and guiding radar link.

In the missile seeker, the X-band error magnitude signal is derived from the AI radar beam by means of a crystal video receiver. The uhf reference signal is processed through a superheterodyne receiver, the output of which is phase compared in a demodulator with the error magnitude signal. The filtered outputs of the demodulator comprise the up-down and left-right dc guidance outputs of the receiver systems.

Other phase reference systems have been considered for Sparrow I, and prosecuted to some extent. Among these are quadrant dual pulse system, superheterodyne FM-PRR, crystal video FM-PRR, and correlation separate phase reference system. Currently, the contractor is directing his efforts toward the CW separate phase reference system discussed above. For this reason, the CW separate phase reference system will be investigated in regard to susceptibility and vulnerability to countermeasures and will be compared in this regard with other types of reference systems.

Tactical Situation

It is apparent from Fig. 3 that a beamrider guided missile may be inherently free from jamming worries, since it rides in a high energy level beam and gets its guidance intelligence from the rearward looking antennas. The above statement, of course, considers only the guidance receiver. In the all-weather case, the AI radar remains as susceptible for Sparrow I as it is for any other weapon. In the optical mode, however, where radar target tracking becomes less important, the beamrider technique has inherent advantages from the countermeasures aspect.

Vulnerability

This missile, like any other device which uses external transmission paths for guidance intelligence, will be susceptible to both the environmental and intentional types of jamming. Vulnerability will be a function of many design parameters. From Fig. 3 it can be seen that the types of interference to be expected will include noise on the radar beam, receiver noise, and intentional jamming noise. The jamming effectiveness of these types of noise will be affected by receiver bandwidth, antenna front-to-back ratio, and the astuteness of the designer in taking advantage of inherent antijam features permitted by the tactical situation parameters. If maximum antijam advantage is taken of the restrictions of the tactical situation in prosecuting the design of the guidance system, the guidance receiver can be made relatively invulnerable to self, or deliberate jamming.

In terms of the natural environment there are several types of self-made or natural noises which may be troublesome in the case of Sparrow I. These are as follows:

a. Angular tracking noise in the AI radar (tracking jitter),

b. Spurious amplitude modulations on the radar beam,

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c. Reflections from the surface of the earth,

d. Friendly interference.

In the case of angle tracking noise originating in the AI radar, the Sparrow I guidance equipment is at a real disadvantage because this noise is largest (in feet) at the target where it is desired to have the smallest errors. There seems to be no remedy for this type of noise except to insure that the tracking bandwidths of the AI radar and of the Sparrow I are as narrow as is consistent with the real tactical problem (as opposed to an infinite problem).

Sparrow I appears to be overly sensitive to spurious modulations on the guidance beam supplied by the AI radar. Specifications for the guidance beam call for a very low noise modulation index in bands of frequencies which are not used by the missile in solving the guidance problem (4). Further reference is made to this situation in the contractor literature (5) as shown on Figs. 6, 7, and 8. Figure 6 shows the receiver output voltage, the error from beam center, and the flap deflection as a function of time for the Sparrow I missile for both low and higher input noise conditions. Two effects are noticeable, namely: (1) the missile flaps move at frequencies greater than the aerodynamic response capability of the missile, and (2) in the presence of higher input noise the missile approaches nyquist instability. Note that for low noise input the missile requires approximately 5 seconds to reduce a 100-foot input error to essentially zero. For a higher noise input, the missile requires in excess of 11 seconds to accomplish the same error reduction (some nyquist instability is evident). Both of these response times are excessive in view of average times of flight. The excessive flap motions, in the case of both noise inputs, will cause unnecessary waste of servo oil. Figure 7 shows the open loop frequency response of the guidance system from the receiver output terminals to the flap deflection. Note that appreciable gain is available at 10 cps and above. Figure 8 shows that the bandwidth of the over-all guidance system is approximately 1 cps. It is then reasonable to deduce that the gain at high frequencies as shown in Fig. 6 is representative of overdesign and is certain to cause servo oil waste. Further, to protect against excessive oil loss the flexibility of the AI radar has been compromised by the inclusion of a noise guard band in the region of 10 cps in the specification for spurious amplitude modulation on the guidance beam.

Figure 9 shows a typical low-altitude attack for a missile launched at a range of 2.8 nautical miles (maximum relative aerodynamic range of the missile in a tail attack against a 500-knot target when launched from a 550-knot interceptor at low altitude). A point of interest occurs when the missile is 3 seconds from impact. Three seconds was chosen as the point beyond which jamming or interference could not deflect the missile enough from its original path to affect appreciably its hit probability (3 missile time constants). The distances at 3 seconds to impact may be derived as follows:

$$D_M - D_I = 2.8 \times 6000 + \frac{500 \times 6000}{3600} t - \frac{550 \times 6000}{3600} t \qquad (1)$$

where

D_M = distance traveled by missile

D_I = distance traveled by interceptor

t = total elapsed time.

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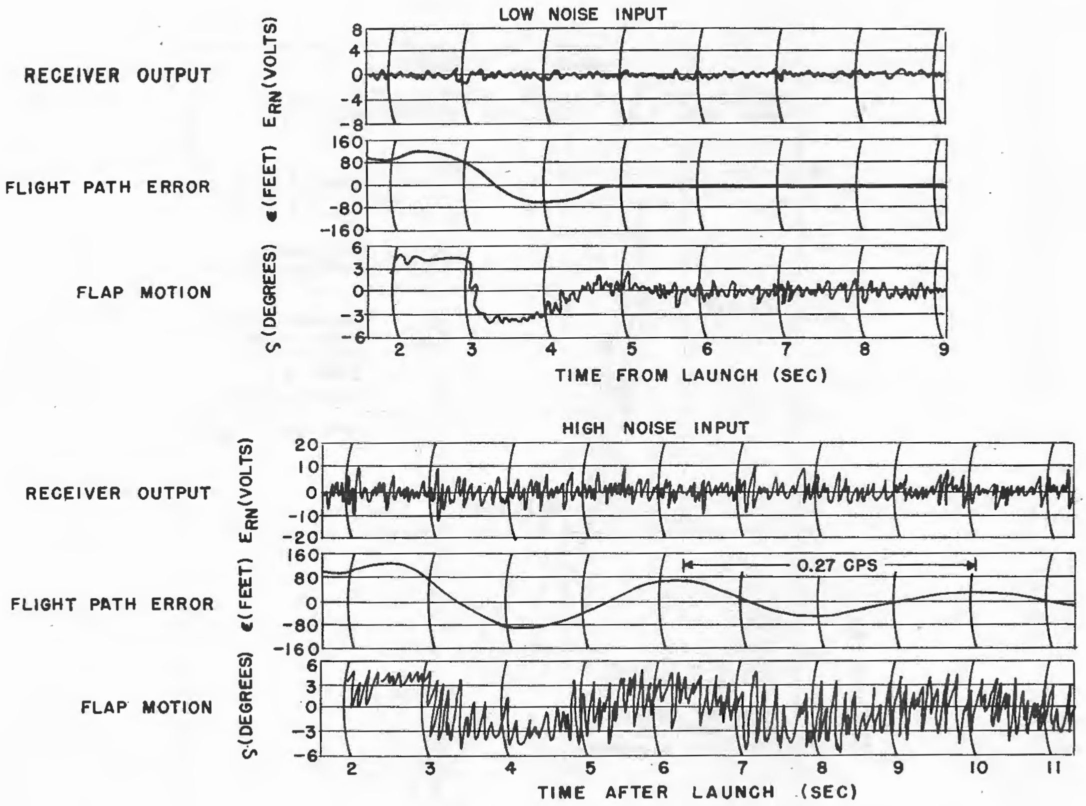

Fig. 6 - Noise study runs showing Sparrow I receiver output voltage, flight path, and flap motion relationships

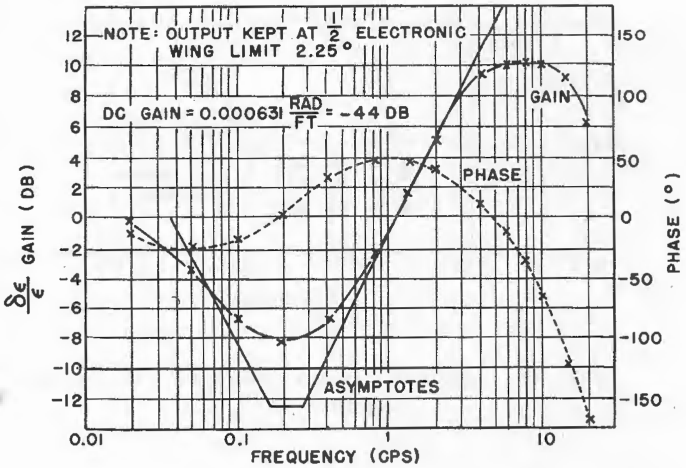

Fig. 7 - Experimental frequency response of error input to Sparrow I missile wing

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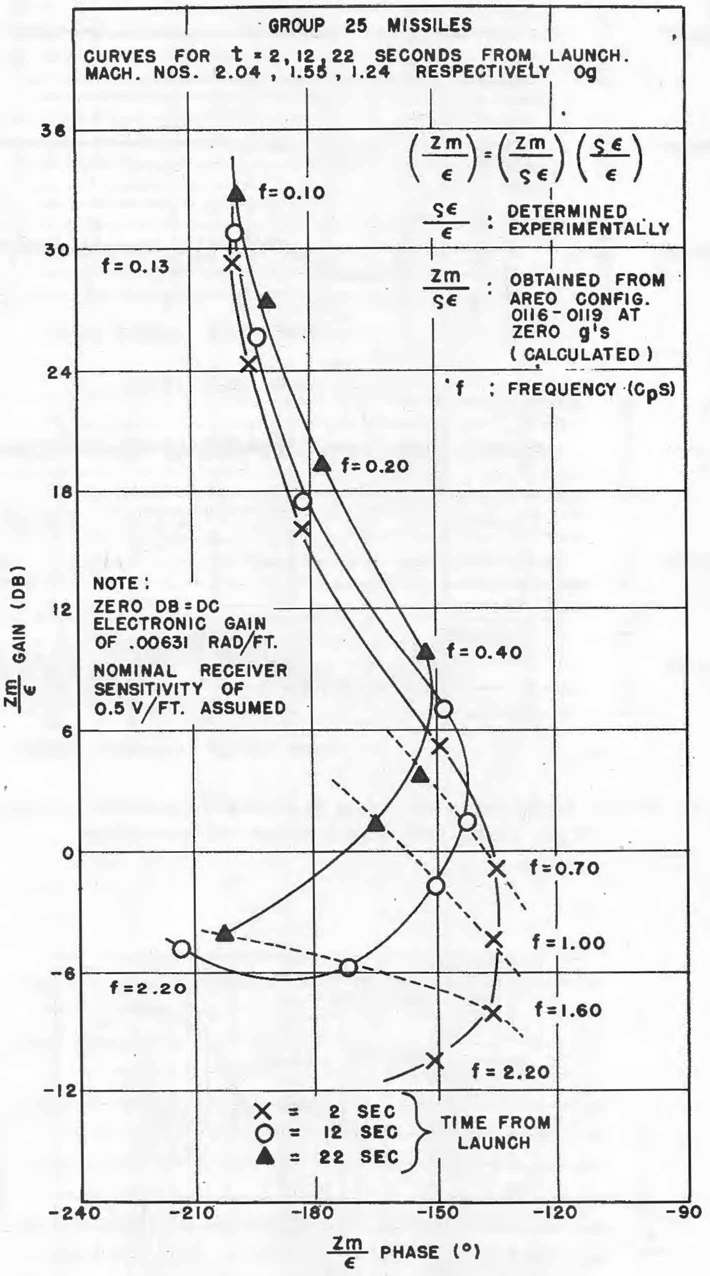

Fig. 8 - Sparrow I beamrider gain vs. phase, open loop

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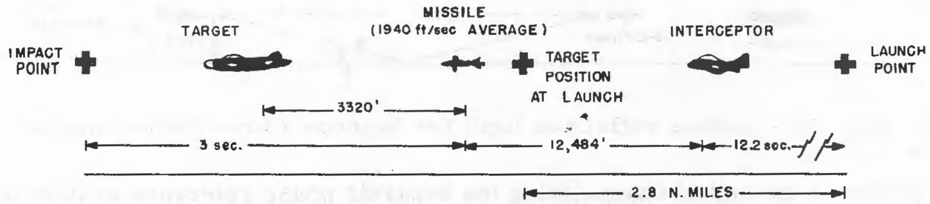

Fig. 9 - Tactical situation model, Sparrow I low-altitude attack

And

$$D_M - D_I = 1940\ t - \frac{550 \times 6000}{3600}\ t \qquad (2)$$

where 1940 ft/sec is the average missile velocity. Thus,

$$t = \frac{2.8 \times 6000}{1940 - 833} = 15.2 \text{ seconds.} \qquad (3)$$

At 3 seconds from impact the distance from interceptor to missile is

$$D_M - D_I = (15.2 - 3)\ 1940 - \frac{550\ (15.2 - 3)\ 6000}{3600} \qquad (4)$$

$$D_M - D_I = 12484 \text{ feet.} \qquad (5)$$

Also at 3 seconds from impact the distance from missile to target is

$$D_M - D_T = 1940 \times 3 - \frac{500 \times 3 \times 6000}{3600} \qquad (6)$$

$$D_M - D_T = 3320 \text{ feet.} \qquad (7)$$

From the typical tactical situtation of Fig. 9 it is of interest to investigate the low angle problem as it affects Sparrow I. Experience has shown that surface reflection can have an appreciable effect on the guidance beam, when the grazing angle at the surface is slightly less than the illuminating beam width. For the AN/APQ-50, the AN/APQ-36, or the AN/APQ-51 the critical angle is expected to be about 3 degrees as shown on Fig. 10. For the previously derived ranges the critical angle will occur when

$$\tan 3^\circ = \frac{h}{12484/2} \qquad (8)$$

$$h = 6242 \times 0.0524 \qquad (9)$$

$$h = 327 \text{ feet.}$$

Thus, trouble from reflections should occur at altitudes of 327 feet or less.

At altitudes below 327 feet the missile can be expected to develop excessive error because of self-jamming due to surface reflections.

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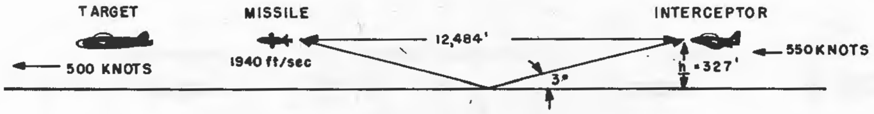

Fig. 10 - Surface reflection limit for Sparrow I low-altitude attack

The proposed method of channelizing the separate phase reference system (operating near 900 Mc) so as to provide signals to several missiles at widely different radio frequencies appears to provide adequate protection from friendly jamming between the missiles. The reason for choice of the 900-Mc band is not known. It appears to be an unfortunate choice because of the fact that high-powered equipment such as friendly and enemy search radars and communications will operate in this same band. Although this channelizing technique can provide adequate protection from jamming between missiles, simpler and less redundant methods to accomplish the same result are available. The most obvious method is frequency modulation of the AI pulse repetition frequency (FM-PRR). This general technique was under development at Sperry for a time, but has been abandoned. It was proposed to devise angle sense in the missile by FM-PRR demodulation while retaining the dual-pulse-per-quadrant radar and missile complexity of earlier versions. Additional circuitry was to be added for the purpose of converting the FM-PRR signals to pulse form. FM-PRR systems as developed for Lark and Terrier apply a more straightforward and far simpler approach to this problem.

The abandoned Sparrow I FM-PRR system was considered by the contractor to be vulnerable to friendly jamming unless each missile was provided a different radio frequency, a difficult and expensive solution. Other less complex means are available, however. Channelizing could be accomplished in the FM-PRR system, for example, by such methods as the use of different PRF's, the use of diversified scan frequencies (an otherwise desirable antijam feature), or the transmission of a coded FM-PRR channel signal.

Referring again to the tactical situation of Fig. 9, it is now desired to calculate the jammer power required to reduce effectively the Sparrow I kill probability by jamming the guidance beam from a target carrying the jammer. An equation applying to this situation is

$$P_j = \frac{P_0 G_0 \frac{F}{B} R_2^2 \frac{J}{S}}{G_j R_1^2} \qquad (10)$$

where

P_j = on frequency peak power of the jammer

P_0 = peak power of the radar (200 kw)

G_0 = radar antenna gain (1995 for AN/APQ-50)

F/B = front-to-back ratio of missile guidance antenna (31.6 for Sparrow I)

J/S = jam-to-signal ratio required to reduce guidance effectiveness (assumed through experience to be 10 db)

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G_j = gain of jammer antenna (assumed to be 1.995)

R_2 = distance from target to missile

R_1 = distance from interceptor to missile.

From the above, and assuming that jamming of a final period of the missile time of flight (equivalent to approximately 3 missile time constants) is not effective in changing the miss distance, the jamming power required can be calculated. The distances R_2 and R_1 are calculated from the 3-time-constant philosophy as shown in Fig. 9.

$$\frac{R_2}{R_1} = \frac{3320}{12484} = 0.266 \tag{11}$$

$$P_j = \frac{200 \times 10^3 \times 1995 \times 31.6\,(0.266)^2 \times 10}{1.995} \tag{12}$$

$$= 4470 \text{ megawatts.} \tag{13}$$

This amount of power is obviously not economically practical for airborne jamming. It was calculated above that 4470 megawatts would be required to jam that part of Sparrow IA guidance intelligence which is transmitted via the AI radar beam. These calculations included only the error magnitude channel. It is now of interest to make a similar investigation for the separate phase reference (SPR) channel. In this case,

P_0 = 10 watts CW (uhf transmitter)

G_0 = 10

F/B = 12 db

J/S = 1

G_j = 1.995

$$P_j = \frac{10 \times 10 \times 15.85 \times (0.266)^2 \times 1}{1.995} \tag{14}$$

$$P_j = 56.2 \text{ watts.} \tag{15}$$

This small amount of power easily can be generated at the uhf reference channel frequency by an enemy jammer. It can therefore be anticipated that the SPR channel will be jammed. It should be noted, in comparing the equations used in the calculation of required jammer power, that jammer power is directly proportional to the interceptor uhf antenna gain and transmitted uhf power. One way of increasing the value of these parameters is to return to a properly designed angle beam FM-PRR guidance system. Such a system is 7.95×10^7 times as difficult to jam. In a countermeasures comparison between FM-PRR and SPR-CW a contractor report (6) compared an apparently obsolete FM-PRR system with the proposed SPR-CW system. Table II of that report gives a quantity -12 db as the J/S ratio to be expected in an FM-PRR system. There is no reason why J/S ratio for FM-PRR should be markedly different from that existing in the standard AI radars where the ratio is of the order of +10 db for CW jamming.

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In general, diversity within any system or part of a system increases the difficulty of the jamming. The term diversity includes capability of varying such parameters as frequency. Currently, several of the parameters which could be otherwise varied to confuse the jammer must be held to a particular value within close tolerances because of the design criteria chosen. For example, the PRF of the AI radar must be held to ±5% because the circuit design of the missile is not broadbanded in this respect. Similarly, the scan rate must be held within the limits of -5% to +15% for the same reason. On the favorable side, the proposed Sparrow I system allows the use of a tunable magnetron in the AI radar without degrading missile performance. The separate phase reference system provides the diversity of two frequencies. However, if either frequency is jammed the system is jammed.

Conclusions and Recommendations

Conclusions:

1. The proposed SPR guidance system for Sparrow I cannot be justified on the basis of countermeasures security.

2. Optimum bandwidths, derived from tactical requirements, have not been used consistently in the design of Sparrow I guidance and control systems. As a result susceptibility to natural or deliberate jamming is higher than necessary.

3. Application of the single-beam FM-PRR technique for Sparrow I guidance, in an otherwise properly designed system, should result in equipment which is comparatively secure from friendly, natural, and intentional jamming.

4. Because of the rearward looking antennas, a properly designed beamrider guidance system should be relatively secure from enemy electronic countermeasures.

Recommendations:

1. It is recommended that a study be made with the objective of establishing bandwidths, and other guidance parameters which are required by tactical application of the Sparrow I missile. The limiting of bandwidths to these requirements should reduce the demands on the AI radar and on the missile control system.

2. The contemplated SPR angle reference portion of the system is vulnerable from the countermeasures standpoint as compared to the guidance beam furnished by the AI radar. It is recommended that a re-evaluation of the single-beam FM-PRR technique be made.

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SPARROW II MISSILE GUIDANCE EQUIPMENT

Status of Sparrow II

The Sparrow II is a seeker missile which utilizes active K-band radar guidance. Currently it is not possible to predict the exact form which operational Sparrow II equipment will take since this system is under development. At this date the Sparrow II program, as described by the Bureau of Aeronautics, is divided into three phases.

Phase 1 - Aero X24A Program — This airborne fire control system is currently called out for the F5D aircraft. The Sparrow II mode initially will have limited scope in that range search for target acquisition is not included, and thus there will be no optical mode for missile launch. At a later date, depending upon the results of Phase 2, some form of range search will be added to this system. It is contemplated that design of the Sparrow II system for the F5D, without range search, will be completed in March 1956.

Phase 2 - "Pure" Sparrow II Program — This system, among others, is currently called out for the F4H aircraft. The design effort will be completed by September 1956. Raytheon is the prime contractor for the F4H weapons system, which is expected to utilize the Sparrow III missile. Under Raytheon, North American Aviation has responsibility for the development of back-up weapons systems using Sparrow IA, II, and rockets. The missile for the F4H will have to be launched blind, because of its physical location on the aircraft, thus seeker range search for target acquisition during flight is a prerequisite.

Phase 3 - Improved Sparrow II — This is a research and design effort directed toward improvement of Sparrow II, utilizing new techniques and circuitry as they become available.

The Bureau of Aeronautics and NRL agreed that the present study should be limited to consideration of the Sparrow II-F5D system with range search. Plans to use the Sparrow II with the F4H system includes acquiring the target with the seeker after launch. This involves so many uncertainties that it will not be considered in this report. It was further agreed that the materials available in published Douglas reports (which are used in the following section), while not precisely correct, represent the best available information describing the F5D system.

In investigating the vulnerability of the Sparrow II to countermeasures, it has been necessary, in some cases, to utilize general information and to make assumptions about specific parameters. Therefore, this report will attempt to point out regions of possible trouble in the missile system which may need further study and design effort. Quantities used, in many instances, provide illustrative rather than exact solutions.

Tactical Situation

In the Sparrow II basic or all-weather mode, the AI radar initially acquires and tracks the target and assists the missile seeker in acquiring the target. It is also possible to operate the system independently of the acquisition radar by selecting the optical mode. In this mode the missile is aimed with a fixed-reticle reflective gunsight. The primary mode of operation, however, is the all-weather mode. The guidance system employs constant true bearing navigation using the AN/DPN-21 active radar target seeker. Conical scan at 200 cps is used. The transmitted peak power is 50 kw. The pulse width is 0.125 μsec, and the gate width is 0.4 μsec. A pulse repetition rate of 4000 pulses/sec is used. The antenna beamwidth is 7 degrees.

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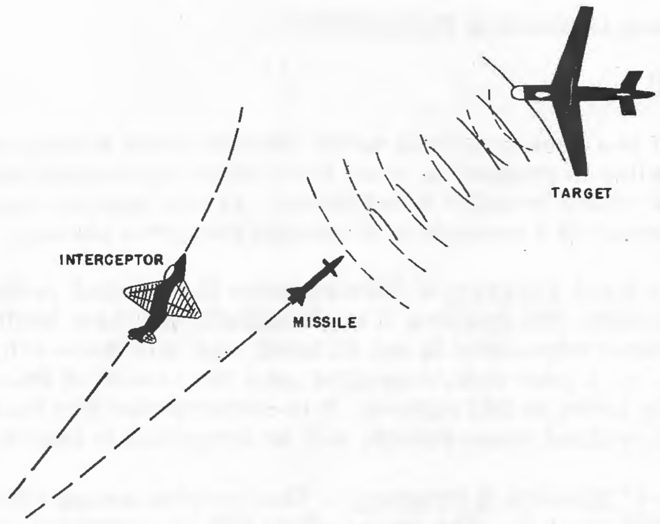

Fig. 11 - Active homing missile guidance technique (Sparrow II)

Figure 11 illustrates the active homing guidance technique and depicts a situation in which Sparrow II might be employed. The interceptor is vectored by CIC to a position from which acquisition of the target can occur. As the interceptor approaches the target area, the pilot will select the missile or missiles to be fired, activate them and choose the mode of fire. During this period, the AI radar in the all-weather case will search for and lock on the target. The seeker antenna is then slaved in angle to the AI radar antenna, and seeker range search begins. Once range-lock occurs, angle slaving to the AI radar is discontinued and automatic tracking is initiated. Additionally, during the period after AI lock-on the "synchronous" slaving system will slave the AI radar alternately to each missile. As each missile locks on the target, an indication is provided to the pilot. As shown by Fig. 11, once the missile is launched the interceptor is free to break away.

The optical mode of operation differs from the all-weather mode in that the seeker antenna is slaved to the optical sight and range search occurs over the probable optical acquisition ranges. Figure 12 is a block diagram of the AN/DPN-21 seeker (7).

Figure 13 provides a block diagram for the all-weather mode of Sparrow II operation (8). The following descriptive information was taken from a Douglas report (9).

1. Coordinate Transformation Unit — this device transforms the elevation and azimuth angles of the AI radar antenna into polar coordinates so that the seeker antenna may be brought to bear upon the target.

2. Angle Slaving Unit — this unit causes the seeker antenna to point in the direction indicated by the coordinate transformation unit. After lock-on occurs, automatic tracking is instituted.

3. Range Search Generator — the range search generator sweeps the seeker range gate through ranges covered by the AI radar range gate until lock-on occurs. In the optical mode, the range gate will be swept over the probable optical acquisition ranges.

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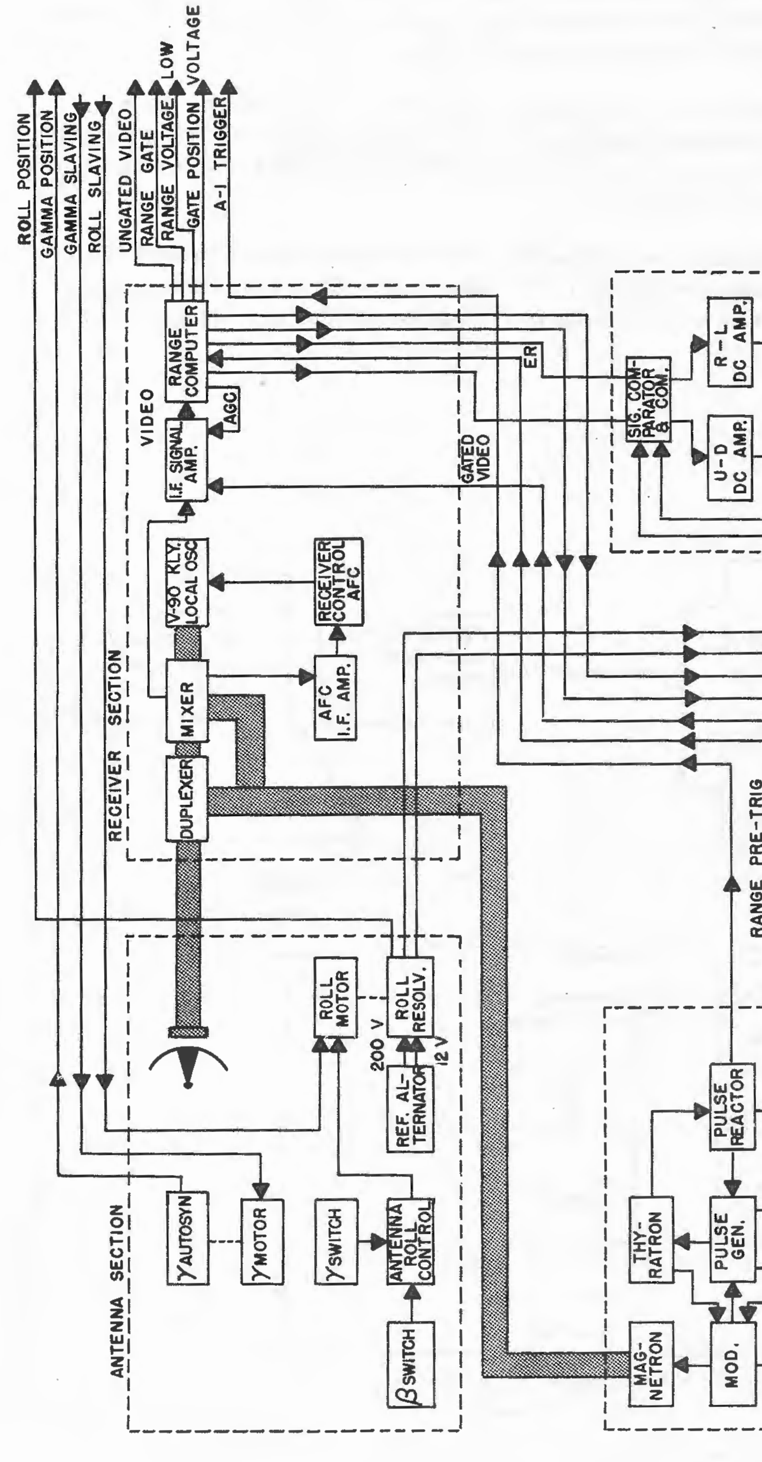

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4. Range Lock Detector — this device determines when the target is in the seeker range gate. It then automatically stops the range search and, after a suitable delay to reduce the false alarm effects, indicates to the pilot that lock-on has occurred and that the missile is ready to fire.

5. Firing Angle Indicator — the firing angle indicator compares the existing lead angle with the allowable lead angles and computes the correct airplane maneuver for the pilot or autopilot. Interlocks will be provided to prevent accidental firing at unsuitable lead angles.

6. Firing Range Indicator — this device compares the present range with the minimum and maximum ranges and indicates to the pilot when the range is acceptable for firing. Interlocks will be provided to prevent accidental firing at unsuitable ranges.

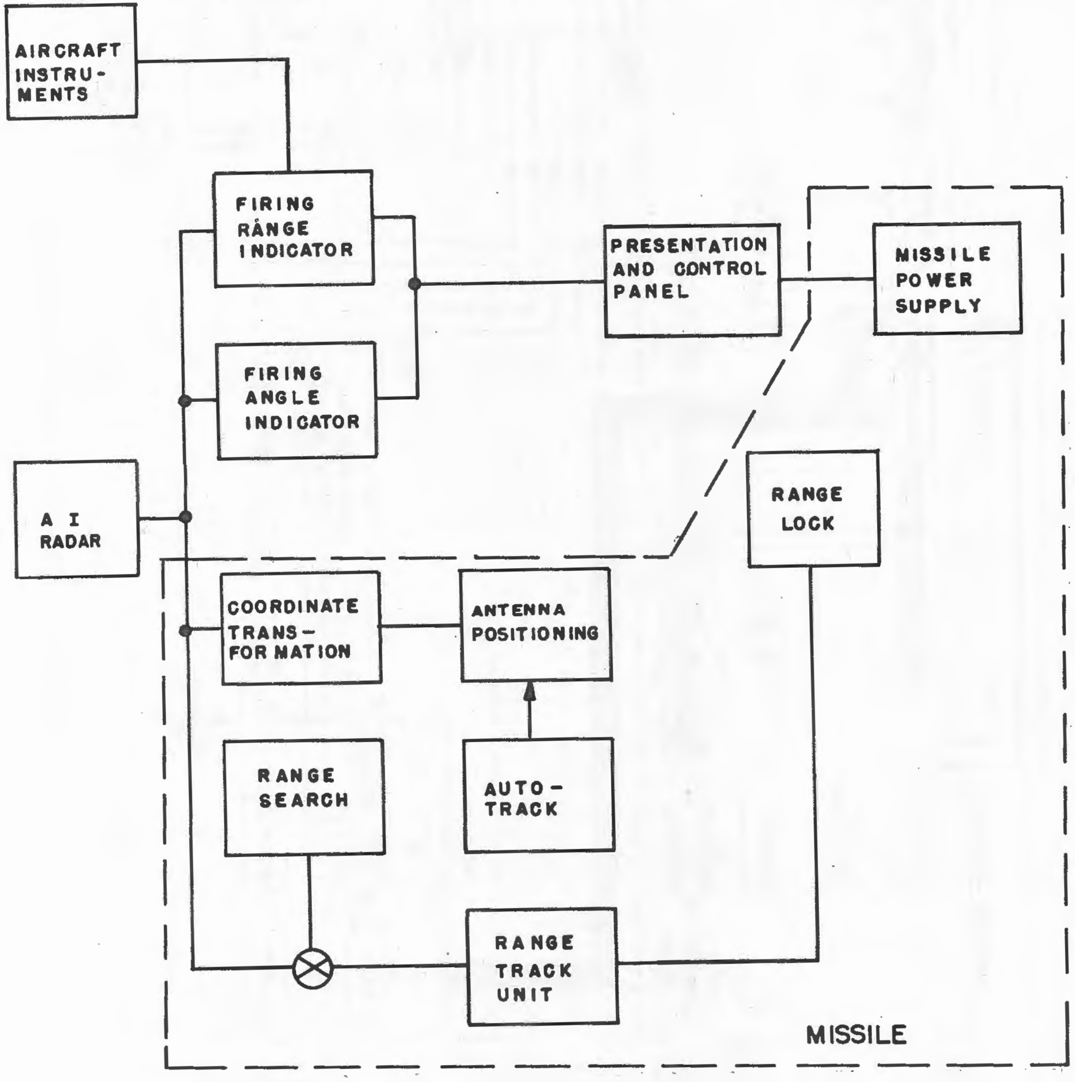

Fig. 13 - All-weather mode of Sparrow II operation

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7. Presentation — the presentation will probably consist of a light and a scope. The light will indicate that a missile is ready to fire and the scope (also used for the AI radar) will provide steering information as well as a visual indication of satisfactory range. The presentation will consist of a circle which represents the allowable launching angle and a dot or mark indicating the actual lead angle. When the dot is within the circle, the missile may be fired. In addition, lights will be provided on the missile turn-on panel to indicate which missiles have not been fired.

8. Armament and Missile Power Switches — these switches provide for energizing the desired missile or missiles and permit the pilot to select automatic or manual fire. The pilot may also determine whether one or more missiles shall be fired at a given target, either manually or automatically. It is planned that the firing button (for manual fire) be located on the control stick for ease of operation.

Figure 14 gives the block diagram for the Sparrow II optical system (8). The functions of the parts of this block diagram are as follows (9):

1. Range Search Generator — the range search generator automatically sweeps the seeker gate over the probable target ranges until lock-on occurs.

2. Range Lock Detector — this device determines when the target is in the range gate and automatically stops the range search generator. It also indicates to the pilot, after suitable delay, that the missile is ready to be fired.

3. Firing Range Indicator — this device employs standard aircraft instrumentation and seeker range voltage to compute minimum and maximum ranges for the particular attack. Preliminary work indicates that the minimum and maximum ranges may be computed with reasonable accuracy by means of relatively simple equations and equipment.

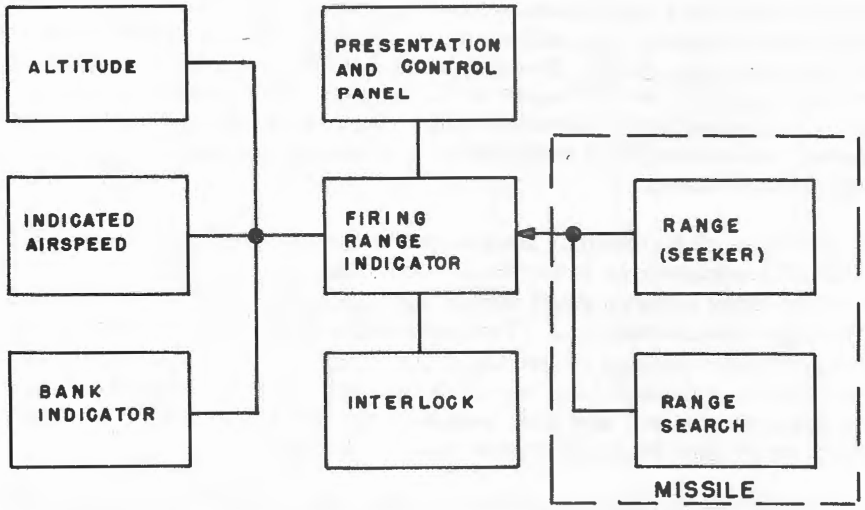

Fig. 14 - Optical mode of Sparrow II operation

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4. Presentation — present plans call for the major presentation to consist of two lights located directly under the gunsight reticle. One light will indicate that a missile (or missiles) is ready to go and the other will indicate that the range is satisfactory. In addition, lights will be provided to indicate which missile (or missiles) have not been fired.

5. Armament and Missile Power Switches — these switches provide for energizing the desired missile or missiles, and permit the pilot to select automatic or manual fire and to determine whether one or more missiles shall be fired at a given target.

Vulnerability

Vulnerability to jamming of the Sparrow II system will be the same for the all-weather and optical modes except during acquisition. During acquisition, if the AI radar is unable to track the target, or if tracking is very erratic, the all-weather Sparrow II seeker will not be able to acquire the target. In the optical case, probability of acquisition by the seeker can vary with seeker vulnerability to jamming. This vulnerability of the AI radar has been covered in detail under another phase of this study and will not be discussed further except as it directly relates to missile operation. The remainder of this section will be restricted to considerations of vulnerability of the guidance equipment.

Once the Sparrow II is locked on in target track, the seeker (Fig. 12) takes over. The functions performed by the sensing portion of the automatic guidance loop of the missile are essentially the same as those performed by any conical scan fire control radar. Thus, it is reasonable to expect that the seeker will be subjected to the same basic kinds of jamming (both intentional and environmental) as can be employed against a fire control radar, namely, chaff, brute force electronic jamming, and deceptive jamming including angle and range pull-off.

In determining the susceptibility of any system, or parts of a system, it is of importance first to consider the performance of the equipment in its normally noisy environment, i.e., environmental jamming. Normal or usual ambient noise for an AI radar includes, for example, altitude line, clutter, friendly interference, etc. It is almost axiomatic that improvement of equipment performance in its normal environment will result in improved performance in the presence of intentional jamming. Inclusion of antijam features which cause incidental deterioration of performance in the normal environment is, conversely and obviously, to be avoided.

Many of the types of intentional jamming which may be encountered by the Sparrow II seeker are directly comparable to forms of environmental interference. For example, the problem of tracking through chaff can be approached from the same design criteria as tracking through the altitude line. Tracking in the presence of clutter is comparable to CW jamming. Proper design of the angle and range tracking circuitry will result in bandwidths limited to and capable of handling the tactical environmental situation. Coincidentally, this design approach will also result in greatly improved seeker performance in the presence of range and angle, deceptive type jamming.

During the next two to three years it is reasonably safe to say that Sparrow II is relatively secure from the electronic jamming. Today there are no operational K-band jammers in the United States. Equipments at this frequency are under development, but if

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the usual equipment evolution process occurs they will not be available in the fleet for at least two to three years. If it can be assumed, as we have in this study, that the enemy has jamming capability comparable to ours, then the Sparrow II would appear to be safe from electronic countermeasures during this time period.

The countermeasure most likely to be employed against the Sparrow II system in the next two to three years is chaff. Missile guidance jamming requires the jammer to carry and dispense chaff cut to a new frequency and having a single purpose (Sparrow II). In the all-weather mode, if the AI radar is chaff-jammed during acquisition, the seeker will not be able to acquire the target. If the jamming includes K-band chaff, the seeker can be expected to acquire chaff in preference to the target. This can occur, moreover, without awareness on the part of the operator. In the optical mode where the target is electrically obscured by chaff, target acquisition by the seeker is improbable. If K-band chaff is included, the seeker will tend to acquire the chaff.

In the period beginning three years hence, Sparrow II can be expected to lose its present advantage of having no electromagnetic K-band jamming opposition. It is predictable that the seeker can encounter K-band brute force and repeat jammers (both pulse-to-pulse and past history types). Thus it is important, where jamming constitutes a threat, that AJ measures for Sparrow II be initiated.

In considering the vulnerability of Sparrow II, it is important to examine some of the tactical aspects of the problem. First it is assumed that in the all-weather case, the average time from the first appearance of the target on the AI radar scope to missile launch is approximately 30 seconds and that the average missile time of flight is 10 seconds or a total time of 40 seconds (these quantities are believed to be tactically realistic). The jammer may jam the AI radar, jam the missile guidance equipment, or both. If AI radar lock-on occurs 10 seconds after the target first appears on the scope, the total time during which the seeker need be active is 30 seconds. This short time period available for seeker jamming prohibits the use of a human operator in the jamming loop. If brute force electronic jamming is to be used, the enemy needs prior knowledge that he will be under attack by Sparrow II, and of the frequency band employed by Sparrow II. He can then employ sweep jammers or pre-set spot jammers to cover the band of interest. He has the option of activating these jammers during his approach to the target area, or of delaying until he detects the presence of the AI radar or seeker. It seems unlikely that he will betray his presence by turning the jammers on at an early time in the engagement. Since a slow responding human operator cannot be employed practically in the seeker jamming loop and since large quantities of barrage-type brute force electronic jamming equipment would be needed to jam Sparrow II, it would appear to be desirable, from the jammer viewpoint, to employ automatic systems of the rapid intercept, analysis, and jam variety, or of the repeat-back types.

It is improbable that the enemy will know, prior to the attack, the type of weapons to be employed against him. It is also doubtful that the enemy can physically or economically afford to employ jamming equipment to operate against every portion of the complex weapons system he will encounter.

Specific Circuit Considerations

Figure 12 is a block diagram of the Sparrow II seeker. It is now of interest to investigate the susceptibility of this seeker to countermeasures and to recommend modifications

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to improve antijam performance as needed. First, emphasis will be placed on making the equipment design optimum for natural environmental or normal usage. From discussions with the contractors it appears that Sparrow II currently has several features which should make it vulnerable to natural interference.

1. Range Gate Width — If the Sparrow II range gate were designed to fit the pulse width employed (0.125 μsec), the seeker would be reasonably safe from many interfering targets. However, a combination of gates is presently used which provides a vulnerable range area 0.4 μsec wide. The contractor stated that the system has a 20-db off-gate rejection. However, it has no rejection in any part of the existing 0.4-μsec gate combination. Thus the Sparrow II should be in approximately the same difficulty as any of the current AI radars (which have 0.5-μsec range gates) in regard to the probability of unwanted signals such as clutter occurring in the gate. A tracking interval of 0.2 μsec will exclude much extraneous noise without reduction of information energy from the target. Ideally, the gate width should be the same as the transmitted pulse width (0.125 μsec), but considerations of a reasonably simple receiver design cause the received echo width to be stretched to 0.2 μsec. The use of a narrow gate width will improve the operation of the Sparrow II seeker both in its natural environment (clutter and altitude line) and in the presence of jamming (both chaff and electronic). It should be clearly understood that the advertised transmitted pulse width of 0.125 μsec is actually 0. 2 μsec in the equipment and, further, that the tracking interval (gate) is 0.4 μsec.

2. Range Tracking Bandwidth — The bandwidth of the range tracking loop will determine the amount of extraneous noise which can enter this and subsequent system elements, and provide some measure of the effect of input noise on system performance as a whole. This bandwidth should be limited in accordance with requirements imposed by the tactical situation. The contractor stated that the system specification calls for the seeker to be able to handle a 30 g maneuver rangewise. For a double integrator range tracking servo system, as used in the Sparrow II missile, the required bandwidth can be determined from the steady-state error expression

$$\epsilon = \frac{\ddot{R}}{\omega_B^2}. \qquad (16)$$

If the allowable error is 0.1 μsec or 16.4 yards, as obtained from the correct narrow gate width, and $\ddot{R}$ is 322 yd/sec^2 (30g), the bandwidth required is $\omega_B = 4.43$ rad/sec. For smaller accelerations, the bandwidth required is even smaller. The ability to track through chaff and other low-velocity interfering signals is inversely proportional to the tracking bandwidth. The range tracking bandwidth of the Sparrow II seeker is stated by the contractor to be ≈80 cps. This bandwidth was derived from the closed-loop transfer characteristic as shown by Fig. 15 (Ref. 10). The closed-loop transfer characteristic was in turn derived from the open-loop characteristic shown by Fig. 16 (Ref. 10). The error characteristic given by the contractor is

$$\epsilon = \frac{\ddot{R}}{445}. \qquad (17)$$

For a 0.1-μsec (16.4-yard) tracking error the maximum maneuver which can be tracked is 7298 yd/sec^2 (680g). This maneuver obviously cannot be generated by any real target. The range tracking system may be expected to pull off onto almost any large interference. This design is inappropriate because it results in a bandwidth (21.1 rad/sec) approximately five times that required to track target information.

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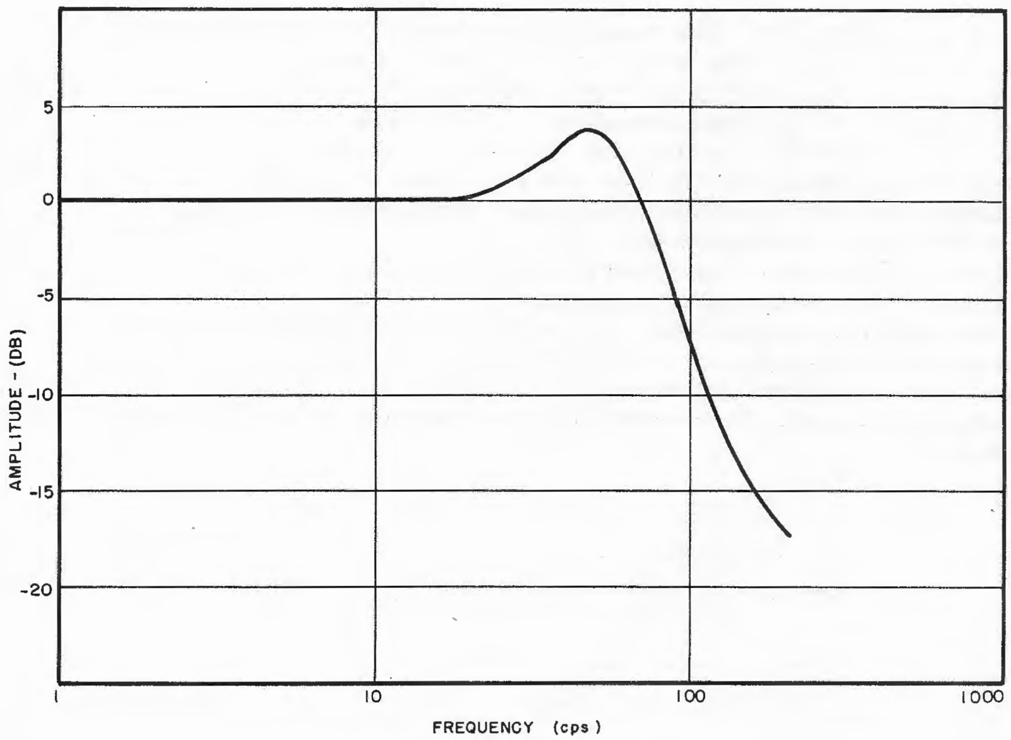

Fig. 15 - Sparrow II range computer experimental closed-loop frequency response

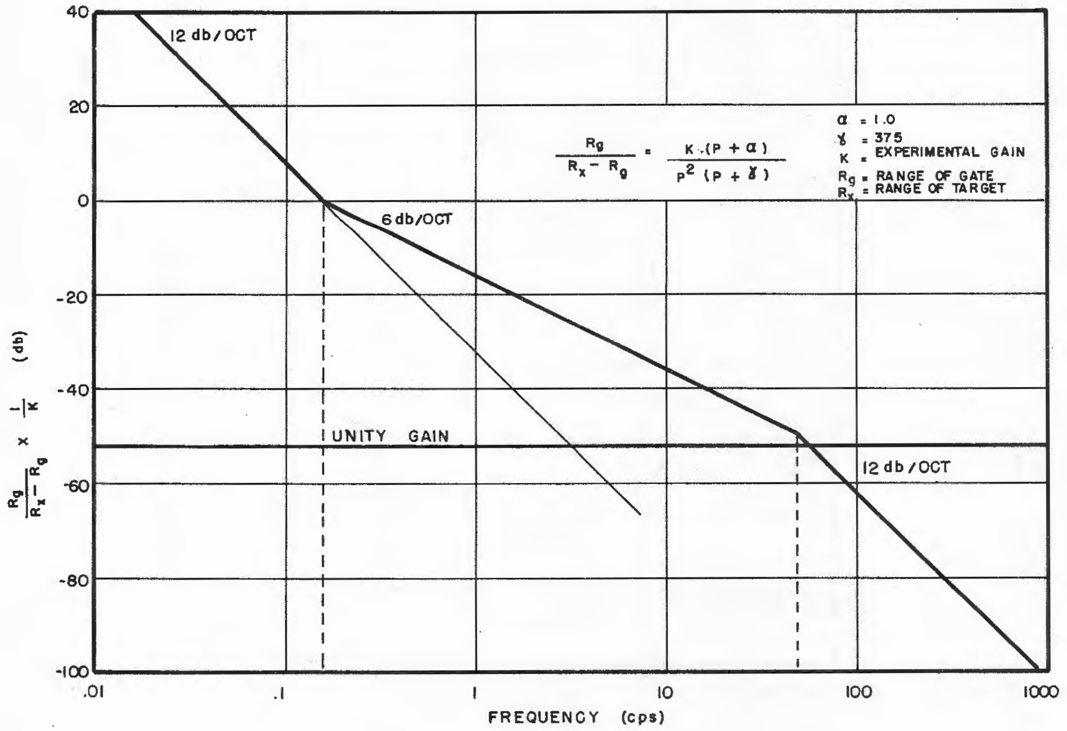

Fig. 16 - Sparrow II range tracking unit calculated open-loop frequency response

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3. Velocity Memory — The contractor has stated that the design criterion for velocity memory was the maintenance of continuous track on smaller than threshold signals in the presence of large amplitude fades of duration up to 2 seconds, consistant, however, with the requirement of range track through boost (11). While this is a desirable design criterion, it is necessary to analyze the transient response of the system in order to predict its performance in the presence of countermeasures (natural or intentional). Figure 17 shows the transient response of the Sparrow II range tracking unit to a step input (10). It is evident that the range tracking unit has completely learned a new input condition in about 0.02 second. A system designed to track only the tactical inputs (acceleration constant = 20) would have a learning time of approximately 0.81 second (11). This means that it would take 0.81/0.02 or 40.5 times as long as the present Sparrow II for the properly designed system to acquire an interfering signal such as chaff, range decoy, clutter, etc. These transient conditions are stated on the basis of zero initial conditions (tracking of a nonaccelerating target). The contractor should study the situation for other target input conditions.

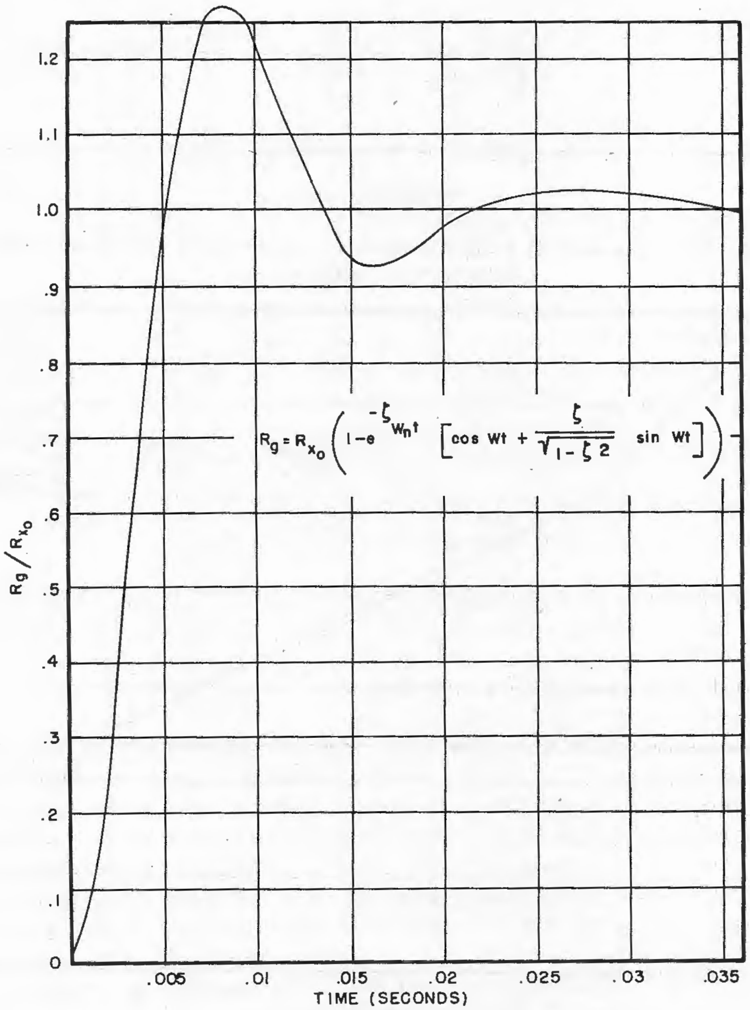

Fig. 17 - Sparrow II range tracking unit calculated transient response to a step input

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Discussion, to this point, has mainly considered interferences inherent in the natural environment. These are analogous to several types of intentional jamming. For example, chaff and altitude line discrimination or suppression present the same kind of problem in the design of a range tracking system. For the Sparrow II seeker in its natural environment, apparent circuit design deficiencies requiring further study include velocity memory and learning time, a restricted tracking bandwidth tailored to tactical requirements, and advantageous utilization of the short pulse through reduction of gatewidth. Circuit optimization for the above will suppress extraneous noise, and improve capability to track through certain normally or intentionally interfering signals.

As example of related interest, tests have shown, in the case of the APQ-50 and APQ-51 AI radars, that proper circuit design reduces the altitude line problem and chaff problem.

It has been indicated previously that gate-width reduction and restriction of tracking bandwidths to those required tactically will improve tracking in the presence of clutter. Here again there is an almost direct analogy between tracking problems imposed by large blocks of clutter and by CW (spot or sweep frequency) type electronic countermeasures. Thus, design of the system to combat interferences which occur in the normally noisy tactical environment can be expected also to pay off in the presence of intentional jamming. For example, in the development period of the AN/APQ-51 AI radar, it was observed in field tests that the system pulled-off the target in range when clutter appeared in the gate. Subsequent utilization of limited bandwidth, and of double integrator tracking characteristics related to tactical requirements, resulted in circuitry that permitted the AN/APQ-51 to track through heavy clutter for periods as long as 10 seconds where a velocity differential above 150 knots existed.

The above sections have illustrated a procedure whereby improvement of seeker operation in its natural environment results in performance improvement in the presence of chaff and brute force electronic countermeasures. The approach suggested can also reduce susceptibility to the more sophisticated techniques such as range pull-off. If the range tracking gate is reduced in width to fit the 0.125-μsec pulse (in practice 0.2 μsec because of inherent receiver pulse stretching), effectiveness of repeat-back jamming will be marginal at best. Current pulse-to-pulse repeaters have an inherent delay in response of about 0.2 μsec. Appreciable reduction of this delay time is not expected. It is evident that the gatewidth of the Sparrow II seeker should be reduced.

Figure 18a illustrates existing and proposed Sparrow II gating systems. It can be seen that lagging the echo pulse there is a 0.2-μsec aperture into which a pulse repeater could be placed. Leading the echo pulse is another 0.2-μsec aperture into which past history type repeaters could place energy. A possible method for reducing susceptibility of repeater type jamming is illustrated by the dotted gate of Fig. 18a. This gate is a "pregate" which selects a restricted interval (0.125 μsec) from which video information is extracted for use in the tracking circuits. While this technique would resolve the problem, it does so by the use of redundant circuitry. The present circuitry could be more simply modified to accomplish approximately the same result by narrowing the gates as shown in Fig. 18b. Currently the Sparrow II has 20-db off-gate rejection. This is not sufficient to combat possible types of natural or intentional jamming. For example, the altitude line signal at 10,000 feet has been measured with the APQ-50 radar (X-band) to be 23 db greater than a 1-square-meter target. This indicates that improvement in off-gate rejection is desirable. To get sufficient off-gate rejection, cascaded gating arrangements probably will be necessary. One such gating scheme is that using the redundant circuitry described above.

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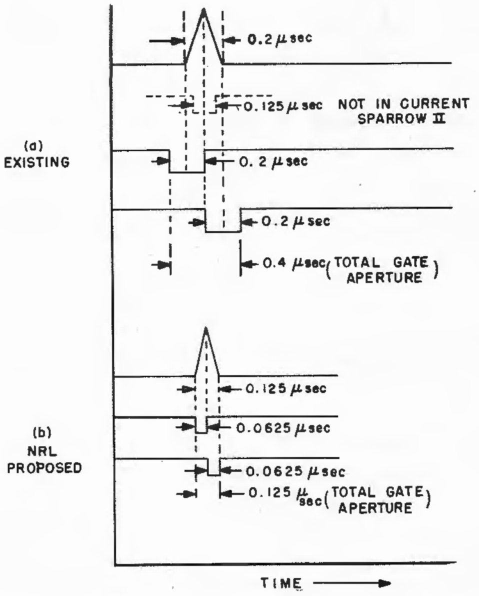

Fig. 18 - Sparrow II gate widths

The inherent delays in a repeat-back, range and angle pull-off jammer are presently approximately half of the time duration of the current Sparrow II gate. If this gate were tailored to fit the video signal, the repeat-back jammer's probability of getting in the gate would be reduced appreciably. In addition, if the gate were reduced in width, the jamming power getting into the seeker from brute force techniques such as spot or sweep-frequency types would be reduced in proportion.

The preceding section described performance of the range-tracking unit in the presence of pulse-to-pulse repeater jamming. A second range pull-off technique utilizes past history (pulse storage and analysis) for jamming. An obvious method for countering this type of jamming is jitter of the PRF. However, in the current Sparrow II seeker, the angular velocity of a motor generator is used to establish seeker PRF. Jitter of seeker PRF is impractical when a device with inertial characteristics of a motor generator is so used. The AI radar is also vulnerable to past history jamming, and to second time around echoes, because of synchronization of its PRF with that of the seeker. This problem will be discussed in more detail in the section on missile auxiliaries.

4. Angle Tracking — in this missile, angle tracking is not accomplished in the usual fashion by moving the radar antenna to correct for tracking error, but instead by moving the missile itself so as to maintain a constant line of sight in space. In order to accomplish this type of tracking the following circuits or loops are brought into play; receiver, agc, scan demodulator, autopilot, airframe, and any associated amplifiers.

These elements are shown in the block diagram of Fig. 19. The agc circuitry, though overly complex, appears to be designed to reduce such effects of environmental jamming as target amplitude noise. However, the seeker in its natural environment can be expected to perform less reliably because of the unnecessarily complex nature of these circuits. For instance, the agc-controlled error signal amplifier, wherein the range multiplication is accomplished, could be simplified or eliminated.

The scan signal demodulators though small and composed of passive elements are overly complex and are designed to take small time samples of the scan modulation envelope rather than use all of the modulation. Reference to Fig. 20 will clarify this comment. A small (10% of cycle time) sample of the error signal is taken by the circuits in the up, down, left, and right coordinates. The circuits compare up and down and compare left and right energies to develop steering error signals. If, because of a fade or other disturbance, one of these pieces of information were to be missing the steering signal would be more noisy than would be the case if the complete scan cycle were used. The use of less than the whole cycle is equivalent to the reduction in integration time in a correlation detector (which this system and many others use for angle error detection). It would be possible, because of the circuits used, to reduce the demodulator complexity by a factor of 2 and at the same time accomplish more noise-free operation.

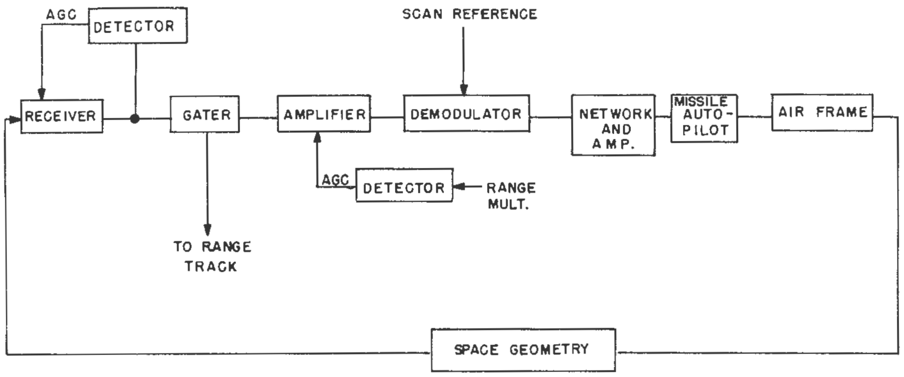

Fig. 19 - Sparrow II angle track loop

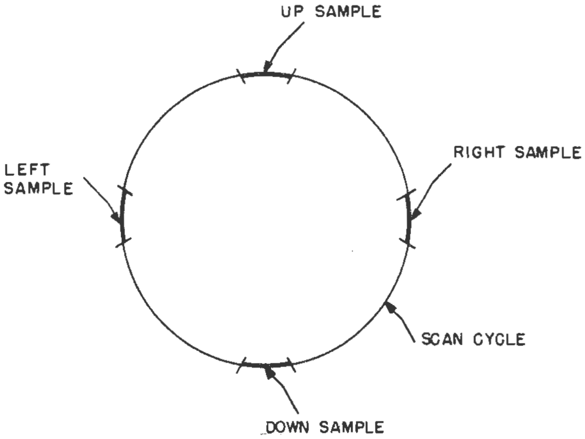

Fig. 20 - Sparrow II demodulation process

Data presented by the contractor shows that the closed angle tracking loop of the system has a bandwidth varying from 1 to 4.56 rad/sec as a function of speed, altitude, and range. This appears to be compatible with the tactical situation. In addition, the transient response of the over-all angle tracking loop appears such that extraneous noise will not introduce violent missile motion.

The flap servo bandwidth appears to be slightly greater than that necessary to make the missile system stable. This increased bandwidth will result in flap noise slightly greater than desirable in the presence of countermeasures.

It is now of interest to determine the effects of deceptive angle jamming on the Sparrow II seeker. Angle jamming can be most easily accomplished by amplitude modulation of the jamming signal at or near the scan frequency. Examination of the angle tracking bandwidth information supplied by the contractor shows that the jammer would have to get within 1 cycle of the scan rate to result in missile motions of such a magnitude as to produce degration of the tracking performance.

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A more sophisticated method of angle pull-off is that under development at Stanford and elsewhere called the "inverse-gain" method. The "inverse-gain" technique employs traveling wave tubes and associated circuitry to supply to the seeker a signal having approximately the same characteristics as the target except that the scan modulation is rotated in phase (usually 180°) to drive the seeker off target in angle.

It has been demonstrated in other radar systems similar in operation to the Sparrow II seeker that this technique can be effective unless some counter-countermeasure is employed. One such antijam measure is to provide in the seeker transmitter a low-modulation-index signal not related to the tracking problem. Comparison between the phase of the transmitted and the received signals can be made in simple circuitry to determine the amount of phase shift the jammer employs at the scan frequency. Automatic circuitry can be designed to rotate the phase of the received scan modulation signal in the reverse sense to that utilized by the jammer. Since the antijam measure does not contribute to the performance of the seeker except against a specific type of jamming, its use in the seeker, in hardware form, should not be contemplated until certain knowledge is obtained as to the enemy's capability and intentions in regard to this type of jamming.

Missile Auxiliaries

Currently it is planned that the Sparrow II seeker and AI radar shall have "synchronous" PRF. The AI radar will sample the PRF of each of the missiles in turn in order that synchronism can occur. As previously discussed in the section on AI radar, reduction of the pulse and gate widths can effectively counter the repeat-back jammers. In order to maintain average power, however, it becomes necessary to increase PRF. This introduces the second-time-around-echo (STAE) problem which can, in turn, be countered by jitter of the PRF. Jitter of PRF will also counter "past history" type jammers. If the synchronous Sparrow II system is used, jitter of the AI radar PRF will not be possible and one effective antijam technique is ruled out.

For the same antijam reasons, it may be desirable to jitter the PRF of the missile seeker. Currently this is impractical because of the inertia and low-bandwidth capability of the rotating machinery used to generate the PRF. Alternatively, the carrier for accomplishing missile-AI radar slaving could be some signal other than the PRF. It could be accomplished, for instance, using the range voltage as a carrier. This would reduce appreciably the burden on the AI radar and would preserve the antijam flexibility of both missile and radar.

Currently, slaving is accomplished by tracking the radar video signal within the missile. Again the PRF is used as the carrier. If interference (chaff, electronic countermeasures, etc.) exists in the vicinity of the AI radar video signal even though it does not disrupt tracking in the AI radar, the missile gate may be, as a result, positioned near but not on the target. The use of some other carrier signal for slaving would alleviate this difficulty. For example, if the AI radar is able to track through the interference, the range voltage, unlike video, would be unaffected by the interference. This use of the range voltage as a carrier would enhance the probability of seeker lock-on of targets which the AI radar is capable of handling. If the missile design were to take advantage of shorter gates and bandwidths consistent with the tactical problem, the missile seeker would be less vulnerable to jamming than the AI radar. This is not presently the case, assuming the enemy has the potential to jam K-band. In addition, if the restrictions imposed by the present synchronous scheme were removed, the seeker has the potential of successful operation under environmental conditions were the AI radar would be jammed.

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Conclusions and Recommendations

It is recommended that a design study be undertaken to investigate in more detail the possible design deficiencies of the Sparrow II system, some of which are described above. It is further recommended that this study be based upon expected tactical situations. Modification of Sparrow II should be directed first toward insuring that the seeker will perform satisfactorily in its natural environment. Such things as reduction of redundant or overcomplex circuits, bandwidth limiting, narrowed gate width, etc. will result in improved operation in the natural environment as well as in the presence of jamming. In addition, the effects of the current synchronous scheme on missile auxiliaries (AI radar) are deemed undesirable. It is recommended that a system be developed which does not place present limitations on the AI radar and the seeker. The system chosen should not restrict flexibility of operation of the AI radar, the missile, or the interceptor aircraft.

Redundant Systems

It has been suggested that redundant systems may be a useful defense against several jamming techniques. Among such schemes considered is injection of K-band energy through appropriate plumbing into the X-band AI radar antenna system. In a situation where range tracking is lost by the AI radar but homing on the jammer is possible, the range information needed for launching computation can be obtained via the K-band injected energy. The Sparrow II guidance contractor is currently studying this problem. Two possible solutions are being investigated. The first is injection of K-band energy into the AI dish via an array of slots cut into the dish. The second is use of a dual frequency feed such that the dish is illuminated by both K-band and X-band energy. Both of these schemes appear feasible and require only sufficient time for development. An advantage to be gained by such a technique is that it requires the enemy to carry equipment to jam both frequencies. A disadvantage to be weighed against this, is that it requires the interceptor aircraft to carry an additional ranging radar (Sparrow II seeker) from which range information for launching Sparrow II can be obtained.

If redundant ranging information of the accuracy required for launching other weapons (guns, rockets) is desired, an extensive redesign would be necessary to make the current Sparrow II range circuitry, or AI radar range unit, compatible with the problem. The Sparrow II range unit is not sufficiently accurate for the generation of lead angles within tolerable error for guns and rockets. The current AI radar range tracking circuits were not designed to cope with the pulse lengths typical of Sparrow II and thus are unsuitable for the redundant system without modification. Current Navy doctrine stresses design permitting weapon diversity (guns, rockets, and missiles). In accordance with this doctrine, redundant systems would be required by specification to have sufficient accuracy to launch all of these weapons with a high kill probability. The K-band injection techniques, as currently proposed, would limit weapons to the Sparrow II in the presence of X-band AI radar jamming.

It was mentioned above that the K-band injection schemes described, while practicable, will require development time. During this period it is not improbable that the enemy will have developed a K-band jammer. This reduces to some extent the potential advantage of the scheme. All of the above arguments, moreover, assume AI radar capability for homing-on-jamming in angle.

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A method for reducing the development time in prosecuting K-band injection is to make use of a Sparrow II missile-mounted seeker, carried in the aircraft as a redundant but low-performance radar. This method would require:

a. Slaving of the seeker gimbals to the homing-on-jamming AI radar,

b. Seeker range search and lock-on capability on its own,

c. Connecting of seeker range information into the pilot's presentation and into the lead computing circuits,

d. Sufficient range accuracy to insure the computation of a lead angle for a tolerable miss distance.

It is, of course, recognized that the use of a Sparrow II mounted seeker is only practical so long as the missile is carried external to the parent aircraft, and is at best a low-performance stopgap in the event early use becomes necessary.

It is concluded that Sparrow II generated K-band injection for ranging provides a feasible, though limited, solution to the problem of launching Sparrow II in the presence of X-band AI radar jamming. Frequency diversity is a general technique for reducing vulnerability of airborne weapons systems to jamming. Its utility will vary with the parameters of each particular application.

* * *

SPARROW III MISSILE GUIDANCE EQUIPMENT

Status of Sparrow III

The Sparrow III is a semiactive homing, CW, air-to-air guided missile. Dayfighter and all-weather fighter versions are under development. The dayfighter version uses a fixed dish CW radar for target illumination. The dish, launching platform (aircraft), and pilot's optical gunsight are boresighted to a common reference. In an attack, the pilot maintains the target within the sight, thereby illuminating the target continuously during seeker preparation and time of flight. Target ranging and closing speed intelligence is obtained from the CW radar beam.

Tactical Situation

Figure 21 illustrates the CW homing-all-the-way technique. In a successful attack the interceptor aircraft is vectored by CIC to an area where airborne target detection can occur. The aircraft is then maneuvered into a suitable attack zone by the pilot and the missile (s) released. The target must continue to be illuminated during missile time of flight.

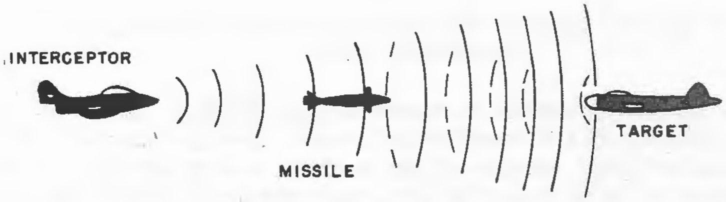

Fig. 21 - Semiactive homing missile guidance technique (Sparrow III)

It is presently proposed that the all-weather version of Sparrow III in the F4H-1 airplane will use the AN/APQ-50 radar with CW injection into the APQ-50 antenna system for target illumination. Radar and illuminator frequencies are at X-band with sufficient separation to permit isolation by filters at the radar and missile receivers.

Tactical use of this system involves target detection and lock-on in the usual manner with the AI radar (or optically in the dayfighter case) and missile release at a suitable launching range, with continued target illumination from the launching aircraft, through missile time of flight. The basic measurement derived from the missile radar is the angular rate of the line of sight from missile to target. From this information, required missile flight path angular rate corrections are derived and accomplished through the seeker pilot. Figure 22 is a block diagram of the system loop for the all-weather mode. AI radar considerations are analogous to those for other missile systems and so will not be discussed here. Since this report concerns itself only with the missile seeker, the discussion will apply equally well to both dayfighter and all-weather versions.

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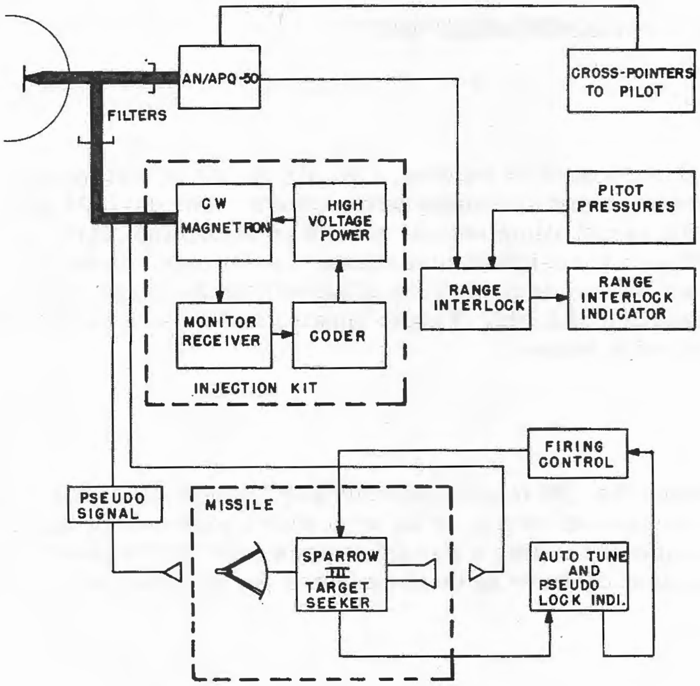

Fig. 22 - Sparrow III missile guidance system, all-weather mode

The CW semiactive target seeker is shown in Fig. 23 (Ref. 13). Radar energy is furnished by the illuminator in the launching aircraft. Energy reflected from a target is received by the gimballed front antenna of the missile; energy arriving at the missile directly from the illuminator is picked up by a rear widebeam (120°) antenna on the missile. Comparison of the frequencies of the two signals yields a doppler frequency which is a function of the relative speeds and positions of the illuminator, the missile, and the target aircraft.

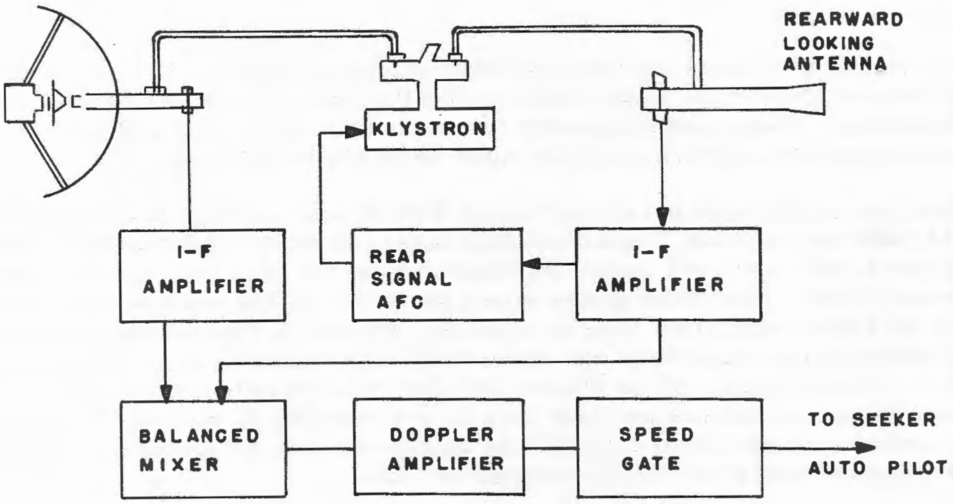

Fig. 23 - Basic Sparrow III target seeker system

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A single klystron local oscillator is employed to heterodyne the front and rear signals respectively into two separate i-f circuits. Initial tuning of the klystron (rear signal lock) is automatically accomplished shortly after the system is turned on by sweeping the klystron over a suitable frequency range until a signal appears in the rear i-f amplifiers. This is applied to lock circuits which stop the klystron at the correct frequency (approximately 30 Mc above the illuminator frequency) and an afc loop which centers the signal in the i-f passband. The illuminator is frequency-modulated at a code frequency which is detected in the missile at the output of the rear i-f amplifier and used to prevent lock on other radars.

The outputs of the front and rear i-f amplifiers are combined in a balanced mixer to produce the net doppler frequency corresponding to the two relative velocities involved which, at the frequencies used, will be below 80 kc for anticipated targets. The mixer feeds a doppler amplifier which amplifies a nominal 80-kc spectrum covering all desired doppler frequencies; the output of the doppler amplifier is applied to a speed gate in which various circuits search for, lock on, and track the doppler signal in frequency.

When the missile is being carried on the parent aircraft, and is warmed up and operating, the target seeker is locked on a pseudo doppler signal which is supplied to the front antenna of a missile by the illuminator in the aircraft. Lock on the pseudo signal indicates correct rear signal lock and checks the over-all operation of the target seeker. Failure to lock on the pseudo signal by any missile causes the launching control to hold fire on the missile in question. At launch, the seeker is forced to lose lock on the pseudo signal and to begin automatic speed search for the target.

Target direction is sensed as amplitude modulation of the doppler signal which is effected by conically scanning the front antenna receiving pattern. The scan modulation is extracted by an AM detector and then compared with the scan reference signal in comparators which resolve the directional error into pitch and yaw components. A plane polarized 6-inch parabolic reflector is utilized by the seeker. Conical scanning at a rate of approximately 285 cycles per second is accomplished by spinning the tri-element antenna at 95 cycles.

The missile is controlled and stabilized by an automatic pilot termed "seeker pilot." In this assembly the error signals from the radar seeker are fed to an electrohydraulic servo system controlling the wings. Roll stabilization signals from a roll rate gyro are introduced through the servo amplifiers, differentially to all four wings. The missile is attitude-stabilized by gyro feedback, and is flight-path stabilized by accelerometer feedback.

Vulnerability

In both versions of the Sparrow III (dayfighter and all-weather systems) launching lead angle and range information is derived from radars carried in the mother aircraft. In addition, the initial seeker search sector is selected from information derived from these radars. Thus, if the AI radar in the all-weather case or the illuminating CW radar in the dayfighter case are jammed, the missile system is also jammed. Means for jamming the pulsed AI radar have been covered in another phase of this study and will not be discussed here.

Figure 21 illustrates the tactical application of Sparrow III. From this sketch it is obvious that several paths are open to either intentional or environmental jamming. The first of these paths is the one mentioned above, namely the path between illuminator and

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target. Next is the target-to-missile path and, finally, the illuminator-to-missile path. Each of these space links is essential for successful missile system operation. Thus, if detrimental noise enters any of these space links, reduction in performance results.

The same basic considerations, related to antijam modifications, that were outlined in the previous missile sections will be applied here. The basic premise is that noise encountered in the natural environment is analogous to and more likely to occur than intentional jamming. Thus, analyses will be directed primarily toward improving system performance in its natural environment. The resulting improvement of operation in the presence of intentional jamming will also be discussed.

Types of environmental noise, as related to the operation of pulsed systems, have been discussed in other sections of this report. Although the Sparrow III utilizes the CW-doppler principle, the same basic noise sources still exist as in a pulsed system but they are examined by Sparrow III in terms of velocity. For example, the altitude signal still looks like chaff, clutter still looks like modulated CW jamming, etc. Proper design of angle and range velocity tracking circuitry will result in bandwidths limited to and capable of handling the tactical situation and no others. Coincidentally, this design approach will result in greatly improved seeker performance in the presence of enemy jamming.

Currently the jamming opposition most likely to be encountered will include chaff and brute force modulated CW jamming. Additionally, more sophisticated jamming methods such as false doppler and angle deception have been proven in the laboratory and will certainly be encountered soon. Although it has been claimed that these sophisticated devices are effective only because the developer knew the system intimately, study of the tactical situation indicates that the enemy could develop similar techniques.

The preceding sections have considered susceptibility of the Sparrow III seeker itself to countermeasures, both natural and intentional. In an assessment of the vulnerability of this missile, it is important also to examine some of the tactical aspects of the problem. As in the case of other missiles, the average time from the first detection of the target-to-missile launch is approximately 30 seconds and the average missile time of flight is 10 seconds. The jammer may jam the AI radar (and the illuminator), jam the missile guidance equipment, or both. If AI radar lock-on occurs 10 seconds after the target first is detected, the total time during which the seeker is operative is about 30 seconds. The short time period available for seeker jamming prohibits the use of a human operator in the jamming loop. If brute force electronic jamming is to be used, the enemy requires some prior knowledge that he is being attacked by a Sparrow III. Unfortunately, the frequencies employed by Sparrow III are located relatively close to those employed by X-band AI radars. In addition, the same brute force techniques which deteriorate AI radar performance will also be detrimental to Sparrow III operation. The jammer can easily employ a common equipment of either sweep or preset spot type to cover both the AI radar and the seeker frequencies simultaneously. These factors largely cancel any advantage accruing from the use of the Sparrow III CW system as a diverse method.

Specific Circuit Considerations

A block diagram of the seeker is given in Fig. 23. It is of interest to examine the seeker circuitry to determine vulnerability to jamming and to expose areas where modification could reduce this deficiency. It is desirable first to reduce equipment vulnerability to environmental jamming (clutter, altitude signal, etc.) and second to reduce vulnerability to intentional jamming particularly where this effect has been obtained coincidentally by improving the normal performance.

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Figure 24 shows the contractor's estimate of the speed gate servo system transfer characteristics. It can be seen that the closed loop bandwidth is about 130 rad/sec. This is the bandwidth required to track a target accelerating with respect to the missile at 20 g's with a tracking error of about 100 cps (4.8 ft/sec). During the major portion of the flight (time from just after boost until near time of impact) the target is capable of maneuvers relative to the missile as shown by Fig. 25.

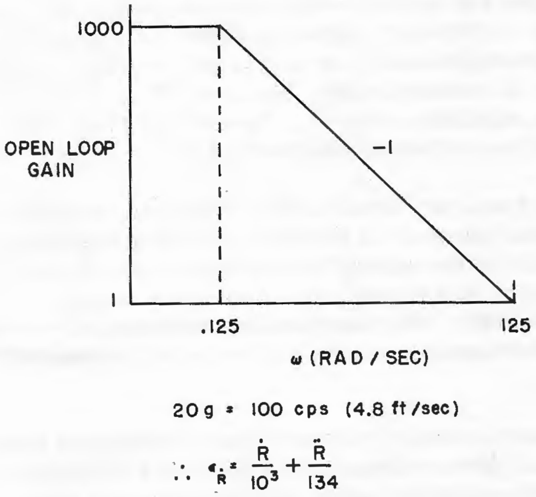

Fig. 24 - Sparrow III open-loop speed gate tracking transfer characteristics and closed-loop speed gate tracking error expression

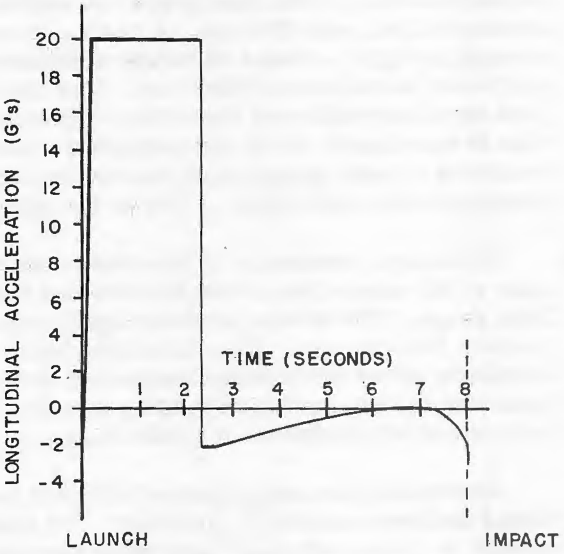

Fig. 25 - Sparrow III typical longitudinal acceleration history

According to the contractor, there is little hope of guide during boost. Since this is the case it appears that a bandwidth tailored for a 3-g maneuver would handle all expected tactical situations. This is true because at the end of boost, the missile decelerates rapidly relative to the target to between 2 and 3 g's. The current speed gate servo system bandwidth thus appears to be much too wide. Chaff and deceptive jammers are capable of producing a 20-g or less acceleration, and in tactical situations these signals will develop a doppler signal of sufficient amplitude to be tracked. Present speed gate servo system design will permit them to be tracked to the detriment of actual target tracking. For a 3-g maneuver, the bandwidth could be reduced to 20.1 rad/sec for the same allowable error (4.8 ft/sec or 100 cps). In addition, the current seeker speed gate bandwidth will allow the deceptive jammer (doppler repeater) to decoy the speed gate off the target in a very short time. If he can get a signal of greater amplitude into the speed gate, deception can result almost instantaneously. Reducing the speed gate tracking bandwidth to that compatible with the tactical situation (3 g's) will increase the jammers problem markedly and cause the jammer to take a longer period of time to complete deception.

In addition, the speed gate interval is presently about 1 kc. This width is required not because of the target's capability to produce such a doppler error but because of the excessively high conical scan frequency (≈ 285 cps), and because of the high modulation index lock-on and arming signals present (≈ 85 cps). These features of the Sparrow III system,

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if necessary, must be paid for in countermeasures vulnerability. For instance, the speed gate might be made as narrow as several hundred cycles if the width were dependent upon the velocity tracking problem alone. Such a change would increase the jammer's difficulty in entering the system approximately fivefold.

The choice of a 285-cps conical scan frequency is a good one from the standpoint of reduction of the target amplitude noise from most jet aircraft. However, difficulty may be encountered in tracking propeller aircraft due to harmonics of the propeller tip frequency falling near 285 cps. A conical scan frequency between 20 and 40 cps would result in only a slight increase in target amplitude noise and would reduce the probability of propeller modulation difficulties. The choice of a frequency between 20 and 40 cps would also be a desirable one from the antijam standpoint because it would permit a large reduction in speed gate width with attendent reduction in vulnerability. Work at NRL, involving hundreds of data samples, in measuring target amplitude noise as a function of frequency supports this conclusion. A few of the samples are shown in Reference 14.

If the scan frequency is lowered to about 40 cps a new limit to the reduction of speed gate width arises due to the deviation of the signal because of the 85-cps coding signal at long range. The 85-cps arming signal appears to be necessary for the operation of the current fuze system. If an alternate fuzing system is adopted, serious consideration should be given to the abandonment of this modulation. Its value in the reduction of friendly jamming in the speed gate locking circuits is questionable in view of the added complexity and reliability problems it could bring.

Narrowing the speed gate will result in a more secure system in the presence of intentional and environmental jamming. For example, performance in the presence of clutter should be improved since narrowing the gate will exclude doppler signals resulting from clutter which lie close to the desired signal and which currently get into the seeker. In addition, the vulnerability to the Saunders doppler repeat-back technique would be reduced because the speed gate could be made narrow enough to exclude inherent phase or frequency delays in the doppler repeat-back jammer.

The angle tracking loop of the Sparrow III includes the entire seeker circuitry. A technique which has been tested in the laboratory and reported to be successful in jamming this angle track loop is a CW signal near the doppler shifted seeker frequency but amplitude modulated at 1 or 2 cps. This caused a corkscrewing effect on the seeker tracking head. The tests were conducted in two ways. First, the transmitted signal (doppler shifted) was amplitude modulated at 1 or 2 cps. This had no harmful effect on the seeker. When a separate signal source was used (amplitude modulated at 1 or 2 cps) the corkscrewing effect was noted. This is very important because it serves as a clue to where the current problem occurs in the seeker. Figure 26 shows the response curve for the Sparrow III receiver. The crosshatched area shows a frequency band into which the expected doppler signals will fall. It should be noted that a spurious side band (not crosshatched) response is provided. Further, the crosshatched area and its mirror image represent the bandwidth of the so-called "video" portion of the receiver. The area lying under the larger curve is the bandwidth of the 30-Mc i-f system of the receiver. Signals falling in the crosshatched area or its mirror image cause the application of agc to the i-f amplifier. However, signals falling outside the crosshatched area or its mirror image are not gain controlled and if they exceed the desired signal by approximately 15 db they will cause overloading in the i-f amplifier. This overloading will cause cross modulation of any intelligence carried on the interfering signal into the desired doppler and scan frequency signal. Referring to the test conditions, a direct comparison of the theoretical cause and test results can be made. According to the test results, a 30% modulation of the jamming signal at 1 to 2 cps could

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cause the seeker to corkscrew around the target at the 100% modulation level (15). This difficulty has been discussed with the contractor. Agreement was reached concerning the mechanization of the seeker in relation to this type of countermeasures. The contractor stated that the only reason for the current 2-Mc bandwidth was ease of manufacturing. Effort will be made to tailor the bandwidth of the i-f to that of the video. It should be noted that the noncrosshatched response to the left of the ordinate axis of Fig. 26 is a spurious sideband response (for receding targets) into which a jamming signal could be placed. This spurious response should be eliminated.

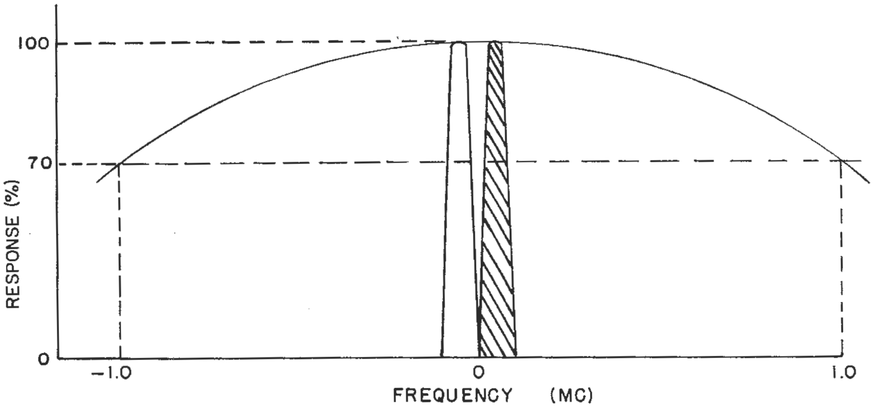

Fig. 26 - Sparrow III response curve of receiver

The Sparrow III seeker appears to be relatively safe from common forms of brute force jamming (15). For example measurements at NAMTC show that CW jamming requires 51 to 54 db J/S ratio, AM noise jamming (10-Mc bandwidth) requires 30 db J/S ratio, and 10-Mc bandwidth noise FM ±7 Mc requires 40 db J/S ratio. However, as described previously, a jammer sweeping at 1 to 2 cps could overload the receiver and cause cross-modulation. This type of jamming is a very probable type because current jammers of the ALT-2 type can sweep the band in the time required to cause the cross modulation. Sweep jammers can cover a wide enough band to affect both AI radar and seeker. However, the 1 or 2 cycle modulation (either from AM or sweep sources) will not affect the pulsed AI radar.

Parameters in the system which relate to countermeasures vulnerability are the relationship between the bandwidths required by the tactical problem and those mechanized by the contractor. Of additional interest is the transient performance of the equipment. Analysis of data furnished by the contractor shows that the system closed-loop bandwidth varies between about 1 and 6 radians as a function of range, altitude, and relative velocity. This bandwidth appears to be quite adequate to handle the tactical requirements but not so large as to represent a vulnerable point either for environmental or intentional jamming. Furthermore, the bandwidth is proportioned in the loop so that no part of the over-all loop has excessive bandwidth. Thus, noise should not be expected to saturate one portion of the loop before others.

The transient performance of the equipment as stated by the contractor, and checked by analysis of his data, shows that no violent maneuver other than that which could be supplied by a target should be induced either by countermeasures or by the natural environment (fading, clutter, etc.).

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Conclusions and Recommendations

Conclusions:

1. If it were not for the current deficiency of the Sparrow III seeker in regard to low-frequency AM or low-frequency sweep jamming, this seeker would be relatively safe in the presence of brute force jamming either intentional or environmental.

2. Because of the choice of parameters (scan frequency and coding signals) the speed gate is excessively wide as related to that required to handle the tactical situation. The excessive width of this speed gate reduces the problem of the jammer when doppler pull-off techniques are used.

3. The current seeker speed gate is capable of tracking a 20-g or greater maneuver. This unnecessary feature allows a deceptive jammer (doppler repeater) to decoy the speed gate off the target in a very short time.

4. The value of the 85-cps modulation in reduction of friendly jamming of the speed gate lock circuits is questionable in view of its added complexity. However, the 85 cps is currently necessary for fuze operation. If an alternate fuzing technique is developed, serious consideration should be given to abandoning the 85 cps.

5. The angle tracking loop bandwidth appears to be compatible with the tactical situation in regard to tracking of the expected target and exclusion of extraneous noise. The bandwidths of the components of the tracking loop appear to be designed to eliminate system performance degradation due to extraneous noise.

6. Analysis of the angle tracking circuitry shows that the transient performance should not cause unnecessary countermeasures vulnerability.

7. Although the CW doppler technique provides one form of diversity, full advantage has not been taken of this fact because the frequency used is not sufficiently removed from that used by the AI radar.

Recommendations:

1. The receiver bandwidth should be made compatible with that of the video to reduce vulnerability to low-frequency AM and FM jamming. Further, the spurious sideband response (for receding targets) should be eliminated.

2. The speed gate width should be reduced. This reduction can only be accomplished by lowering the scan frequency to a known safe band. If the scan frequency is reduced to a very low frequency, the 85-cps coding signal then becomes the limit to speed gate width reduction.

3. The necessity for the 85-cps modulation should be re-evaluated.

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SIDEWINDER MISSILE GUIDANCE EQUIPMENT

Status of Sidewinder

The Sidewinder is a passive infrared-homing-air-to-air guided missile. It is important to consider the countermeasures vulnerability of Sidewinder since installation of this weapon on a large number of aircraft is planned. This section will be restricted to consideration of seeker vulnerability. The vulnerability of the AI radar will depend upon whether the day fighter version or the night fighter version is considered. For example, it is anticipated that the Sidewinder will be used with range-only radars in day fighter installations. The vulnerability of the ARO will be quite different than that of the radar used with the all-weather systems. These equipments are discussed in detail in the section on AI radar.

Tactical Situation

Figure 27 is an illustration of the passive homing guidance technique. This sketch illustrates a tactical situation in which Sidewinder might be employed. For the remainder of this section, the discussion will be limited to the all-weather case. After takeoff the pilot switches to missile standby. The interceptor is vectored by CIC to a position from which AI radar detection can occur. The target is acquired by the AI radar and an aided attack course is flown during which the seeker acquires the target. At the time of seeker acquisition, a distinctive audible tone is presented to the pilot. After this the missile can be launched. After launching, the parent aircraft is free to break away.

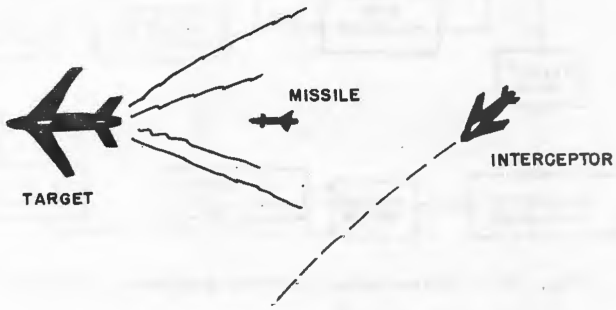

Fig. 27 - Passive homing missile guidance technique (Sidewinder)

The seeker of the Sidewinder utilizes a gyro-stabilized seeker telescope which tracks infrared radiation emanating from the target. This seeker telescope measures the rate of rotation of the line of sight from missile to target. When rotation occurs the torque-balance control servo deflects the fins (also causes head tracking) causing the missile to turn in the direction of the rotation of the line of sight, but at a greater rate. As the missile lead angle error is reduced, the rotation of the line of sight drops off and turning commands are reduced.

Figure 28 is a block diagram of the Sidewinder seeker. The scanning disk and detector cell are used to collect target information. Infrared radiation from the target is collected by a rotating gyro telescope spinning on a central ball support bearing. After being reflected

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from a secondary mirror, the image of target and background is formed on a rotating chopper which alternately transmits and obstructs radiation from the target. The detector consists of a lead sulphide cell which converts the modulated radiation provided by the chopper into electrical signals. The output of the detector cell goes to an amplifier unit which in turn supplies precession voltages to gyro precessing coils. The amplifier unit also supplies signals to the two phase discriminators which ultimately furnish signals to the control surfaces of the missile. An optical filter in front of the detector rejects all radiation of wavelengths less than about 2 microns. Thus, most of the radiation from a jet target will come through to the detector while most of the radiation from clouds and earth and other objects illuminated by the sun will be rejected. In the gyro telescope the scanning pattern generates a pulse train forming the target signal. In order to establish the position of the wheel when the disk scans the target, an analogous pattern of gearlike teeth is impressed into the soft iron rim on the gyro wheel. Two pairs of coils, one pair for each coordinate axis of the missile, are mounted adjacent to the gyro rim. These coils, powered by permanent magnetic cores and the variable-reluctance teeth on the gyro rim, generate wave trains from which the instantaneous orientation of the gyro wheel can be established. The scanning disk and the reference generator are physically part of the gyro rotor (16). The phase discriminators then compare the target signal with the reference signal and derive position information. The outputs of the phase discriminators are then supplied to magnetic amplifiers which in turn supply power to the fin servos to drive the missile flaps.

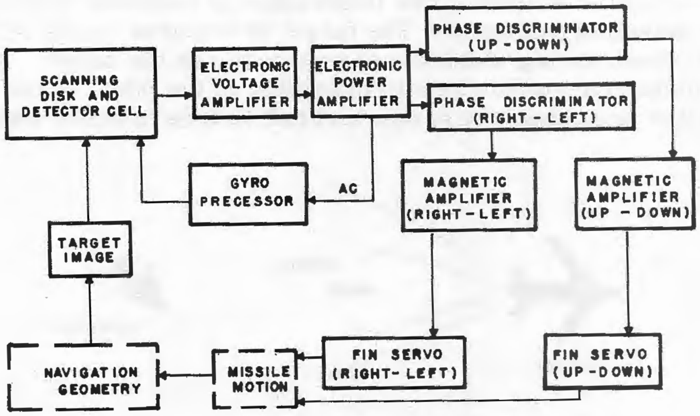

Fig. 28 - Sidewinder seeker guidance system

Thus, the signal voltage is fed in controlled phase relationship to two torque-producing servos. The first precesses the gyro in such a direction as to reduce the error angle and the second applies torque to the steering surface of the missile. The first torque causes the gyro to track the target. The second torque will cause the missile to turn at a rate such as to generate a flight-line rate of change to sight-line rate of change of about 3.5 (navigation ratio) for a missile velocity of 1800 ft/sec and a maximum turning rate of 10 g's. At values above 10 g the steering surfaces approach saturation.

Vulnerability

The same basic things can be said about the vulnerability of Sidewinder that have been said about the missile guidance equipments used with the other missiles. In the tactical situation, available time is very short for the jammer. In addition, countermeasures

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techniques that are effective against the other Navy air-to-air missile guidance equipments will not work against Sidewinder. At the present time the countermeasures technique most seriously considered for use against Sidewinder is use of heat decoys such as rockets or flares and fuel contaminants. Utility of these methods presupposes that the enemy will know when he is under attack by Sidewinder. Diversity in application of air-to-air missiles reduces the probability that the enemy will know in advance that Sidewinder will be used against him. Since it is a passive device, the enemy will not be able to detect energy from the missile which will disclose when and if Sidewinder is being used. Other possible countermeasure techniques to be used against Sidewinder include towed decoys, smoke puff decoys, radiation scattering material, and jet engine shielding.

Since the enemy will be limited in time and in the number of rockets or flares he can carry to use as heat decoys, he must know fairly precisely when to launch the decoy. Several techniques to detect the launching of Sidewinder have been proposed but to date have not been proven in tactical application. One method proposed is the use of infrared-sensitive devices which will detect the firing of any rocket. A second method proposed is the use of a tail warning radar. The latter proposal looks the more promising. Neither of these warning systems can identify the guidance technique used by the missile. Additional information is therefore required if effective missile countermeasures are to be employed.

As long as the present diversity in air-to-air missile types is continued, Sidewinder guidance equipment, as well as that of the other air-to-air missiles, appears to be fairly secure from countermeasures. This emphasizes the need from the antijam viewpoint for continuing diversity and for an increased effort toward development of multipurpose missiles. This philosophy could be advanced by development of interchangeable guidance units.

Specific Circuit Considerations

Figure 28 shows that a feedback loop exists from the output of the amplifier unit to the gyro in the detector unit. This feedback loop is used to precess the gyro in such a manner as to reduce the line-of-sight error toward zero. Thus, any motion of the missile which tends to precess the gyro is compensated for by detecting the target error angle which would result from the precession. The seeker head is, to a degree, self-stabilizing because in effect it is a free gyro. However, motions of the airframe transmitted into the seeker head through gimbal friction introduce destabilizing errors. Any errors so introduced must be corrected by the tracking head using the target as a stable space reference. This is a simple method of accomplishing antenna stabilization relative to the complexity of generating a stable reference within the missile. It has one major disadvantage. The use of this form of stabilization dictates a tracking system bandwidth which is greater than that required to solve the tactical problem (target tracking). The use of this larger bandwidth insures that additional noise will enter the tracking loop. This noise may be that created by the natural environment (target scintillation, multiple targets) or by intentional jamming (decoys). Figure 29 gives the open and closed loop response of the tracking portion of the Sidewinder system. The bandwidth is 20 rad/sec. This compares to 6 rad/sec bandwidth which is used in the Sparrow III to solve the tracking problem. Sparrow III, however, utilizes an internally generated stabilization signal. Analysis shows that this 6 rad/sec bandwidth is compatible with solution of the tactical problem. Reduction in bandwidth as prescribed above will improve system performance, both in the presence of natural and intentional jamming, but at the cost of increased complexity. In order to stabilize within the airframe, an auxiliary pair of gyros would be required. These gyros would measure airframe motion in pitch and yaw and apply the appropriate corrections to the antenna. The improved performance versus resulting complexity should be resolved

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by system analysis utilizing the effects of the various noise sources. This requires information on signal scintillation and multiple target noise which is not currently available to the authors.

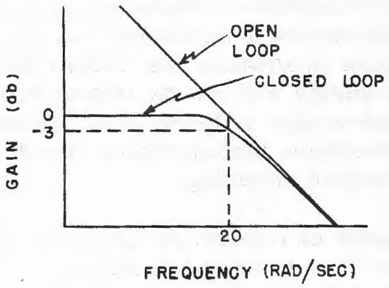

Fig. 29 - Sidewinder tracking bandwidth

For a decoy rocket or flare to be effective, the Sidewinder missile must be capable of tracking the input line-of-sight rates which such a decoy might introduce. The Sidewinder missile system was designed to track a target input motion corresponding to a minimum value of 10 g's acceleration. So long as the heat decoy inputs have characteristics which do not exceed the tracking limits of the system (10 g minimum) and are of sufficient power to mask the target, successful jamming will result. Limited test results, which are currently available to the authors, indicate that Sidewinder will readily pull-off onto and track rocket decoys launched at right angles to the flight path of a high-performance bomber target. Since the tracking loop is nonlinear, analysis of system performance when subjected to decoy-type countermeasures is a lengthy one. It is recommended that such analysis be undertaken by the contractor.

A simple decoy technique which may be effective against Sidewinder is that of dropping flares. It is not within the scope of this study to define the requirements for such countermeasures. Tests (17) have indicated that a 1-pound flare will burn for 13 seconds and produce as much infrared energy (from 1.8 to 3.0 microns) as is radiated by the six jets of a B-47. A study should be made to determine the potential effectiveness of flares and to provide remedies, if indicated.

Analysis of the over-all Sidewinder system shows that a reasonable design approach has been used. The navigation ratio of 3.5 used in the system yields a bandwidth compatible with the tactical problem. In this regard the Sidewinder transfer characteristics approach those of other current systems.

Analysis of the circuit details of the Sidewinder seeker shows that a very simple and probably reliable circuit has been developed. However, it was noted that an unusual waveform for scanning (as compared to a conical scanning radar) is used. Figure 30 shows Sidewinder seeker raw data and detected and smoothed waveforms. Full advantage is not presently taken of this scan-pattern to reduce the already low probability of countermeasures decoying at the scan rate. This could be accomplished rather easily and with a reduction in circuit complexity. The unusual waveform is converted, in the present seeker, to a near sinusoid before phase comparison is accomplished. The upper diagram of Fig. 30 shows how the target and reference waveforms are generated. The lower diagrams show the time relationships of the waveforms. The seeker converts the raw data by envelope detection and smoothing before the target and reference signals are compared in the phase detectors. There appears to be no reason why the raw data could not be used. The use of raw data would, besides reducing circuit complexity, provide some protection against interference near the scan rate.

It has been noticed that most of the Sidewinder literature refers to the use of coulomb friction to reduce "limit cycling" or oscillation of the missile. The exact cause of this oscillation is not clear but the tendency toward oscillation can have undesirable effects in the presence of natural noise or enemy countermeasures. The tendency to oscillate indicates that the system is marginally stable at best and that low-level natural or intentional noise may cause outright oscillation.

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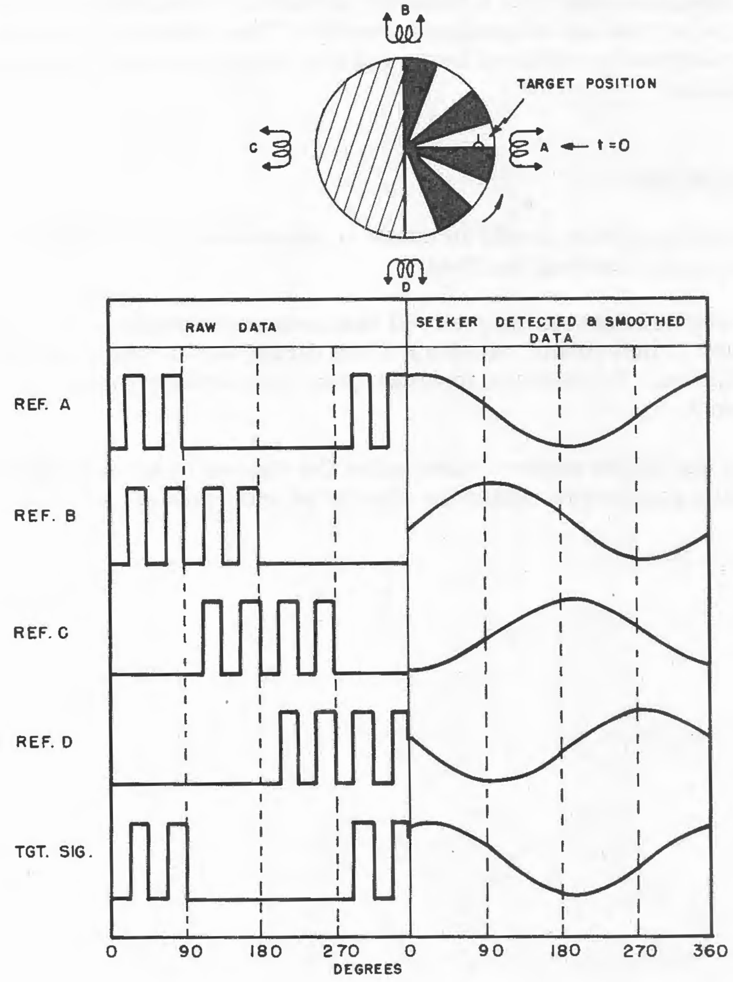

Fig. 30 - Sidewinder seeker waveforms

Conclusions and Recommendations

Conclusions:

1. The tracking bandwidth used in the Sidewinder angle tracking loop is greater than that required by the tactical situation. This will allow extraneous noise (either intentional or environmental) to degrade system performance more easily.

2. The over-all system bandwidth is compatible with that required by the tactical situation.

3. The manner in which angle information is derived in the Sidewinder appears to be overly complex. It is believed that direct use of the raw data for phase comparison purposes, instead of intermediate conversion to sinusoids, would result in reduced complexity and provide antijam protection against interference near the scan rate.

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4. Sidewinder has exhibited a tendency toward oscillation along the flight path. This has been reduced by the use of coulomb friction. The tendency to oscillate indicates that the system is marginally stable at best, and that even low level interference may cause outright oscillation.

Recommendations:

1. A systems analysis should be made to determine the advantages and disadvantages of reducing the angle tracking bandwidth.

2. An assessment should be made of the apparent reduction in circuit complexity and countermeasures vulnerability resulting from direct use of raw data for deriving angle tracking information. Conversion to sinusoidal form before phase comparison is believed to be unnecessary.

3. A study should be made to determine the causes of an apparent marginal stability of Sidewinder and corrective measures should be incorporated to reduce this tendency.

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HOMING-ON-JAMMING

The Bureau of Aeronautics problem request which initiated this study included a requirement for consideration of missile capability for homing-on-jamming. In addition, several recent Defense Department studies have recommended that air-to-air missiles be adapted to perform this function. Before one can categorically state whether such a capability is essential it is important to determine the relative vulnerabilities to countermeasures of the various links in the over-all system loop. The basic reason for having air-to-air missile homing-on-jamming is the deterrent effect this capability will have upon enemy jamming of either the AI radar or the missile guidance equipment. In a report covering an earlier phase of this study, it was concluded that the search radar and communications are the most vulnerable links in the over-all air-to-air missile system loop. As a corollary, the AI radar and missile guidance links are relatively invulnerable. Thus enemy expenditure on equipment, talent, and space to jam the AI radar and missile guidance equipment may be expected to be less than that to jam search radar and communications. Antijam measures for search radar and communications are more urgently needed than similar measures for airborne elements of the weapons systems.

The AI radar is common to several missile guidance systems, has an appreciable "on" time, and is considered to be the most vulnerable of the airborne elements. Reduction of AI radar vulnerability can be accomplished directly by antijam circuitry and indirectly by adapting air-to-air missiles to home on AI radar jamming. Both techniques will be considered. Homing-on-jamming which is directed against a missile guidance system appears to deserve the lowest priority when the air weapons system is considered as a whole.

A major redesign effort would be required to adapt any of the present air-to-air guided missiles for homing on energy directed at jamming the AI radar. It appears to be more feasible and productive to apply antijamming and homing-on-jamming efforts to the AI radar. The AI radar with minor modification can be adapted to homing-on-jamming. A more difficult task but one which is vital is a program directed toward improvement of AI radar performance in its normally noisy environment as well as in an environment including intentional noise. It is considered to be more profitable to concentrate on improvement in AI radar performance in the presence of noise, while maintaining the inherent antijamming features provided by diversity in missile guidance systems which currently are available. For example, it would not be desirable to change K-band Sparrow II parameters to give homing-on-jamming capabilities against energy directed at the X-band AI radar. Further, homing-on-jamming capabilities, which would tend to deter the enemy from jamming, can be built into the AI radar without sacrifice in normal system performance. The design procedures for modification to the AI radar are provided in a separate report (18). Homing-on-jamming quick fixes could be installed in current AI radars, but will not provide for range tracking. Range information for missile launching, however, can be obtained by means such as optical estimation, seeker lock-on indications, computation from previously known rates, etc. A long range program for improvement of the AI radar, including range tracking capability in the presence of brute force jamming, is currently underway.

A second avenue of approach is that of making the missiles capable of homing-on-jamming directed at the specific missile guidance equipment. If, in the case of Sparrow I, the present vulnerable SPR link is eliminated and if the AI radar is modified as stated above, Sparrow I airborne components would no longer be vulnerable to types of jamming which lend themselves to homing. Sparrow II is at K-band so energy directed against it will not influence other elements of the system. Moreover, simple modifications to Sparrow II will allow it to home on K-band jamming. For homing on spot frequency jamming, this modification consists of gating the receiver in the i-f amplifier so that continuous energy is broken into pulse form. The seeker would react to these jamming pulses in the same fashion as it does to an echo. This modification is similar to that previously described for providing homing-on-jamming capability to the AI radar.

The Sparrow III system currently has a J/S ratio for pure CW jamming of greater than 50 db. In a practical sense it is invulnerable to noise-modulated CW, or other more sophisticated forms. If countermeasures limitations described in earlier sections of this report are removed from the missile guidance equipment, homing-on-missile guidance jamming should not be required. For successful operation of Sparrow III, the illuminator must continuously angle track the target. Thus the AI radar (assuming CW injection) would require homing-on-jamming capability in the presence of AI radar jamming.

In addition to the above, numerous other homing-on-jamming schemes have been proposed. Among these is that of modification of the Oriole monopulse seeker for homing-on-jamming. The major physical and circuitry redesign effort required to counter the potentially small threat does not seem to be economically justifiable beyond experimental demonstration of feasibility.

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