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PROBABILITY OF INERCEPT
FOR COUNTERMEASURES RECEIVERS
[UNCLASSIFIED TITLE]

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ABSTRACT

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The probability of intercepting an electromagnetic transmission, particularly that of a radar system, by a countermeasures receiver has been a major concern of designers and operational groups. In spite of the effort expended by many investigators, the concept of probability of intercept has remained somewhat nebulous and often misunderstood. This condition resulted, in part, from the lack of a suitable definition of probability of intercept and from an insufficient examination of the factors that influence the problem.

As a result of the work described in this report, the concept of probability of intercept has been clarified. It may be defined as a function of time that represents the chance of an intercept occurring for a specific set of over-all parameters. Perhaps the greatest effort in the past to improve the probability has been in minimizing the effect of coincidence of intermittent events. There are, however, at least three other important factors that influence the probability of intercept. These are (1) frequency spectral characteristics, (2) modulation characteristics, and (3) receiver sensitivity. The first two of these factors are important in determining whether or not a receiver is capable of intercepting various signal types either as entities or in the presence of other signals. The factor of receiver sensitivity is important in establishing the detection ranges not only of the major lobe but of the complete 360-degree coverage.

The consideration of these factors provides a more sharply defined and constrained concept of intercept probability, so that quantitative, comparative information can be obtained for different receiver techniques. Although some gross comparisons have been made for a few signal types and receiver techniques, functions of sufficient accuracy to be of use in evaluation of systems will not be available until the completion of a new computer and simulator by the Countermeasures Branch of the Naval Research Laboratory.

PROBLEM STATUS

This is an interim report on one phase of the two problems, work is continuing.

AUTHORIZATION

NRL Problems R06-02 and R06-07
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PROBABILITY OF INTERCEPT FOR COUNTERMEASURES RECEIVERS [UNCLASSIFIED TITLE]

INTRODUCTION [Unclassified]

Discussions concerning the effectiveness of countermeasures receivers in detecting the presence of radar transmissions invariably introduce the term "probability of intercept." Too often this term is used rather loosely and without regard to all of its major contributing factors. Thus we hear that a certain receiver has a "high probability of intercept" and some other receiver is inherently one of "low probability of intercept." In each case, of course, specific conditions are implied which make the statements essentially true. It is possible, however, to select different sets of conditions so that the intercept probability of these two receivers is reversed: the one which had a high value for one set of conditions now has a low value, and the one that had a low value is now endowed with a high value. This apparent conflict is capable of being resolved if the entire mechanism of the intercept problem is examined with respect to the contributing factors.

CONCEPT OF CUMULATIVE PROBABILITY [Unclassified]

At this point it is advisable to define the term "intercept." For the purpose of the following analysis, an intercept will denote recognizing the presence of a signal and making this presence known to a decision element. Thus, the existence of a voltage across a resistor does not by itself constitute an intercept. Instead, the voltage must be of such a nature, or be capable of acting on other circuitry in such a way, that a decision element or classifying storage device is able to report a signal.

Electronic reconnaissance is not usually concerned with a single event occurring in some short interval of time. The problem is one of intermittent or cyclic events that are functions of the parameters of the transmission and intercept receiving systems. Consequently, the probability of intercept is not based on a single event randomly disposed in time but is a function of the period of time available to intercept an intermittent event. To define probability of intercept without the aid of a mathematical model leaves something to be desired. A definition which can be deduced from the mathematics, may be stated as "the probability of intercept is a function of time and represents the chance of an intercept occurring for a specific set of over-all system parameters."[1,2]

As an illustrative example, consider a receiver tuned to station WWV. Assume that propagation conditions are satisfactory for reception but that the receiver B+ is turned off. If the B+ is turned on at some random time, what is the probability of intercept of one of the time pulses? The obvious answer is unity, but is restrictive on the condition that a long enough period of time for observation elapses. Figure 1 shows that the probability value rises with time, after the B+ is turned on, with a constant slope until a value of about 98% is reached at the end of one second. The slope then changes and the probability reaches a value of unity at time equal to two seconds. At first glance this period of two seconds may seem about twice too long, but it must be remembered that there is no pulse corresponding

[1] Beck, H. M., "Time-Dependent Probabilities," NRL Report 3915 ([redacted]), December 29, 1951

[2] Wald, B., "Computation of Countermeasures Intercept Probabilities," NRL Report 4612 ([redacted]), September 1955

to the 59th second and that the receiver might have been turned on immediately after the pulse of the 58th second.

Consider an example with a longer waiting period: Assume that a clock has been modified so that the minute hand has been replaced by a disc which covers the entire face, and that this disc has a narrow radial slot about the size of the minute hand that was removed (Fig. 2). A clock-watcher is provided and the clock is started. What is the probability that the clock-watcher will see the hour hand through the slot in the disc ? That is the same as, what is the probability of the intercept of the hour hand with the minute slot ?

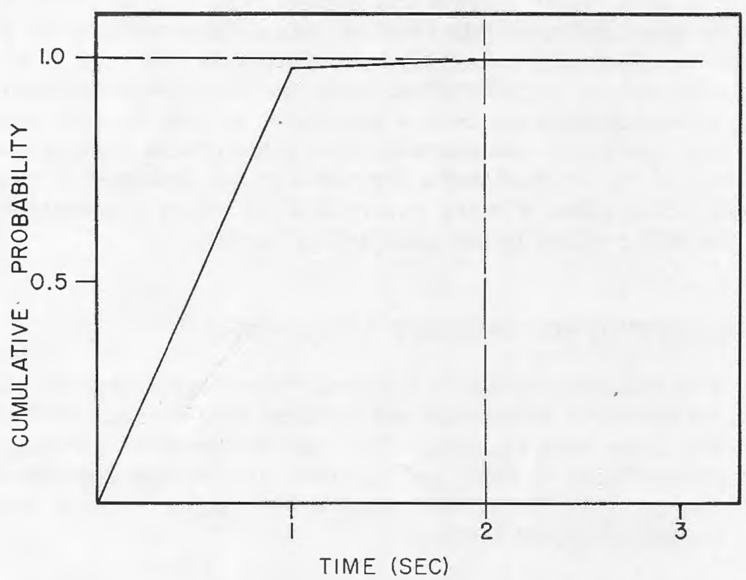

Fig. 1 - Probability of intercept of a time pulse of WWV [Unclassified]

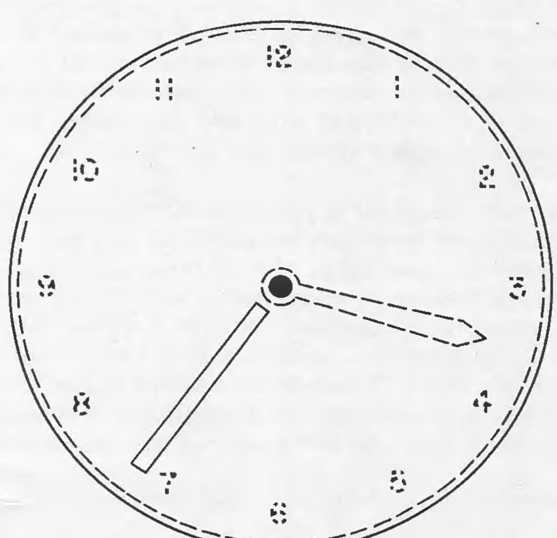

Fig. 2 - Clock with minute hand replaced with slotted disc [Unclassified]

[redacted]

[redacted]

The probability value rises (Fig. 3) from zero; when about 33 minutes have elapsed the watcher has a 50% chance of seeing the hour hand and at 65-5/11 minutes the probability has reached unity.

Thus we understand that the question "What is the probability of intercept?" is incomplete. The questions and the answers should both involve time explicitly. A proper question would then be "What is the probability of intercept after one minute, or five minutes, or ten minutes?" or "How long will it take before the probability of intercept reaches a value of 0.50 or 0.75 or 1.00?"

FOUR FACTORS INFLUENCING INTERCEPT PROBABILITY [redacted] (u)

General Discussion [[redacted]] (u)

With the definition of intercept and the concept of intercept probability established, it is possible to examine the factors that influence the general intercept problem. Although the following analysis is concerned mainly with radar transmissions, the same factors have a place with respect to missile guidance, beacon and IFF systems, and some communication systems.

The examination of any list of possible factors influencing probability reveals the difficulty of reducing such a list to a few factors that are really independent. Four factors have been recognized which, although not completely independent, provide the basis for a comprehensive evaluation. These are (1) frequency spectral characteristics, (2) modulation characteristics, (3) receiver sensitivity, and (4) coincidence of intermittent events. The first two factors are important in the relation to the definition of intercept. The remaining two factors are directly related to the probability problem.

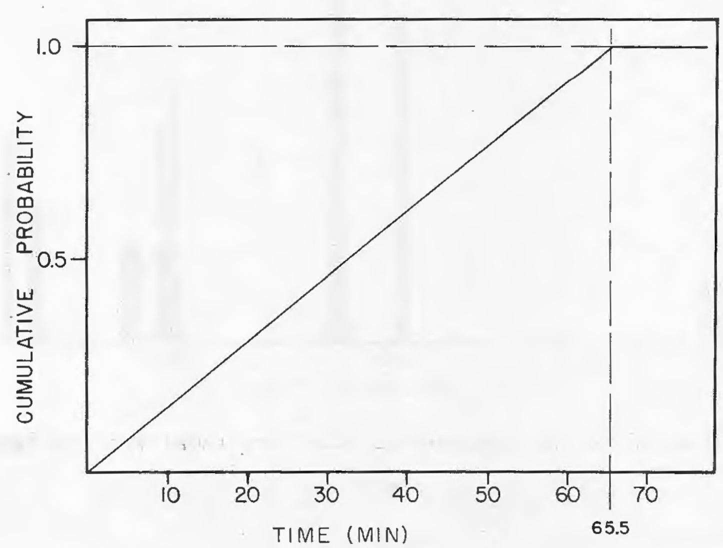

Fig. 3 - Probability of intercept of minute and hour hands [Unclassified]

[redacted]

Frequency Spectral Characteristics [[redacted]] unc

The analysis of the frequency spectral characteristics shows that signal activity in the microwave region is spread over a large spectral range, with the particular frequency region being dictated to some extent by the purpose of the signal. Thus it is noted that long-range search radars operate at the lower end of the spectrum to take advantage of certain propagation characteristics and physical limitations of operating equipments. Other systems, such as gun-laying radars, operate at higher frequencies where the required accuracy of spatial resolution can be acquired.

Although there are operations at different frequencies within the microwave spectrum, these operations are not spread out in a uniform frequency distribution pattern but appear in a few relatively narrow frequency bands (Fig. 4).[3] This condition is essentially a matter of engineering economics and arises from the narrow bandwidths that go along with high-gain directive antenna systems and the associated high-power oscillator and matching systems. In addition, the logistics of replacement parts for the systems tends to restrict activity to relatively few, narrow spectral regions. As far as any future activity is concerned, the frequency region of occurrence cannot be accurately predicted, but such activity very likely will occur in bands of relatively high density.

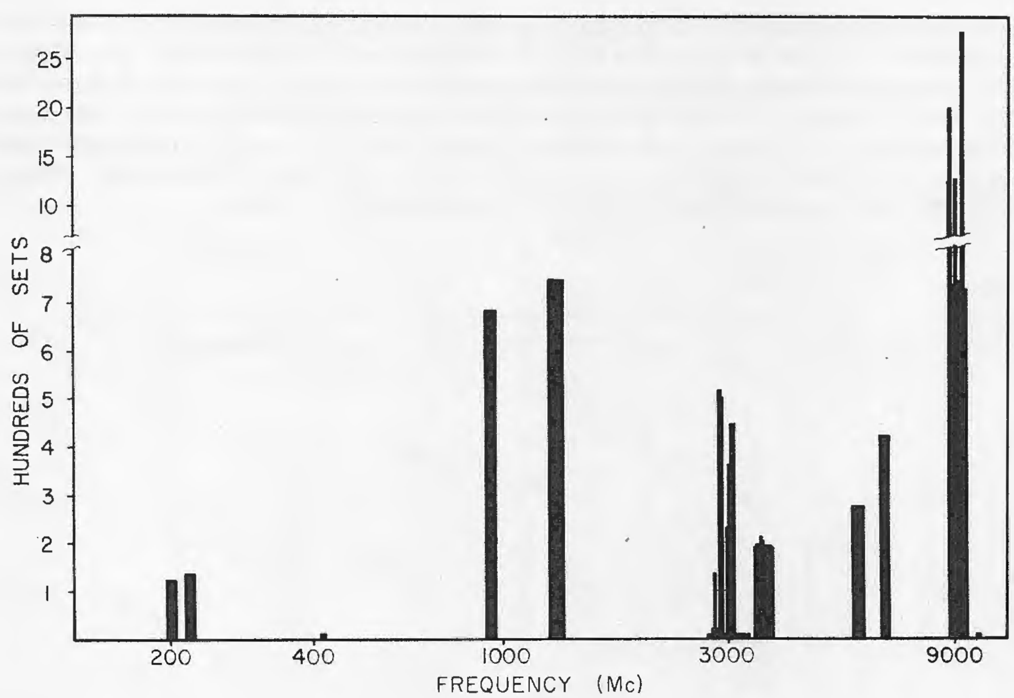

Fig. 4 - Distribution in frequency of U.S. Navy radar systems [[redacted]] uncl.

[3]Upp, C. B., "U.S. Navy Radar Systems Survey," NRL Report 4128 ([redacted]) (uncl), April 24, 1953

[redacted]

[redacted]

The effect of these frequency spectral characteristics on the intercept problem is twofold. For an intercept to occur, the receiver must, first, be capable of providing coverage over the useful frequency spectrum, and second, be capable of resolving the signal activity likely to occur within the narrow operating bands so that new signals may be recognized and reported in the presence of other signals.

Modulation Characteristics [[redacted]al] (unclass)

The influence of modulation characteristics on intercept is essentially a case of yes or no. That is, either the receiver is capable of recognizing and reporting the presence of a signal or it is not.

At the present time, the greatest activity in the microwave region is that of radar systems with normal pulse modulation. Although receivers may be tailored explicitly for pulse reception, it must be recognized that the pulse characteristics depend on the application of the particular radar system and may be expected to range from less than 0.1 μsec to more than 20 μsec for pulse widths, and from less than 50 cps to greater than 5000 cps for the repetition rates. Consequently, the intercept receiver characteristics must be compared to these limits to determine whether an intercept is possible.

Aside from radar applications, electronic reconnaissance is interested in other forms of pulse-modulation systems. These might include IFF and beacon systems, multipulse-coded communication, and pulse-modulated systems for missile guidance and communication. These systems incorporated one or more of the following variations: short trains of two or more pulses, and modulation of pulse characteristics such as amplitude, width, time, rate, and position. Generally speaking, a receiver that is capable of intercepting the normal type of radar transmissions over the range of characteristics previously listed is also capable of detecting these other forms of pulse systems. A problem exists, however, in the ability of the decision element to determine the nature of such signals.

In addition to pulse systems, other modulation methods have been applied to the microwave spectrum for radar, missile guidance, and communication. Frequency modulation has been used in all three categories. At these frequencies the deviation may be of the order of several megacycles so that wideband detectors are necessary.

Amplitude modulation (other than pulse) can be applied satisfactorily to certain microwave sources for both missile guidance and communication systems. Such modulation may have frequency components in excess of one megacycle, depending on the application.

Successful application of cw doppler-shift systems has been made to missile guidance and tracking radars, and the combining of FM and cw has produced very effective missile systems.

Since various forms of modulation have present, and possible future, application in microwave radar and other systems, it must be acknowledged that an intercept by a receiver is dependent on the capability of handling the various modulation characteristics generated by such systems.

Receiver Sensitivity [[redacted]] (unclass)

That receiver sensitivity influences the probability of intercept is recognized by many investigators, although the extent of this influence may not be fully appreciated. The receiver

[redacted]

with the greatest sensitivity has an advantage in the maximum detection range. The major advantage, however, is not the increase in range with respect to the main beam of a radar transmission, but rather the increased range at which the minor-lobe structure can be detected. This effect results from the propagation characteristics associated with microwave radiation.

For a typical search radar, the field strength as a function of range is shown on Fig. 5 for fixed altitudes of radar and intercept antennas. Near the transmitter the field corresponds to the free-space condition, and as the range is increased the field is subject to cyclical amplitude variations caused by interference phenomena. As the range corresponding to the radar horizon is approached, a further change in propagation mode occurs and the field strength is attenuated rapidly in the diffraction region. At some greater range, propagation by scatter takes place with an attenuation rate much less than that of the diffraction region. Any of the modern intercept systems operating against most radar systems are sufficiently sensitive to detect the major lobe of the radar in the diffraction region; and in some cases, this detection may extend into the scatter region.

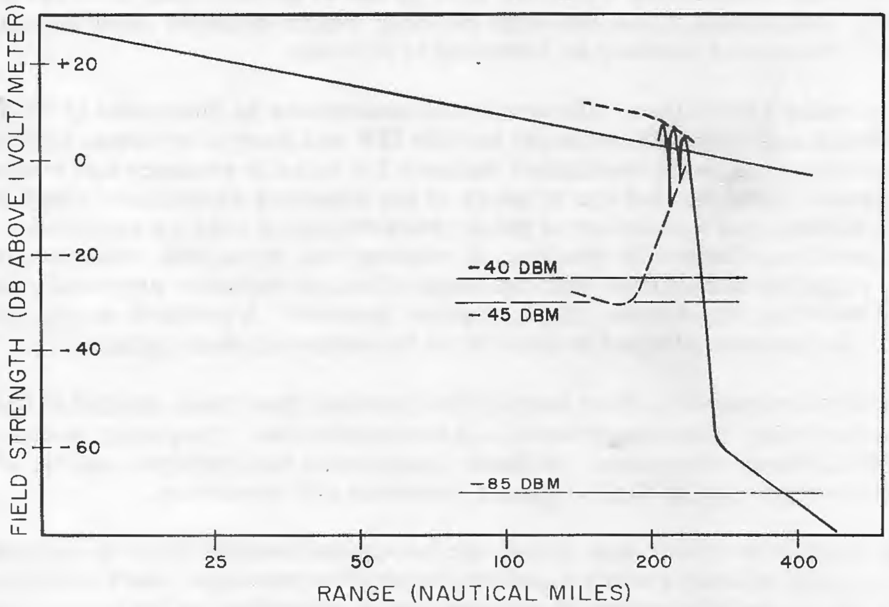

Fig. 5 - Field strength as a function of range for a typical radar

[redacted] (und)

In Fig. 5 the field strengths required for detection by three receivers of different sensitivities are shown. These sensitivities are for -40 dbm, -45 dbm, and -85 dbm and correspond to the field operating values that may be expected of a crystal-video system, a dispersive traveling-wave tube system, and a superheterodyne, respectively. Neglecting scatter propagation, a comparison of maximum ranges of detection shows that the superheterodyne receiver has an advantage of perhaps 15 to 20 miles over the less sensitive receivers. In other words, the 40- to 45-db sensitivity advantage does not produce any outstanding range increase. If, however, the radar transmitter power were reduced by 40, 50, or 60 db, the most sensitive receiver would not lose much in the way of detection range, while the less sensitive receivers would be operating back within the free-space region with greatly reduced detection ranges. A radar antenna, when rotating, produces the effect of a variation of transmitter power as observed by an intercept receiver. This variation may be translated into a detection-range contour through the application of the field-strength diagram.[4]

As an example of this translation, consider a radar of the AN/CPS-6B type operating at about 3000 Mc. It has a nominal power output of 800 to 1000 kw and the lower vertical beam has a gain of 40 db and the azimuth pattern shown in Fig. 6.* This plot is based on a -60 db center. Over a sector of 120 degrees in the forward direction, the pattern has a lobe structure that is about 40 db or less below the main lobe power. There is an additional rear lobe of the same order of magnitude, and all nulls are less than 60 db below the major lobe. The contour for detection, rangewise, is a function of the altitudes of the transmitter and the receiver and the sensitivity of the receiver. If the radar antenna is assumed to be 150 feet above the surface and the intercept receiver is in an aircraft at 40,000 feet, the range pattern for a receiver of -40 dbm sensitivity (Fig. 7) shows a maximum detection range of about 250 miles with side-lobe ranges of about 240 miles, 190 miles, and a couple of stragglers at about 100 miles. For a receiver with a -45 dbm sensitivity (Fig. 8) the maximum range has increased less than 10 miles. More of the forward lobes can be detected at about 240 miles, and some of the other lobes reach out to about 200 miles.

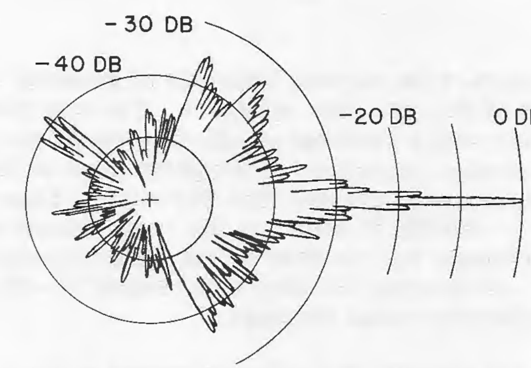

Fig. 6 - Antenna-power pattern of low beam of AN/CPS-6B radar [[redacted]] (uncl)

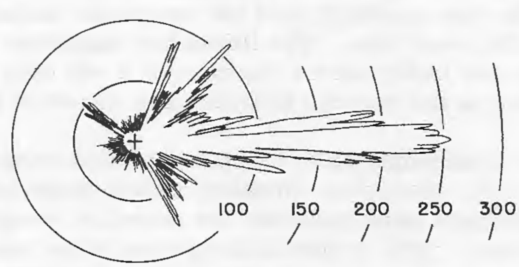

Fig. 7 - Detection-range contour of an AN/CPS-6B radar by a receiver of -40 dbm sensitivity [[redacted]] (unclass)

[4] Bullock, G. M., "Countermeasures Interception of Various Radars," NRL Report 4046 (unclass)([redacted]), October 1, 1952

*The raw data for this pattern plot was provided by A. T. Waterman, Jr. of the Electronics Research Laboratory of Stanford University

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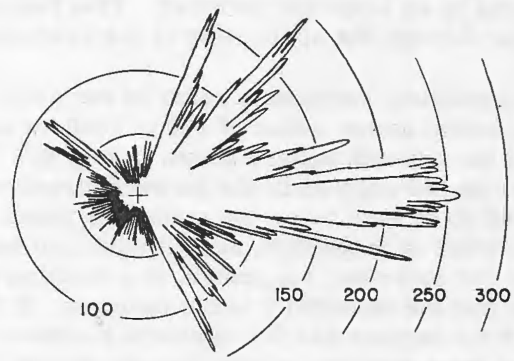

Fig. 8 - Detection-range contour of an AN/CPS-6B radar by a receiver of -45 dbm sensitivity [[redacted]] (unclass)

This pattern could be replotted for various intervals of receiver sensitivity to show the progressive range growth of the side-lobe structure. The next plot (Fig. 9) shows a 40-db change to show the effect with a receiver of -85 dbm sensitivity. The extension of the main lobe is possible by scatter reception. Throughout most of the 360 degrees, the detection range of the lobe structure is greater than 250 miles. Thus for any range less than 250 miles, the receiver is capable of detecting the radar transmission whether the radar main beam is directed toward the receiver or not. The superposition of the contours for receiver sensitivities of -40 dbm and -45 dbm with respect to -85 dbm (Figs. 10 and 11) provide comparisons of the effective range contours.

Different range contours are expected for different values of the influencing parameters of the radar power, antenna and altitude, and receiver sensitivity, antenna and altitude. As an illustration of the effect of different receiver altitudes, the field-strength plot shown in Fig. 12 is that of a shipboard L-band set, AN/SPS-6B, with an antenna 130 feet above the surface. The secondary side-lobe radiation and the back-lobe radiation of this radar are of the order of 40 db below the main lobe. The limits for maximum detection range and average back-lobe radiation are indicated for the case of a -85 dbm receiver. The detection-range contours corresponding to the various altitudes are shown in Fig. 13.

Detailed study of the field-strength plots and the detection-range contours show two important factors. First, in the operational problem where range and time are basic commodities, the probability approach must consider the detection-range contours rather than the antenna pattern of the radar. This is particularly true in the case of high-sensitivity receivers where the detection-range contour is essentially no more than a bump or a spike sitting on an approximately circular pattern. Second, an intercept receiver system at an altitude of less than 1000 feet above the normalized surface, even if especially configured with receivers of laboratory sensitivity and high-gain antennas, is at a range disadvantage compared to an operational, high-sensitivity receiver and antenna that might be carried by a high-altitude aircraft.

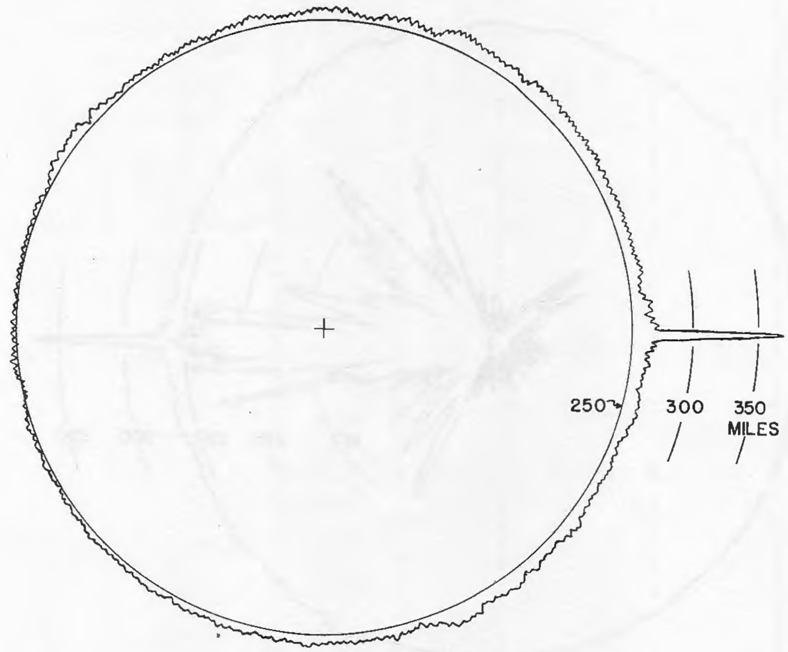

Fig. 9 - Detection-range contour of an AN/CPS-6B radar by a receiver of -85 dbm sensitivity [[redacted]] (unclass)

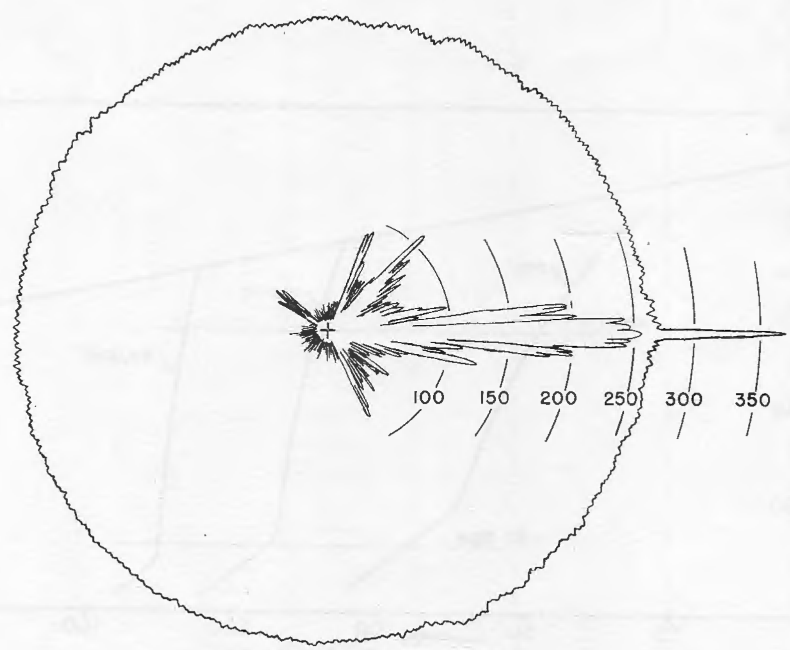

Fig. 10 - Superposition of detection contours for -40 dbm and -85 dbm receivers [[redacted]] (unclass)

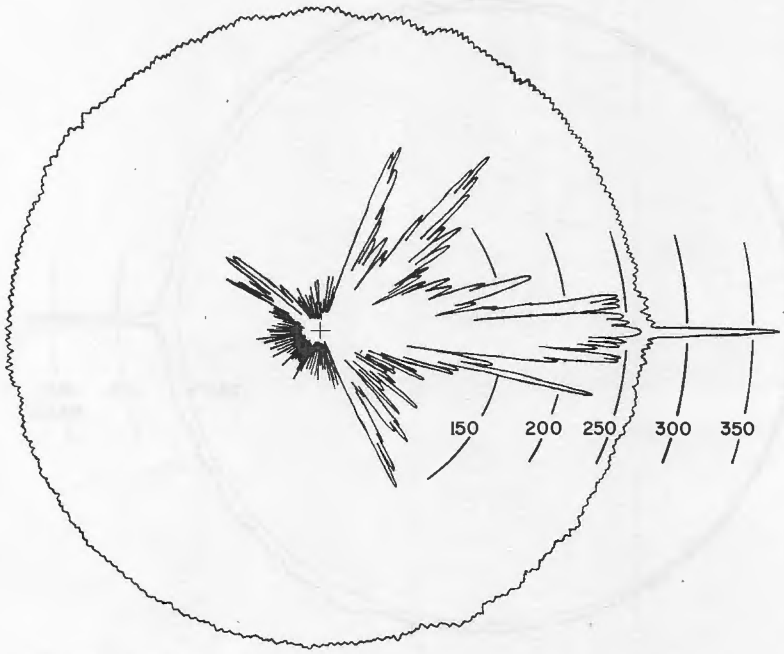

Fig. 11 - Superposition of detection contours for -45 dbm and -85 dbm receivers [[redacted]] (unclass)

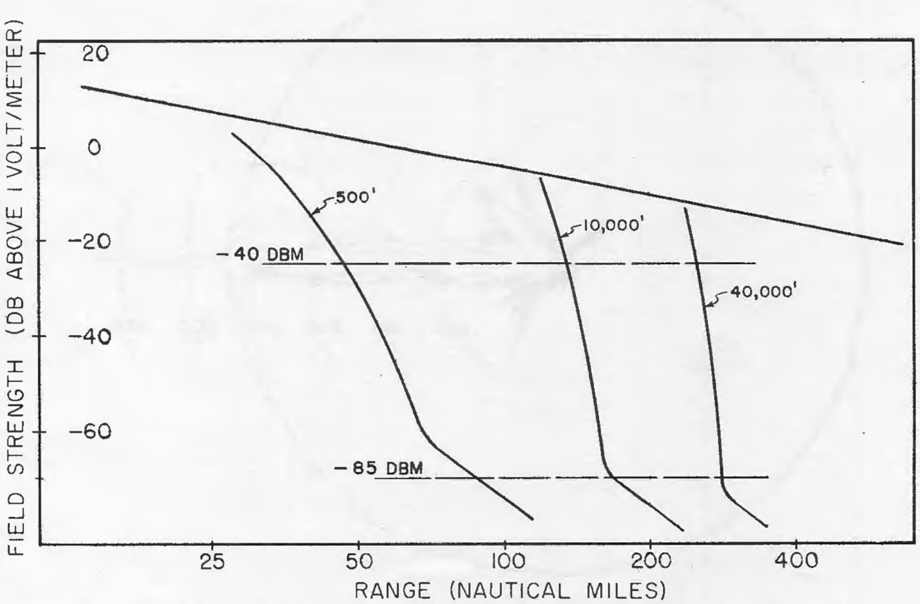

Fig. 12 - Field strength vs. range for AN/SPS-6B radar system [[redacted]] (unclass)

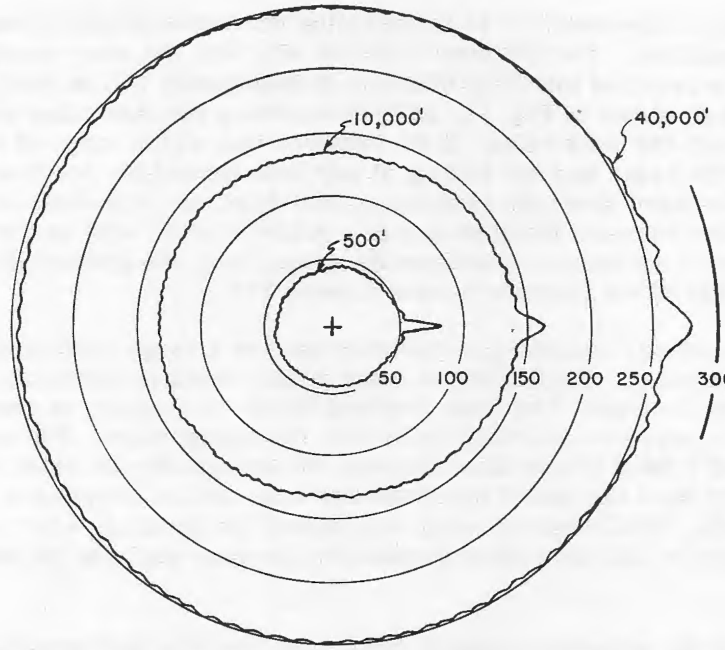

Fig. 13 - Detection-range contours of an AN/SPS-6B radar by a receiver of -85 dbm sensitivity [redacted] (unclass)

Coincidence of Intermittent Events [redacted] (unclass)

The fourth factor influencing intercept probability is the coincidence of intermittent events. A substantial effort has been made by various investigators to minimize the effect of coincidence with considerable success. It was just a few years ago that the designer of intercept equipment was faced with the problem of a manual- or motor-tuned receiver being tuned to the radar transmitter frequency at the time when the radar was looking toward the receiver and the receiver DF antenna was looking at the transmitter. And if he wanted to make the problem more difficult, it was possible to include panoramic scanning within the receiver passband. Today, there are wide open systems to eliminate receiver tuning, channelized crystal-video systems to provide rough frequency discrimination without tuning, multiple antenna systems to provide direction-finding information without a rotating system, and combinations of these and other ideas. The purpose of these systems has been to improve the probability of intercept, or to be more exact, to improve the cumulative probability of intercept with time by eliminating the effect of as many of the intermittent or cyclic parameters as possible.

EFFECT OF THE FOUR FACTORS ON INTERCEPT PROBABILITY [redacted] (unclass)

On the basis of the concepts and factors that have been presented, it is possible to indicate in a qualitative way the nature of the cumulative probability functions for some simple cases.

Assume a crystal-video receiver to be operating within the detection range of the main lobe of a radar transmitter. The intercept receiver will then see each sweep of the radar antenna, and the time required for the probability to reach unity will be equal to the period of the radar antenna as shown in Fig. 14. Different antenna rotation rates will require different periods to reach the unity value. If the receiver was within range of detection of a tracking radar, but the radar was not looking at any time toward the receiver, then the probability remains at zero since the receiver cannot detect the side-lobe structure of the radar. One might also consider the approach of a guided missile with an FM/cw system: although the receiver is perhaps in a sufficiently strong field, the probability remains zero because of the inability of the receiver to detect cw or FM.

For a second receiver, consider a superheterodyne in a range position where side and back lobes may be detected. The numerical value of this range is essentially the same as that of the preceeding example. The time required for the probability to reach unity is the same as the time to complete a scanning cycle over the tuning range. For an AN/APR-9 receiver operating at S-band this is approximately 90 seconds for the most pessimistic case where the signal is at one end of the frequency scan, and is independent of the radar rotation rate (Fig. 15). This receiver would also detect the tracking radar and the FM/cw missile guidance system, and the rate of probability increase would be the same as for the search radar.

A comparison of the probability plots of these two receivers indicates the desirability of providing a superheterodyne receiver with a much faster rate of frequency scanning for general intercept and reconnaissance use, since shorter periods would be required for the probability to reach unity. Such a receiver, with a scan time of two seconds to tune the region of 2300 to 4450 Mc, has been developed by the Countermeasures Branch of the Naval Research Laboratory and has been in operation for about a year and a half.[5] This receiver has a probability of unity at a time of four seconds (maximum when the signal is at one end of the frequency scan) for the signal examples of the preceding illustrations and is compared

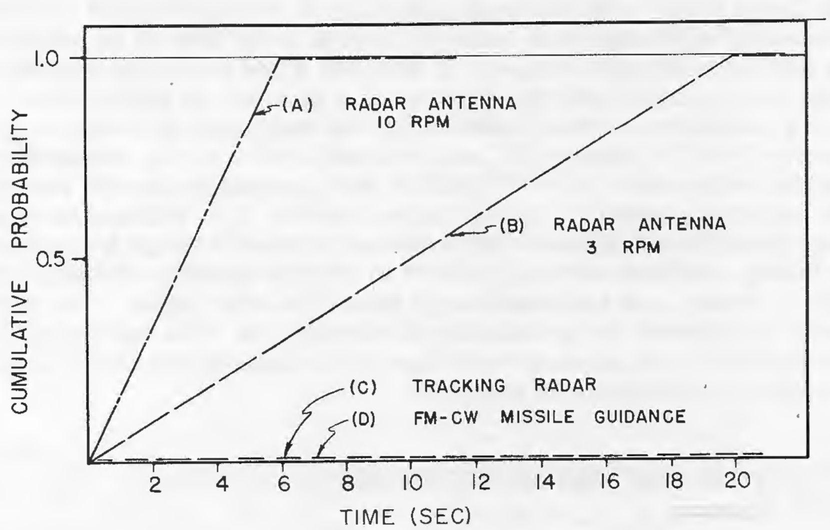

Fig. 14 - Probability of intercept by a crystal-video receiver
[redacted] (unclass

[5]Wald, B., "Rapid Scanning Techniques for Countermeasures Receivers," NRL Report 4410 ([redacted]), September 8, 1954
(unclass)

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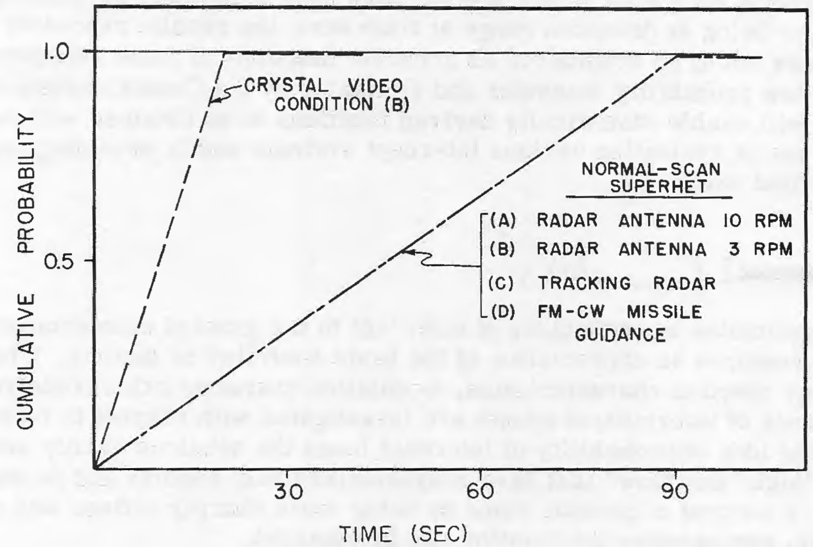

Fig. 15 - Probability of intercept by an AN/APR-9 receiver [[redacted]] (unclass)

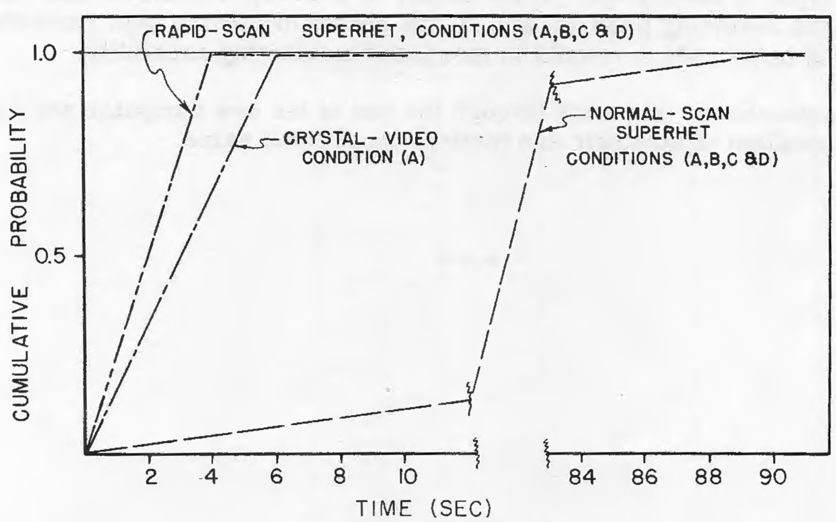

Fig. 16 - Probability of intercept by a rapidly scanned superheterodyne receiver [[redacted]] (unclass)

to the crystal-video and AN/APR-9 receivers in Fig. 16. A further decrease in the period for unity probability can be achieved for this receiver if it is sector-scanned over a smaller range of frequencies. A 500-Mc sector, for example, would require about one second for build-up to unity probability.

Since the preceding examples of this section have been simplified by assumptions, such as the receiver being at detection range at time zero, the results represent gross comparisons and are not to be considered as accurate functions of these receivers. The completion of the new probability computer and simulator by the Countermeasures Branch of NRL, however, will enable statistically derived functions to be obtained with sufficient accuracy to be of use in evaluating various intercept systems and in providing operational information of tactical use.[6]

CONCLUSIONS [[redacted]] (Unclass)

The proper application of probability of intercept to the general countermeasures receiver problem requires an appreciation of the basic contributing factors. When the effects of frequency spectral characteristics, modulation characteristics, receiver sensitivity, and coincidence of intermittent events are investigated with respect to techniques of receiver design, the idea of probability of intercept loses the nebulous quality and loosely applied terms of "high" and "low" that have characterized past reports and papers. It becomes, instead, a concept of greater value by being more sharply defined and constrained so that quantitative, comparative information can be obtained.

An important result is evident from the present phase of the study. For general electronic intercept and reconnaissance, a rapidly scanned superheterodyne system of proper design provides more utility and greater capability in comparison with crystal-video systems of various configurations and dispersive traveling-wave tube systems. This conclusion is deduced from (1) the short time required for the probability to rise to unity for signals of most types of modulation, (2) the ability to intercept radiations that may not be directed toward the receiving position, and (3) the ability to provide high resolution in crowded operating bands, which results in increased monitoring capability.

The future extension of this work through the use of the new computer and simulator will provide information of strategic and tactical operational value.

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[6] See Reference 2

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