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PROBABILITY OF INTERCEPT FOR VARIOUS COUNTERMEASURES RECEIVER SYSTEMS UNDER AVERAGE TROPOSPHERIC SCATTER CONDITIONS

[UNCLASSIFIED TITLE]

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ABSTRACT

[~~Confidential~~]

The probabilities of intercept of three receiver systems were compared when operating against an airborne early warning radar of the AN/APS-20 type. The receiver systems considered were a fast-scan superheterodyne receiver, AN/WLR-1, incorporating first an omnidirectional antenna with a gain of 5 db, and then a fast-scanning directional antenna of the AN/SLA-3 type, and a wide-open DF crystal video receiver. This report is concerned only with tropospheric propagation conditions for an over-water path with the threshold of the normal scatter zone defined to be 50 db below free space in the diffraction zone, and with the scatter attenuation rate assumed to be 0.2 db per nautical mile. By utilizing intercept range curves which incorporate average scatter information for a ship-to-ship (h_T = 130 ft) and a ship-to-aircraft intercept path (h_T = 20,000 ft) together with probability of intercept data derived from a probability computer, time for 90% probability of intercept versus range curves were computed for the three receiver systems under various intercept operating conditions. Assuming the receiver directional antenna and the radar antenna scan to be 360°, and that the radar is continuously operating, the AN/WLR-1 has a higher probability of intercept when incorporating the omnidirectional antenna than when using the directional antenna for ship-to-ship and ship-to-aircraft intercept paths. The improvement for the former intercept link is much more pronounced than that for the latter, and the major increase in probability of intercept is achieved only after long waiting periods. If the radar and receiver operating conditions are varied so that the radar is transmitting periodically, or if the receiver antenna is sector scanning, the advantage of the omnidirectional antenna can be marginal. The only advantage of the DF crystal video receiver without rf amplification over the AN/WLR-1 is simplicity since it has been shown that the AN/WLR-1 with an omnidirectional antenna has a higher probability of intercept under all conditions.

When the radar is operating intermittently, it becomes necessary to greatly increase the sensitivities of existing receiver systems if high probability of intercept is desired in the scatter region. A crystal video receiver which utilizes low-noise traveling-wave tubes as rf amplifiers has an order of sensitivity that will permit interception of signals in the normal scatter region after one rotation of the radar antenna. A study should be made to determine the feasibility of designing a practical DF crystal video receiver with existing TWT techniques. A radar countermeasures intercept system which incorporates both a highly sensitive DF crystal video receiver and an AN/WLR-1 seems to be the most efficient. This investigation also indicated that an analysis to determine the optimum rate for receiver antenna rotation for highest probability of intercept as a function of receiver, radar, and signal characteristics, could be well warranted.

PROBLEM STATUS

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

AUTHORIZATION

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PROBABILITY OF INTERCEPT FOR VARIOUS COUNTERMEASURES RECEIVER SYSTEMS UNDER AVERAGE TROPOSPHERIC SCATTER CONDITIONS
[Unclassified Title]

INTRODUCTION [Unclassified]

The probability of intercept of a countermeasures receiver is a function of the electrical characteristics of the receiver and the radar system, and of the propagation conditions. In this report an Intercept Probability Computer (1) is used for all probability calculations. This computer can simulate a particular receiver and radar system and compute the probabilities of intercept obtained at different time intervals. In order to determine the range at which specific probabilities would exist, field-strength curves of the radars must be calculated. Since it is advantageous to keep the investigation in general terms so that receivers and radar systems in other frequency ranges can be analyzed, a general method for determining the propagation characteristics of any type of radar is described. In order to facilitate fleet operations, the probability calculations will be based on average scatter propagation variations.

A receiver system which utilizes exclusively either superheterodyne or crystal video receiving techniques cannot be expected to give optimum results as a countermeasures device under all conditions and for all situations. Therefore, the relative merits of the individual receiver systems should be analyzed in terms of probability of intercept so that by combining the favorable features of the various types, a highly efficient countermeasures system could be devised. In analyzing these systems some of the principal points of interest are:

1. The effect on probability of intercept when the directional antenna of a rapid-scan, rf-tunable superheterodyne receiver of the AN/WLR-1 type is replaced by an omnidirectional antenna.

2. The total time required to attain a certain probability of intercept when both signal analysis and azimuth information are required, and the relative merits of using the directional antenna or both antennas for this purpose.

3. The comparison of a DF crystal video with a rf-tunable superheterodyne receiver in terms of probability of intercept.

4. The performance of a radar countermeasures intercept system when the two receiver systems are combined.

It is also desirable to know the improved probability of intercept that could be expected when the sensitivity of the two receiver systems are improved within practicable limits.

INTERCEPT RANGE AS AFFECTED BY SCATTER PROPAGATION [[redacted]]

An intercept range curve for a radar (Fig. 1) indicates the signal level that would exist at the input terminals of a receiver as a function of the range from the radar transmitter. This curve is essentially comprised of the interference, diffraction, and scatter zones. The former two zones can be determined by using conventional propagation theory (2),

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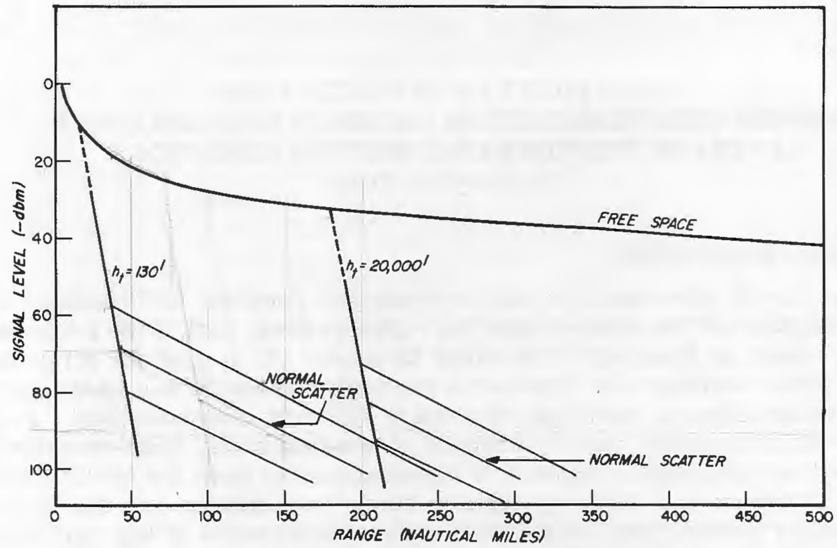

Fig. 1 - Intercept range curve for AN/APS-20 radar when receiver antenna height is 130 feet

since experimental investigations, such as those of Megaw (3), indicate the theory to be valid within reasonable limits. The region close to the transmitter corresponds to the free-space condition, but as the range is increased phase reinforcements and cancellations produced by reflections from the earth's surface cause a varying field, which is called the interference zone. For simplicity, the interference-zone variations will not be considered in range calculations. Instead, a free-space condition will be assumed to approximately the radio horizon. In the vicinity of the radio horizon, the earth interferes with straight line reception, and the diffraction-zone mode of propagation becomes prevalent. At some greater range, the transition to scatter is made.

The exact location of this transition is usually difficult to define because it is a function of many interdependencies, such as atmospheric and weather conditions, and terrain contours. Since this investigation is concerned with fleet operations, propagation computations can be made assuming an over-water path. This means that the smooth-earth theory predominates, and the scatter zone* can be defined with reasonable accuracy. Recent field investigations of tropospheric scatter propagation (3-6) indicate that in the frequency region of 100 to 4000 Mc, for average meterological conditions, the scatter zone seems to start in the diffraction zone about 50 db below free space. The fact that the positioning of the scatter zone is largely independent of frequency in this frequency region, is also verified by Mellen et al.(7) and by Gerks (8). References 3 through 6 were also used to determine the rate of attenuation in the scatter region. Since these rates varied from 0.13 db per nautical mile to 0.215 db per nautical mile, with most rates clustered at the higher figure, an attenuation rate of 0.20 db per nautical mile was used in computing the intercept range curves. Most field investigations have indicated that a slight hump exists in the scatter attenuation curve. Since this hump is of little significance as far as this investigation is concerned, the scatter attenuation curve was drawn as a straight line (Fig. 1).

*This discussion is confined to tropospheric scatter in the frequency region of 100 to 10,000 Mc with no mention of ionospheric scattering.

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Sufficient scatter propagation measurements have not been taken in the 4000 to 10,000 Mc region to define accurately the intercept range curves. A gradual increase in atmospheric absorption (9) (attenuation caused by water vapor and oxygen absorption) exists under fair weather conditions in this frequency range, but there is no abrupt change from the absorption in the 100 to 4000 Mc range. Atmospheric absorption in the higher frequency range, however, increases at a rapid rate under adverse weather conditions such as rain or heavy fog. This information indicates that in fair weather atmospheric absorption should cause little change in scatter attenuation between the two frequency ranges under discussion, but the question of scatter efficiency still remains. Since recent investigations (10, 11) have shown that the scatter zone at a wavelength of 3.2 cm is about 10 db below the scatter level expected at S-band, a method for determining the scatter threshold at X-band similar to that used in the 100 to 4000 Mc range should be used warily until more data is available.

Weather conditions affect the strength of scatter signals as does the formation of "ducts" or layers by temperature inversion. The latter phenomenon was not considered in the intercept curve computations. Since scatter propagation is characterised by signals which are fast fading with the amplitudes having a Rayleigh distribution (5), and signals which are under the influence of a "duct" are relatively slow fading, the two modes of propagation are distinguishable. In the references given, only the signals which exhibited scatter characteristics were considered in determining the intercept range curves. The scatter signal levels shown in Fig. 1 represent the median of the Rayleigh distributed amplitudes. This means that the scatter signal exceeds this level 50% of the time; however the level exceeded by the scatter signal 90% of the time is 8.2 db* below the median. The effect of weather conditions is reflected in the seasonal variation in median signal strength. Dinger and Gardner (12) show a difference of about 8 db between winter and summer scatter signal strengths at 400 Mc with, of course, the latter being better. For this reason, and because of the many other intangibles involved during scatter propagation such as other meteorological effects and sea calmness variations, it is necessary to qualify the scatter region described by defining an above normal and a below normal scatter propagation condition. The former is defined in this text as 10 db above the normal scatter median and the latter as 10 db below the median.

Figure 1 shows intercept range curves for an AN/APS-20 radar which has an operating frequency of 2880 Mc, an antenna gain (G_T) of 30 db relative to an isotropic antenna, a peak power of 1 megawatt, a pulsewidth of 2 μsec, a repetition frequency of 350 pps, and a scan rate of 6 to 10 rpm. The two intercept curves shown in Fig. 1 are for radar antenna heights (h_T) of 130 ft and 20,000 ft with the receiver antenna height (h_r) at 130 ft. The high-altitude radar antenna simulates a ship-to-air search and the lower, a ship-to-ship search. Since the intercept curves are calculated by assuming an isotropic receiving antenna, in order to get the maximum range of a receiver system operating against this AN/APS-20 it is necessary to add the receiver antenna gain (G_r) to the receiver sensitivity in -dbm and read the range in nautical miles off the desired curve. The "effective gains" of the receiving and radar antennas when detecting in the scatter region are somewhat less than the gains expected in free space. It is difficult to determine these "effective gains" so free-space gains were used to give a good approximation. Norton et al. (4) show the theoretical relationship between the path antenna gain and G_T and G_r in the scatter propagation region when $G_T = G_r$, and when $G_T > G_r$. More path antenna gain is realized if $G_T = G_r$ than if $G_T > G_r$. Results reported by Trolese (10) indicate less path antenna gain than the average estimates given by the method explained in the above reference, but the same trend is indicated. A more extensive field study of this phenomenon is needed before a valid method of analyzing the path antenna gain in the scatter region can be verified.

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*Calculated by using the Rayleigh distribution equation.

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It has been shown in the literature that the effective bandwidth* of the scatter medium decreases as the transmission path is increased. This leads to an additional transmission loss when this bandwidth is not adequate to reproduce the transmitted signal without attenuation. Since the bandwidth requirements are stringent when narrow pulse modulated signals are to be intercepted, it is necessary to get at least a rough estimate of the usable bandwidths for various scatter transmission paths. Unfortunately field investigations concerning this phenomenon are lacking; however, Gerks (8) has described a method of estimating the maximum allowable bandwidth when the antenna beam angle and path length are known. Table 1 shows the maximum range and an estimate of the maximum usable bandwidth under the three scatter propagation conditions when a receiver with a sensitivity of -85 dbm and G_r of 15 db is operating against the AN/APS-20. The transmitter antenna was assumed to have a beamwidth of 3°. The maximum range information was determined from Fig. 1 by using the receiver sensitivity stated above in the various scatter regions. Of course, this maximum range is attained only when there is coincidence between the main lobes of the transmitting and receiving antennas and when the receiver is on frequency. It can be seen from Table 1 that for certain scatter propagation conditions serious degrading of narrow pulsewidth signals (0.1 μsec) would take place at the maximum ranges especially when h_T = 130 ft. As will be seen in a later section, the probability of intercepting signals at these ranges within a reasonable period of time with present receiver sensitivities is rather low, and for the ranges obtained, within a reasonable period of time, the transmission path bandwidths are adequate for intercept of narrow pulse signals without attenuation. It should be noted however that as receiver sensitivity and transmitter power are increased transmission bandwidths become increasingly more important.

TABLE 1

Maximum Ranges and Usable Bandwidths When h_T = 130 Feet and 20,000 Feet

AN/APS-20 Antenna Height (ft)	Below Normal Scatter		Normal Scatter		Above Normal Scatter	
	Maximum Range (naut. mi)	Usable Bandwidth (Mc)	Maximum Range (naut. mi)	Usable Bandwidth (Mc)	Maximum Range (naut. mi)	Usable Bandwidth (Mc)
130	147	10	195	4	238	1.8
20,000	245	80	286	16	328	6

PROBABILITY OF INTERCEPT INVESTIGATION [redacted]

This probability of intercept study will be confined to analyzing the performance of an AN/WLR-1 when incorporating either an omnidirectional or a directional antenna, and also the performance of a DF crystal video receiver when trying to detect an AN/APS-20 type of radar. Since the latter radar is typical of most high peak power radars, general conclusions can be reached from this investigation. The characteristics of the AN/APS-20 under discussion have been stated. It is imperative to have a complete azimuth antenna pattern plot for this investigation, but unfortunately the antenna plots for the AN/APS-20 that are available cover only the vicinity of the main lobes. An antenna power pattern (13) for the AN/CPS-6B radar (Fig. 2) which operates near 3000 Mc, will be used to simulate the AN/APS-20 antenna pattern. The inaccuracies obtained by this substitution are not of a serious nature, and will not detract from the validity of the overall conclusions reached.

*This is the bandwidth needed to pass the modulation components of the signal.

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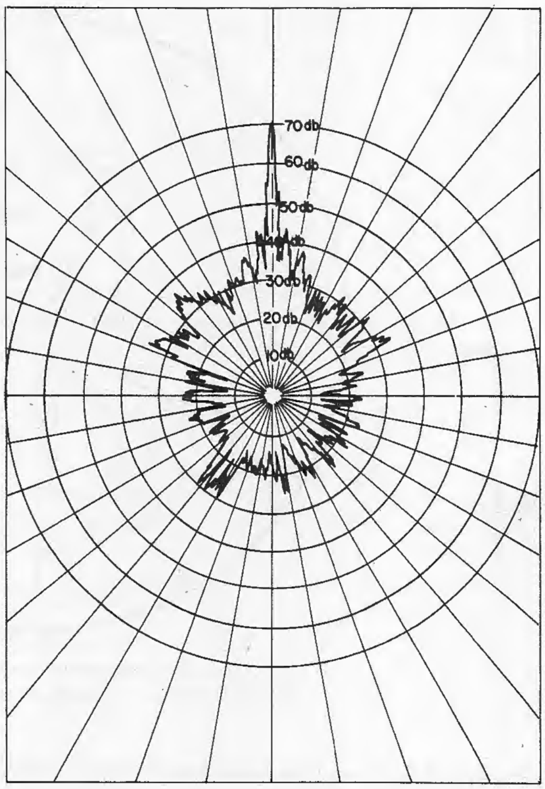

Fig. 2 - Antenna power pattern of vertical low beam of AN/CPS-6B radar

The minimum signal level for positive intercept for the AN/WLR-1 with the S-band tuner in operation was assumed to be -85 dbm. This assumes a noise figure of 17 db for the tuner and also assumes that the intercepted radar pulse has the characteristics specified for the AN/APS-20 (pulsewidth = 2 μsec, prf = 350 pps). The evaluation of the effect of signal characteristics on sensitivity was obtained from the data taken in the author's present threshold studies of the signal analysis display of the AN/WLR-1. Since the design of the S-band tuner for this receiver has been optimized (14), the noise figure mentioned should be obtainable. Figure 3 shows the antenna power pattern* of the AN/SLA-3 type receiving antenna which has a measured gain of 15 db above an isotropic antenna. The omnidirectional antenna pattern is usually characterized by nulls which are a function of antenna design and shipboard installation. For a well-designed antenna, these nulls are usually quite sharp when there are no major shipboard obstructions in the antenna beam path; hence a circular omnidirectional antenna pattern, which was assumed for this investigation, could be used without introducing serious error. Since experimental omnidirectional antennas have been designed which have gains of 5 db with good patterns, this figure was used. The DF crystal video receiver defined has a sensitivity of -50 dbm which includes the stipulated omnidirectional antenna gain.

Range Detection Analysis

In order to attain a better understanding of the probability computer information, it is necessary to draw the azimuth detection range curves of the receiver systems in question.

*The antenna power patterns and gain measurements were made by Mr. John Ihnat of the Radio Division, NRL.

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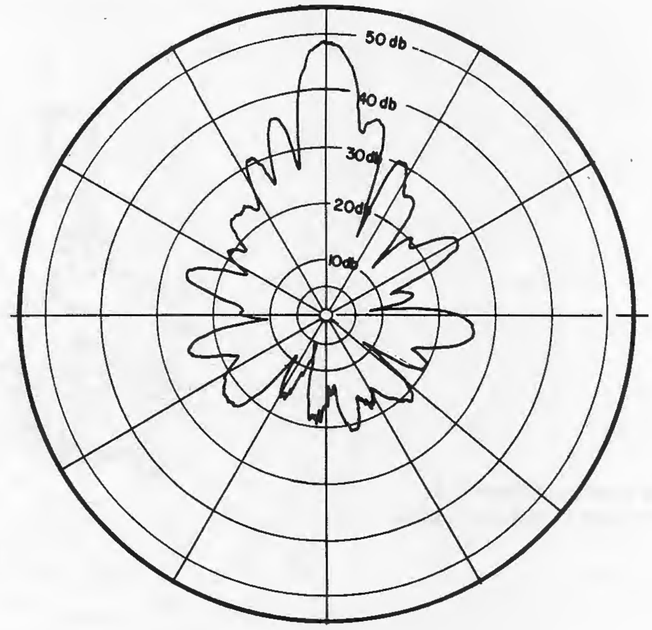

Fig. 3 - Antenna power pattern for
AS-605(XN-1)/SLA-3 antenna at 3000 Mc

Figures 4 and 5 show the detection range contours of the AN/WLR-1 assuming -85 dbm sensitivity when the AN/APS-20 antenna height is 20,000 feet and 130 feet, respectively. These curves were plotted by using the information in Figs. 1, 2, and 3. In Fig. 4, Curve I shows the detection range when the main lobe of the directional antenna is looking at the rotating radar antenna and Curve II shows the detection range when the average minor lobe of the directional antenna (35 db down) is looking at the rotating radar antenna. Curve III shows the detection range when the omnidirectional antenna is operating against a rotating radar antenna. With the directional antenna rotating, the detection range varies with Curve I as a maximum and Curve II as the approximate minimum. If the receiver is on frequency, instantaneous detection is assured at about 10 miles. With the omnidirectional antenna, instantaneous detection is assured at about 180 miles. In terms of instantaneous intercept, the omnidirectional antenna looks favorable, but it must be remembered that the AN/WLR-1 with this antenna yields no bearing information; if bearing information is desired it is necessary to switch to the directional antenna. Obviously, the question arises as to how much time would be required before the rotating directional antenna would achieve the same probability of intercept as the omnidirectional antenna. The Intercept Probability Computer resolves this question expediently, and also gives the desired relationship between range and time for a certain probability of intercept. This relationship will be taken up thoroughly in the following sections.

The same general discussion is applicable to the detection range contours when the transmitting antenna is at 130 feet (Fig. 5). Here, instantaneous intercept range should still be about 10 miles for the directional antenna, but would decrease to 25 miles for the omnidirectional antenna. The detection range contour for DF crystal video receivers for the two transmitter antenna heights would be similar to Curve II in both Figs. 4 and 5. Since there is only a 15-db discrepancy in the diffraction zone between the crystal video detection range curves and the minor-lobe curves, producing separate crystal video curves would not be warranted. In other words, the main lobe of Curve II of Fig. 4 would be 188 miles for the crystal video instead of the 195 miles shown, and for Curve II of Fig. 5 it

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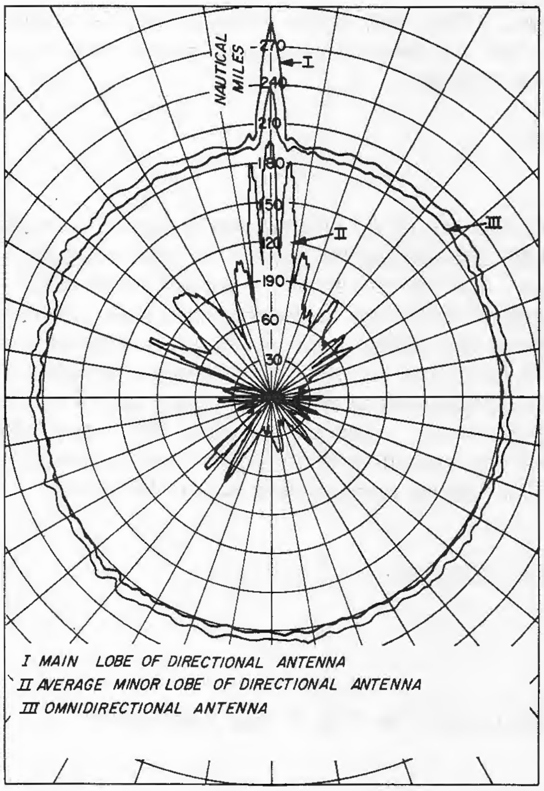

Fig. 4 - Detection range contour of an AN/APS-20 radar by an AN/WLR-1 when incorporating an omnidirectional and directional antenna for normal scatter conditions and when h_T = 20,000 feet

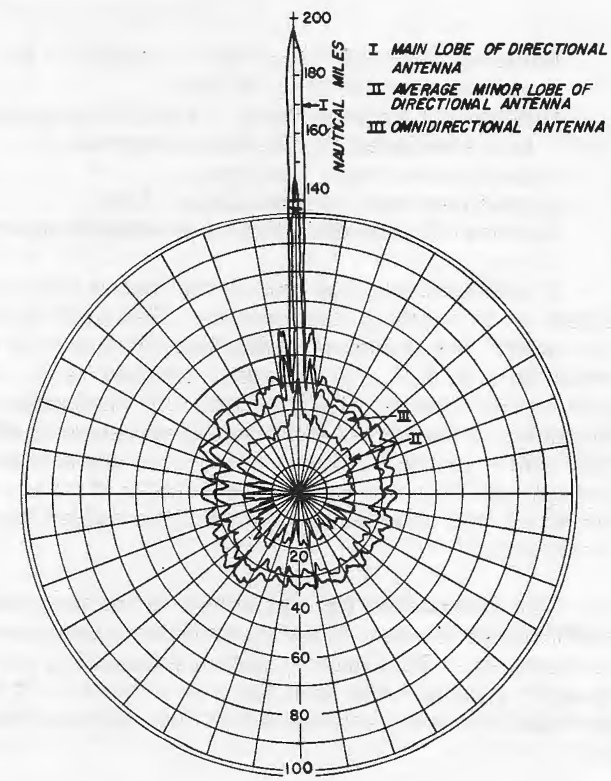

Fig. 5 - Detection range contour of an AN/APS-20 radar by an AN/WLR-1 when incorporating an omnidirectional and directional antenna for normal scatter conditions and when h_T = 130 feet

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would be 34 miles instead of the 40 miles shown. The rest of the azimuth points would, of course, change according to Figs. 1 and 2, but the overall detection range contours would be essentially the same as the two Curve II plots.

Probability Computer Raw Data

The Intercept Probability Computer used consists of an analog and a digital section. Probability of intercept curves were obtained by simulating the receiver and transmitter characteristics under test in the analog section, and by utilizing the digital section to record the time to achieve desired probabilities of intercept as attenuation was inserted in 10-db steps. Then by using the necessary correction factor, the attenuation values were converted to relative signal levels, and then to effective ranges by utilizing a propagation intercept curve such as Fig. 1. In this way the relationship between range and time for a certain percentage probability of intercept was found. Curves for 50%, 75%, and 90% probability of intercept for both the directional and omnidirectional receiver antennas are shown in Figs. 6a, b, and c, respectively. The analog section was set as follows:

Transmitter (AN/APS-20):

Frequency: 3000 Mc
Peak Power: 1 Mw
Antenna Scan Rate: 10 rpm
Antenna Gain: 30 db (The power antenna plot shown in Fig. 2 was simulated as closely as possible.)
Signal PRF: 350 pps

Receiver (AN/WLR-1):

Receiver Scanning from 2000 to 4000 Mc in 2 seconds
Receiver Sensitivity: -85 dbm
Directional Antenna Gain: 15 db (The power antenna plot shown in Fig. 3 was simulated as closely as possible.)
Antenna Scan Rate: 300 rpm
Omnidirectional Antenna Gain: 5 db
Receiver Bandwidth: 10% of scanned frequency band (20 Mc)

It was assumed that the signal was in the center of the 2000-Mc band; therefore if a signal is on bearing, the time for 100% probability of intercept would be 2 seconds. Obviously, for the same conditions the time for 90%, 75%, and 50% probability of intercept would be 1.8, 1.5, and 1 second, respectively. If the signal were considered at any other part but the center, the time for 100% probability of intercept would be increased; for example, if the signal were at either extreme edge of the band this time would be 4 seconds. The center of the band was chosen for convenience, but the general trend of the probability curves would be the same irrespective of where the signal was placed. The computer was set up so that at least two consecutive pulses had to be detected before an intercept was indicated.

The attenuation figures shown in the probability curves can be converted directly to signal level in -dbm if the transmitter peak power is 1 watt and the transmitting antenna is isotropic. This means that an attenuation correction factor must be used for the specific type of radar that is to be detected. It is desirable to have the abscissa units of the probability curve correspond to the ordinate units of the intercept range curve, so that

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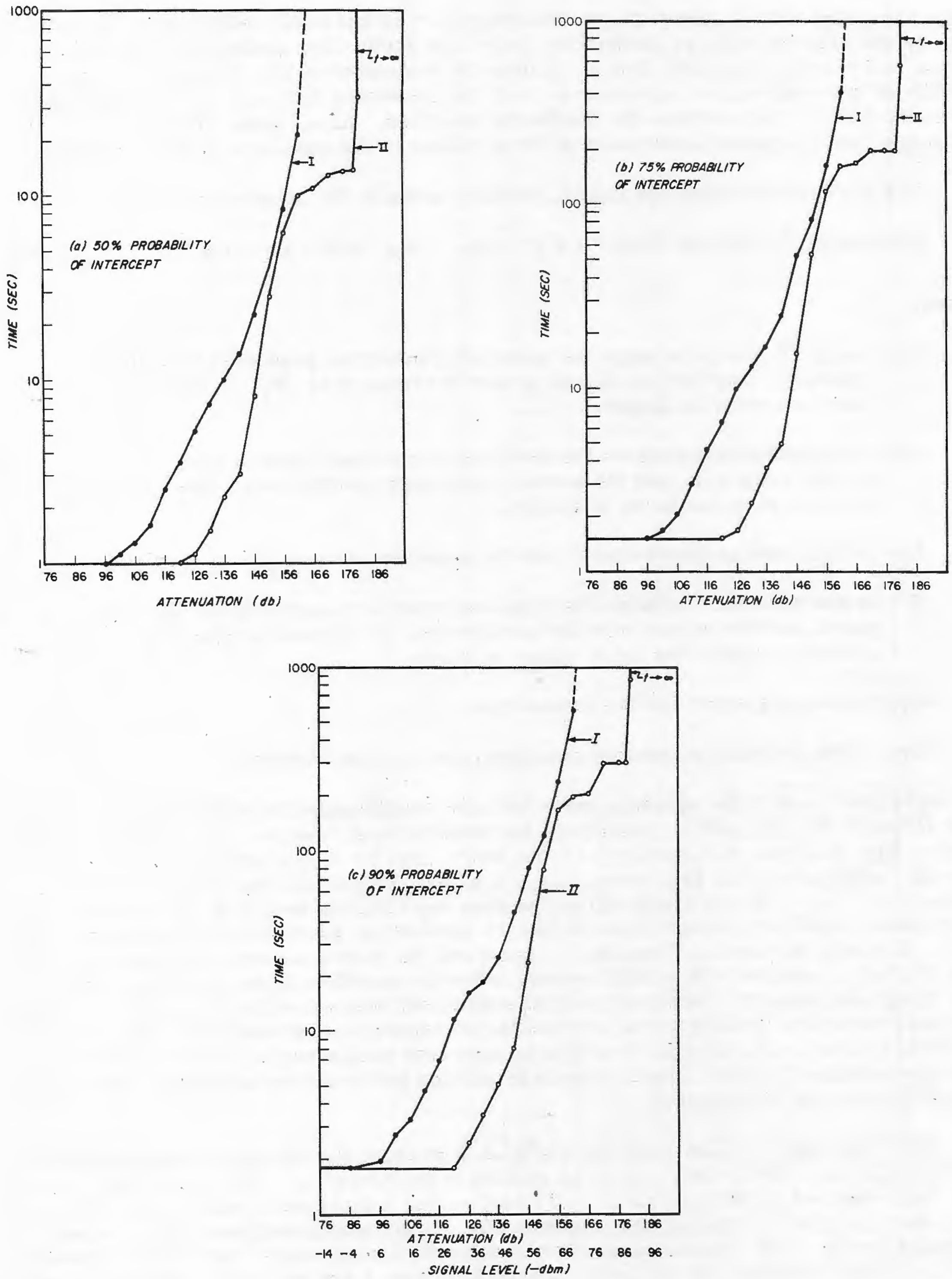

Fig. 6 - Time for specified percentage probability of intercept as a function of attenuation when receiver is frequency scanning. Curve I, directional antenna (G_r = 15 db); Curve II, omnidirectional antenna (G_r = 5 db).

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time for probability of intercept-versus-range curves are easily obtainable. This condition can be achieved by using an attenuation correction factor that would allow for variations in radar and receiver characteristics. It must be remembered that these particular probability of intercept curves are accurate only for receivers that scan at the 2-second rate over the 2-kMc band and have the bandwidth specified. Also, large variations from the stipulated antenna gains would necessitate a change in the simulated antenna patterns.

The attenuation correction factor, with all terms in db, is given by

$$\text{Attenuation Correction Factor} = P_T' + A_T' + A_R' + S' - P_T - A_T \qquad (1)$$

where

P_T' is the difference between the assumed transmitter peak power for the computer, and the actual peak power of transmitter. (P_T' is positive when the latter is larger.)

A_T' is the difference between the assumed transmitter antenna gain for the computer, and the actual transmitter antenna gain. (A_T' is positive when the latter is larger.)

A_R' is the same as above except that the receiver antenna gain is involved.

S' is the difference between the assumed receiver sensitivity for the computer, and the actual receiver sensitivity. (S' is positive when the absolute value of the latter figure is larger.)

P_T is the peak power for the transmitter.

A_T is the transmitter antenna gain above an isotropic antenna.

If the receiver and radar systems under test are simulated in the computer, only the last two terms of Eq. (1) need be considered for attenuation correction. The second abscissa line in Fig. 6c shows this correction from which time for 90% probability of intercept versus range curves can be derived, i.e., a signal level of -36 dbm would exist at 28 miles when h_T = 130 feet and at 181 miles when h_T = 20,000 feet (Fig. 1), and for the directional receiving antenna it would take 16 seconds for probability of intercept to reach 90%. It should be noted in Figs. 6a, b, and c that the maximum intercept range for the AN/WLR-1 is reached within 1000 seconds when the omnidirectional antenna is used, but the maximum range for the directional antenna is not reached within this period. In the curves concerning the directional antenna the extrapolations (dotted lines) have relatively large slopes because, in order to obtain an intercept in this region, there must be coincidence between the main lobes of the transmitting and receiving antennas, and also the receiver must be on frequency.

If an intercept is made when the AN/WLR-1 is using the omnidirectional antenna, a switch must be made to the directional antenna to get a bearing. Curve I of Fig. 7 shows the time required for 90% probability of intercept for a directional antenna when the signal frequency is known. For the data shown in Fig. 7, the analog section of the computer was adjusted for the same system parameters previously stated except that the receiver was considered on frequency at all times. Curve II of Fig. 7 can be used to simulate a receiver system which consists of a crystal video receiver and a 5-db omnidirectional antenna. Since the crystal video receiver considered has a sensitivity of -45 dbm, the attenuation

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correction would have to include the S', P_T, and A_T terms. Figure 7 illustrates that the omnidirectional antenna reaches the maximum range for 90% probability of intercept within 17 seconds and that the directional antenna reaches it within 200 seconds.

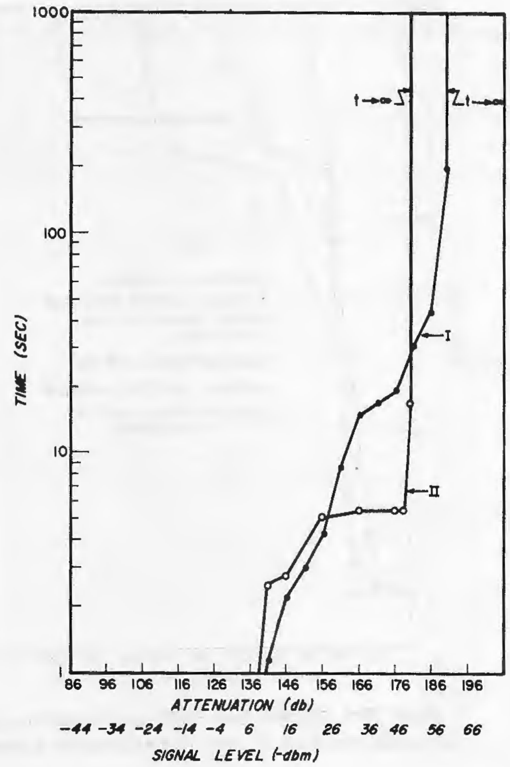

Fig. 7 - Time for 90% probability of intercept as a function of attenuation when receiver is not frequency scanning. Curve I, directional antenna (G_r = 15 db); Curve II, omnidirectional antenna (G_r = 5 db).

Comparison of Omnidirectional and Directional Antennas

The question to be answered is whether it is necessary for a receiver of the AN/WLR-1 type to have both an omnidirectional and a directional antenna for optimum system efficiency or if the latter antenna would suffice. Since the two intercept paths which are of primary importance to fleet operations, mainly the ship-to-aircraft and the ship-to-ship paths, are represented in the intercept ranges curves shown in Fig. 1, it is possible to draw general conclusions pertaining to this antenna comparison under the three scatter conditions when the receiver is operating against a radar of the AN/APS-20 type. This comparison can be made in terms of range and time for 90% probability of intercept by using the raw probability data as described in the previous section. Only the 90% probability of intercept curves were used for this investigation, the 50% and 75% probability curves being inserted only so that the reader could determine the magnitude of increase in range that could be expected as the probability requirements are decreased.

The AN/APS-20 radar characteristics and receiver antenna gains specified in the previous section were used for all the probability of intercept calculations. Since the raw probability data obtained from the computer assumes that the radar is operating continuously and that both the transmitting and receiving antennas scan 360°, these conditions are reflected in all the probability of intercept curves of this section. For the present, the antenna comparison will be made on the assumption that these conditions prevail. Later, however, other factors such as intermittent radar transmission and receiver antenna sector scan will be considered. Figure 8a shows the comparison between the omnidirectional and directional antennas where h_T = 130 feet for normal and below-normal scatter conditions with the obvious conclusion being that the omnidirectional antenna has the advantage both at short and long ranges. Figure 8b illustrates the antenna comparison for the above-normal scatter condition, and once again the omnidirectional antenna shows a definite advantage over the directional antenna at all ranges. The improvement in probability of intercept for the omnidirectional antenna at the long ranges is greater than that at the short ranges, because signal levels which represent the long ranges are well in to the scatter region.

Figures 9a and 9b show the time for 90% probability of intercept as a function of range for a ship-to-aircraft intercept path. Figure 9a shows the directional antenna for all scatter

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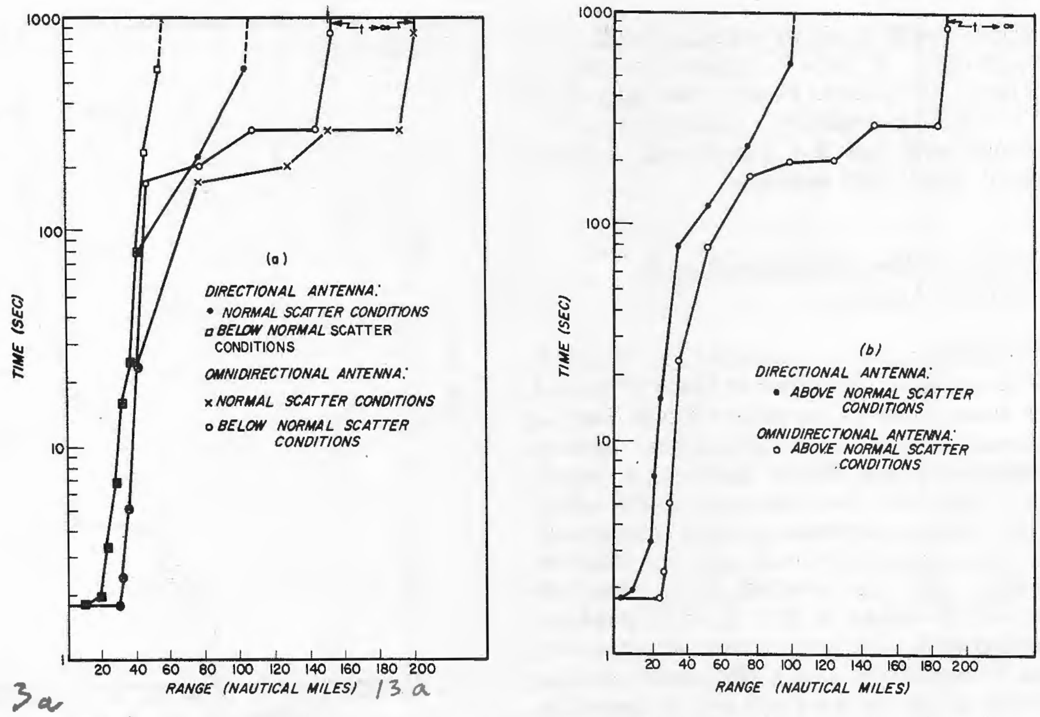

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Fig 13a

~~Fig. 8~~ - Time for 90% probability of intercept as a function of range for the omnidirectional and directional antennas when h_T = 130 feet and S = -85 dbm

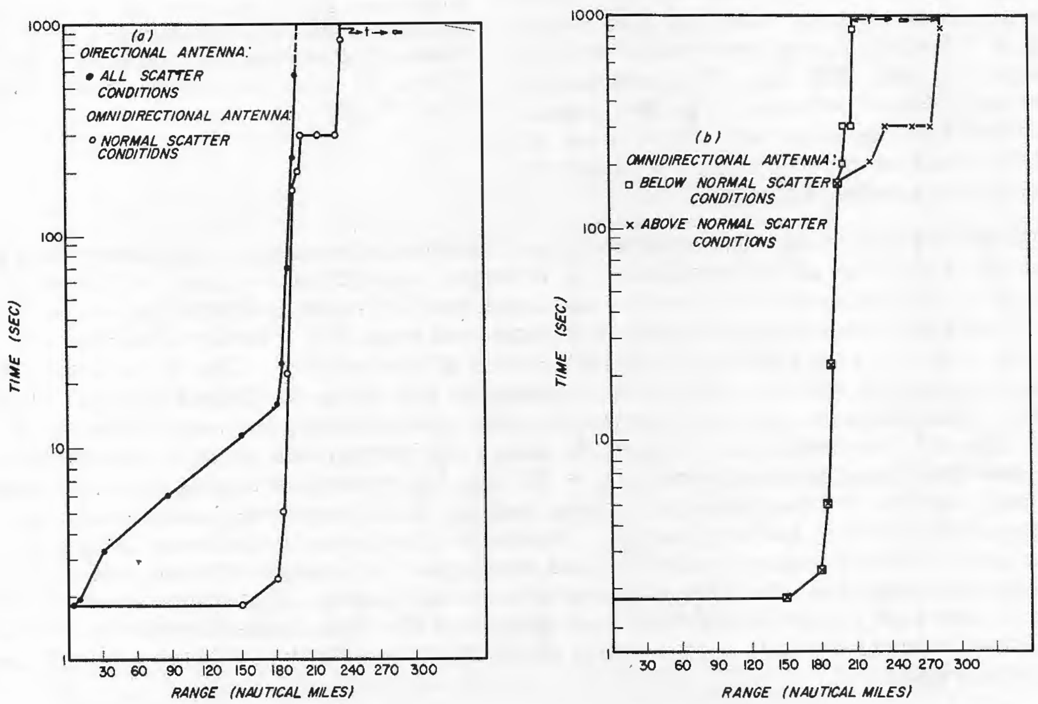

Fig. 9 - Time for 90% probability of intercept as a function of range for the omnidirectional and directional antennas when h_T = 20,000 feet and S = -85 dbm

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conditions, and the omnidirectional antenna for normal scatter conditions while Fig. 9b shows the latter antenna for below- and above-normal scatter conditions. The directional antenna has the same curve for all scatter conditions, since the signal level that will be intercepted in a reasonable time (at least 100 seconds) does not reach the scatter zone. Once again the omnidirectional antenna seems to have the advantage, but it is not as pronounced as when h_T was 130 feet. At short ranges, approximately 2 rotations of the radar antenna (1 revolution in 6 seconds) are needed in order for the probability of intercept of the directional antenna to achieve that of the omnidirectional antenna. Although the use of an omnidirectional results in some improvement in probability of intercept at long ranges after long waiting periods, this advantage becomes a function of the aircraft's bearing with respect to the ship because of the fast opening and closing rate of range of present aircraft.

As was stated above, a signal with a pulsewidth of 2 μsec and prf of 350 pps was assumed when the AN/WLR-1 sensitivity was -85 dbm. If the pulsewidth is decreased to 0.1 μsec, the receiver sensitivity decreases by about 9 db.* To simulate the AN/WLR-1 intercepting a 0.1-μsec signal from a radar of the AN/APS-20 type another series of probability of intercept curves was plotted with S = -76 dbm (Figs. 10a, 10b, and 11). The same general conclusion can be drawn from these diagrams as from the previous ones, although since the advantage for the omnidirectional antenna at larger ranges is due to the minimum detectable signal level being in the scatter region, any decrease in receiver sensitivity would have a greater effect on the range of the receiver system which used the omnidirectional antenna. In this discussion, no allowance was made for scatter-path bandwidth deficiencies since Table 1 indicates that the bandwidth is sufficient to reproduce the signals considered without attenuation even at the longest ranges where 90% probability of intercept is assured within 1000 seconds.

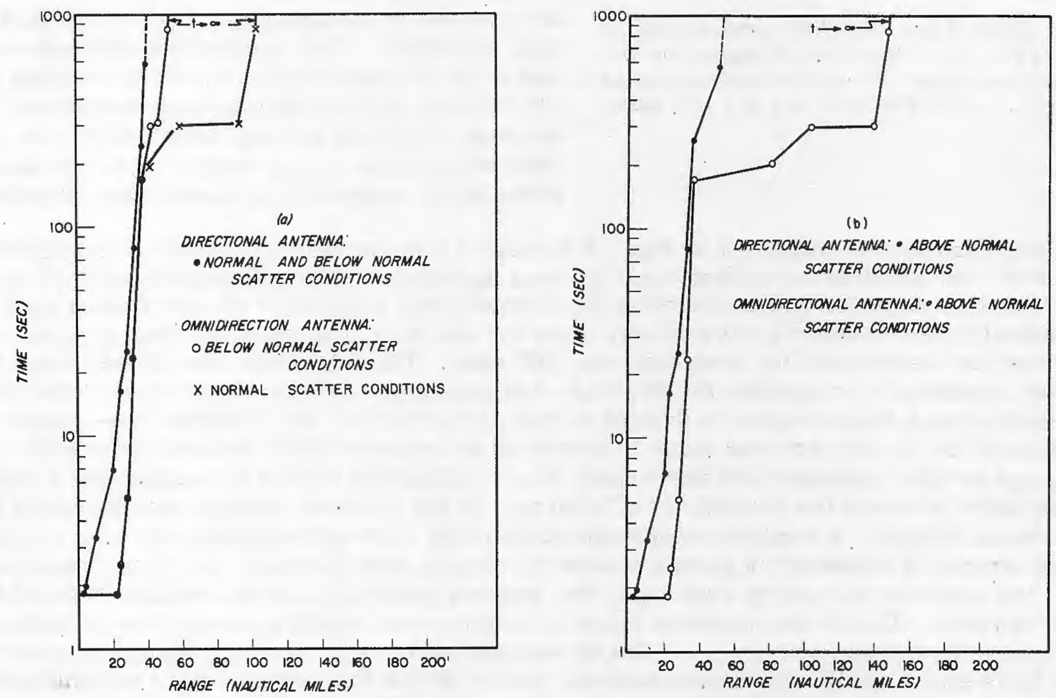

Fig. 10 - Time for 90% probability of intercept as a function of range for omnidirectional and directional antennas when h_T = 130 feet and S = -76 dbm

*Results from author's present threshold studies on signal display for AN/WLR-1.

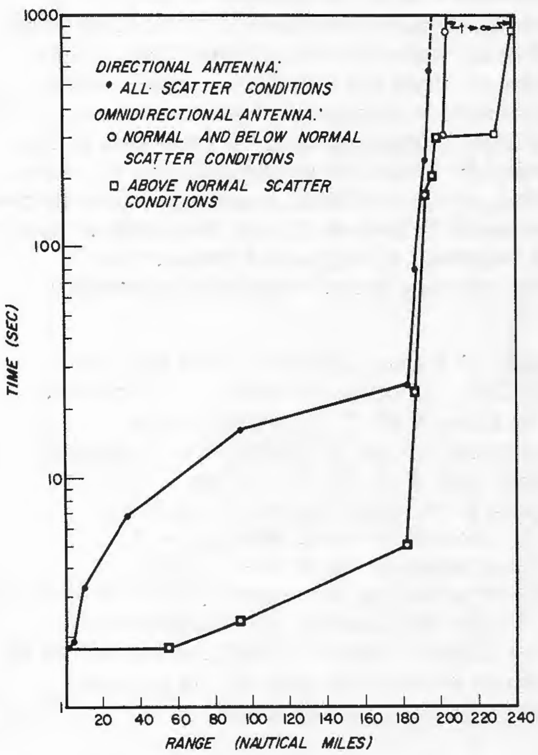

Fig. 11 - Time for 90% probability of intercept as a function of range for the omnidirectional and directional antennas when h_T = 20,000 feet and S = -76 dbm

If bearing information is required when the omnidirectional antenna is in use, Curve I of Fig. 7 shows the additional time necessary to obtain the bearing when 90% probability of intercept is to be assured. By comparing this plot with Curve II of Fig. 6c, it becomes obvious that the time for 90% probability of intercept in the case of the non-frequency-scanning receiver for a particular signal level can be considered negligible compared to the time required when the receiver with the omnidirectional antenna is scanning. For example, at attenuations of 146 db and 176 db the times involved in Curve II of Fig. 6c are 23.5, and 300 seconds, respectively, while for the same attenuations the times involved in Curve I of Fig. 7 are 2.2 and 19.5 seconds, respectively. This indicates that the omnidirectional antenna probability of intercept curves show with reasonable accuracy the time for intercept when frequency and bearing information is required, assuming switch-over is made instantaneously. It must be remembered, however, that when both receiving and transmitting antennas are rotating, the maximum range where an accurate bearing can be obtained by the AN/WLR-1 is determined by the transmitting antenna backlobe structure. This means that although intercepts can be made in the scatter zone when the AN/WLR-1 incorporates an omnidirectional antenna, accurate bearing information can be obtained only out to the range where the back lobes of the transmitting antenna are detectable.

The information contained in Figs. 8 through 11 shows that a receiver of the AN/WLR-1 type with the specified omnidirectional antenna definitely has a higher probability of intercept than this receiver when incorporating a directional antenna of the AN/SLA-3 type. Essentially these results are valid only when the AN/SLA-3 antenna is rotating at the rate assumed for the probability computations, 300 rpm. This high rate was chosen since the present tendency is to operate the AN/SLA-3 at maximum speeds. For signal repetition rate and system characteristics defined in this investigation, this rotation rate seems to be too high, but no attempt was made to arrive at an optimum rate for best probability of intercept for the intercept link described. Since utilization of this favorable rate could appreciably increase the probability of intercept of the receiver system incorporating the directional antenna, a complete study should be made to determine this rate as a function of the number of consecutive pulses needed for signal identification, the signal repetition rate, the receiver frequency scan rate, the antenna patterns, and the rotation rate of the radar antenna. Use of the optimum value of rotation rate would decrease the advantage of the omnidirectional antenna over the directional antenna at the short ranges but would have little effect on the directional antenna results at the long ranges since coincidence of the antenna beams is still necessary for intercept. Since the original advantage of the omnidirectional antenna in the smaller ranges for a ship-to-aircraft intercept path was not excessive, the expected improvement with the directional antenna when the antenna rotation rate is optimized could equalize the probability of intercept for the two antenna systems in this region. Even assuming the most favorable antenna rotation rate, the

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omnidirectional antenna would still have a 90% probability of intercept within 5 minutes at a much longer range than the directional antenna for the ship-to-ship intercept path, and to a lesser extent for the ship-to-aircraft path. It can be concluded that if both antennas are scanning 360° and the radar is operating continuously, the omnidirectional antenna has a definite advantage in probability of intercept over the directional antenna for a ship-to-ship intercept path, but not much of an advantage for a ship-to-aircraft intercept path.

Other radar and receiver operating conditions can exist which could change the above conclusions completely. If, for example, certain operations do not require full 360° receiver antenna scan then as the sector scan is decreased the probability of intercept for the directional antenna increases, and it will finally reach a point where it will be better than the omnidirectional antenna. If the radar operation is periodic, so that the radar is on just for 1 or 2 rotations then off for a period of time, the omnidirectional antenna advantage at long ranges would be minimized, since long continuous radar operation must exist to obtain the good probabilities of intercept. Since intercept will be guaranteed consistently only at the shorter ranges, the requirement of obtaining the optimum rotation rate for the directional antenna becomes increasingly important. Since it is believed that most future search radars will be operated on an intermittent basis, a thorough study of optimum rotation rate is imperative.

Receiver System Probability of Intercept

In comparing a wide-open crystal video receiver and an rf-tunable superheterodyne receiver, the common belief is that the former has the advantage in simplicity of design and probability of intercept. Naturally the advantage of simplicity cannot be contested, but it is doubtful whether a crystal video receiver without rf amplification has any distinct advantage in probability of intercept over the AN/WLR-1. By utilizing Curve II of Fig. 7, 90% probability of intercept curves for a DF crystal video receiver were computed when antenna heights for the AN/APS-20 were 130 feet and 20,000 feet (Fig. 12). This was assuming a receiver sensitivity of -45 dbm and an omnidirectional antenna gain of 5 db. The curves for the three scatter conditions are the same since the receiver sensitivity does not result in interception of signals in the scatter zone. It can be seen in Fig. 12 that an intercept would be assured within one rotation of the transmitting antenna (5.4 seconds instead of 6 seconds due to 90% probability of intercept condition) out to the approximate maximum range of intercept. At the maximum range, 17 seconds are needed for 90% probability of intercept instead of the expected 5.4 seconds, because at this range signals are being intercepted at the peak of the transmitter antenna beam and any slight variation from this peak could result in a miss. In comparing Fig. 12 with Fig. 8 and Fig. 9, it can be seen that the crystal video receiver has a slight advantage over the AN/WLR-1 when using a directional antenna at short ranges, especially where $h_T = 20{,}000$ feet, but this tunable receiver has the advantage at the longer ranges, especially when the scatter zone is reached ($h_T = 130$ feet). Obviously, if the optimum rotation rate for the directional antenna were used, the advantages of the crystal video receiver at the lower ranges would be decreased. If the omnidirectional antenna is used with the AN/WLR-1, as is suggested when a 360° receiver antenna scan is contemplated, the probability of intercept for this system is better than that for the crystal video receiver under all conditions.

Since most search radars are effective at least to the radio horizon when operating against large targets, a countermeasures receiver must be capable of intercepting radar signals in the scatter region if any appreciable advantage in range over the radar is to be achieved. This study has indicated that a long period of time must elapse before interception can be made in the scatter region with present receiver system sensitivities. In most cases this waiting period is too long to be of any tactical importance. When detecting

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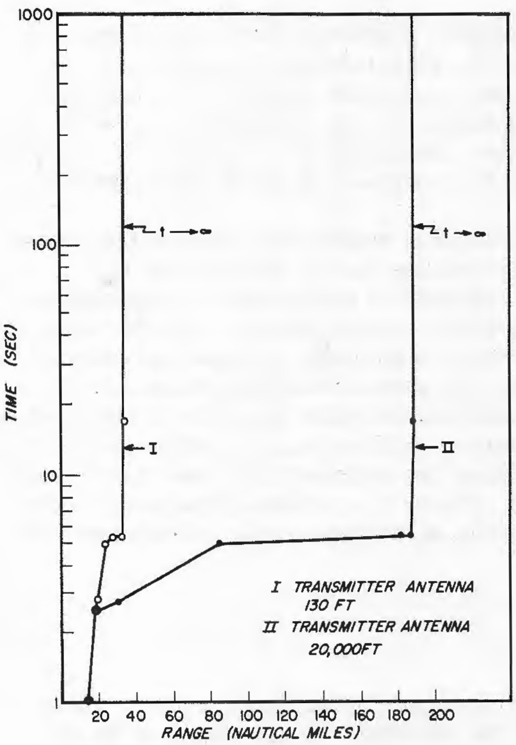

Fig. 12 - Time for 90% probability of intercept as a function of range for the DF crystal video receiver with S = -45 dbm and A_r = 5 db. These curves represent the three scatter conditions.

radars which are operating intermittently, the time in most cases will not be available to achieve a high probability of intercept for signals in the scatter zone. In order to assure intercepts beyond the diffraction zone against this type of radar, a receiver must be capable of intercepting signals in the scatter region after 1 or 2 radar antenna scans. It can be seen from Figs. 1 and 6c that in order for the AN/WLR-1 with an omnidirectional antenna to reach the threshold of the normal scatter region within 2 scans of the radar antenna, the receiver sensitivity must be improved 15 db when h_T =130 feet and 30 db when h_T = 20,000 feet. Also from Figs. 1 and 7 it is evident that the crystal video receiver should be improved 20 db when h_T = 130 feet to reach the normal scatter threshold within 1 scan of the radar antenna and 34 db when h_T = 20,000 feet. Obtaining at least a 15 db improvement for the AN/WLR-1 without sacrificing any of the favorable characteristics of this receiver is difficult. By utilizing a low-noise rf amplifier such as traveling-wave tube or a tunable backward-wave amplifier,* sensitivity improvement for this receiver could be as high as 10 db. Using a low-noise broadband TWT before the rf preselectors is at present the most convenient way of obtaining this improvement in sensitivity. Unfortunately by using a TWT in this fashion, serious intermodulation and cross-modulation problems could arise, and the low saturated power level prevalent in a low-noise TWT enhances chance of overload. A series of 90% probability of intercept curves was computed assuming a receiver sensitivity of -95 dbm in the same way as previously discussed (Figs. 13 and 14). As was expected, the range was extended appreciably only after long waiting periods. However, the above normal scatter region is reached, when the AN/WLR-1 incorporates an omnidirectional antenna, after 2 rotations of the radar antenna when h_T = 130 feet (Fig. 13b). For a continuously operating radar this sensitivity enhancement definitely improves the intercept system when long waiting periods can be tolerated especially for a ship-to-ship intercept path; however for intermittently operating radars, and when only short waiting periods are of tactical interest, the improvement in receiver sensitivity resulted in comparatively little range increase. It must be remembered that this discussion pertains to intercepting radars of the AN/APS-20 type; conditions could arise when operating against a radar of low power and low antenna gain where a definite improvement would be achieved in intercept range with this improvement in sensitivity. This would be especially true when operating over a ship-to-aircraft intercept path when it is necessary to get in the diffraction region during a scan or so.

Assuming a gain of 5 db for the omnidirectional antenna, the crystal video receiver sensitivity can be increased from -50 dbm to -75 dbm† by inserting a broadband, low-noise

*Low-noise, tunable backward-wave amplifiers are in the experimental stages of design, but they have shown promise.

†Investigations have been made using the RCA 6861 TWT and sensitivities of this order were obtained.

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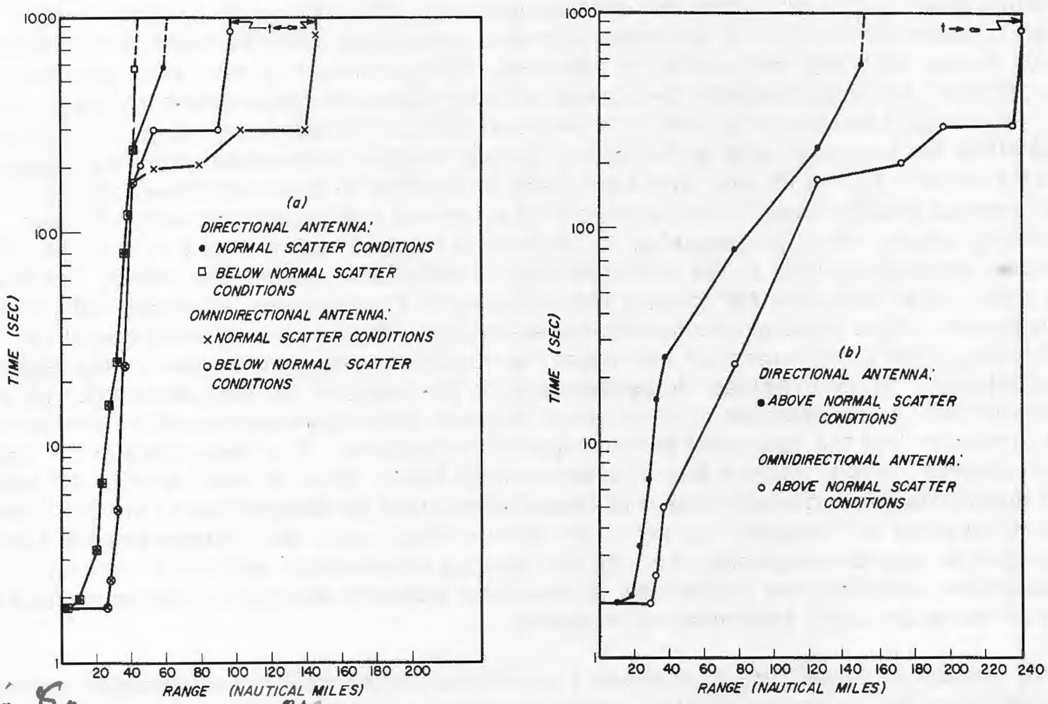

Fig 8a 8(a)

~~Fig. 13~~ - Time for 90% probability of intercept as a function of range for the omnidirectional and directional antennas when h_T = 130 feet and S = -95 dbm

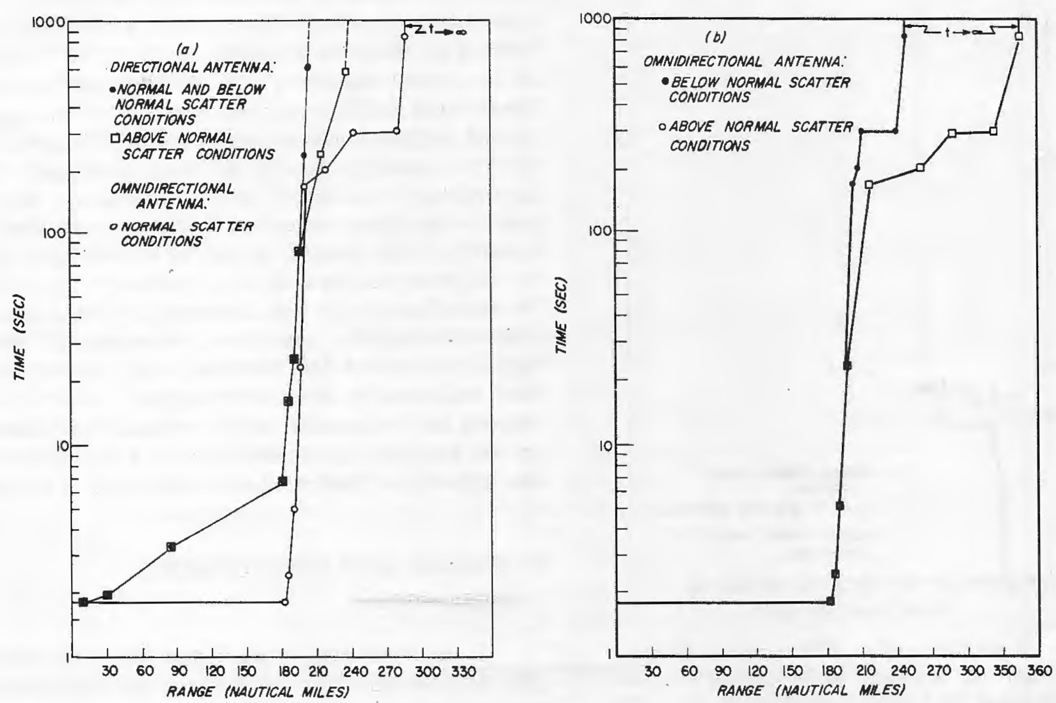

Fig. 14 - Time for 90% probability of intercept as a function of range for the omnidirectional and directional antennas when h_T = 20,000 feet and S = -95 dbm

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traveling-wave amplifier before the crystal detector. This increase in sensitivity is enough to make it possible to intercept signals from an AN/APS-20 radar in the normal scatter region with 90% probability of intercept after 1 rotation of the radar antenna when h_T = 130 feet, but unfortunately the normal scatter region is not reached when h_T = 20, 000 feet. It is highly desirable to have this receiver at least 10 db more sensitive, since this would allow for intercept also in the below-normal scatter zone when operating against an AN/APS-20 with h_T = 130 feet, and also make it possible to intercept lower power radars in the normal scatter zone. The advantage of a crystal video receiver with -75 dbm sensitivity can be seen by comparing the curves in Fig. 15 with Curve I in Fig. 12. Certain questions arise pertaining to the practicability of using low-power, low-noise, traveling-wave tubes in an effective DF crystal video system. The problem of weight and power requirements of the present permanent-focussing traveling-wave tube could soon be resolved with the development of low-noise, periodic-focussing tubes now in the experimental stages. Since overload characteristics of the receiver as well as sensitivity must be considered, a compromise must be made between the noise contributed by the traveling-wave amplifier and the saturated power capacity of the tube. If a four-channel DF crystal video receiver, which utilizes four traveling-wave tubes, is to be considered, the feasibility of duplicating the characteristics of these tubes must be determined to ensure obtaining accurate bearing information. A receiver system which uses one traveling-wave amplifier with separate signal-comparing circuits for bearing information would, of course, be advantageous providing the probability of intercept capabilities of this system remain the same as the wide-open, four-channel receiver.

No attempt is made here to endorse a particular DF crystal video receiver system as the most practical, since a complete study has not been made of all the factors involved. The main purpose of this report is to recommend a receiver system that would operate most efficiently as a radar intercept device. If such a receiver with the order of sensitivity specified could be successfully designed, signals from a search-type radar would be intercepted in the scatter zone during one rotation of the radar antenna; the bearing and frequency-band information derived from this intercept would enable a receiver of the AN/WLR-1 type to identify the signal frequency and characteristics in a short period of time. The maximum time required to determine the frequency of the signal would be 4 seconds; it would then require about 5 seconds to switch to signal analysis and determine the signal characteristics. Another advantage of the highly sensitive DF crystal video receiver is that reasonably accurate bearing information should be obtainable when signals are detected in the scatter zone, which is not possible when the direction finder of the AN/WLR-1 is used.

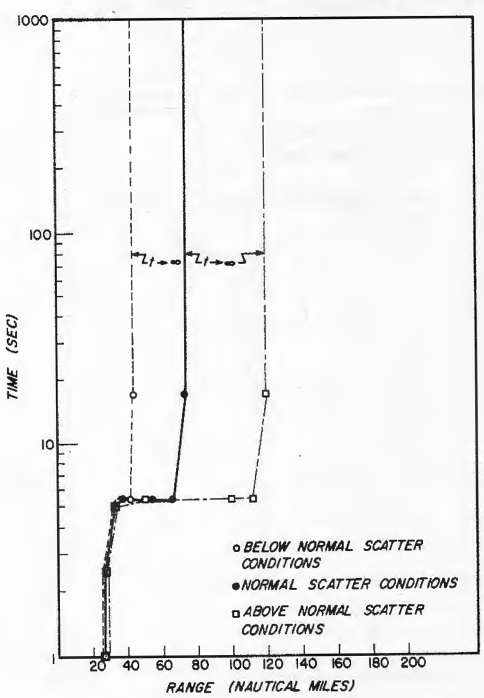

Fig. 15 - Time for 90% probability of intercept as a function of range for the DF crystal video receiver with S = -70 dbm, A_r = 5 db, and h_T = 130 feet

SUMMARY AND CONCLUSIONS

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If an over-water path and average atmospheric and weather conditions are assumed, normal tropospheric scatter seems to start in the defraction zone, about 50 db below free

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space and has an attenuation rate of about 0.2 db per nautical mile. Most of the literature indicates that this definition for the scatter region is approximately accurate for the frequency range of 100 to 4000 Mc. Enough measurements have not been taken above 4000 Mc to define this scatter region accurately. To allow for variations in meteorological conditions, two additional scatter zones were defined with one 10 db above the normal scatter region, and the other 10 db below. By utilizing this propagation information together with the probability of intercept raw data, it was possible to compare the probability of intercept capabilities of various receiver systems when operating against an AN/APS-20 radar for the propagation conditions confronting fleet operations most of the time.

If the radar and receiver antennas scan 360 degrees and the radar operates continuously, a receiver of the AN/WLR-1 type has a higher probability of intercept when utilizing an omnidirectional antenna with a gain of 5 db than when using an AN/SLA-3 fast-scanning directional antenna. The probability of intercept advantage with the former antenna is much more pronounced for a ship-to-ship intercept path than for a ship-to-aircraft intercept path. Having the radar transmitting intermittently or the directional receiver antenna sector scanning can greatly decrease the advantage of the omnidirectional antenna, and if carried to extremes can at least equalize the systems. Since the time for obtaining bearing information is negligible compared to time needed for intercept with the omnidirectional antenna, it can be said that for general operating conditions it would be advantageous to have the AN/WLR-1 incorporate both an omnidirectional antenna and a directional antenna especially when operating over a ship-to-ship intercept path. An AN/WLR-1, which has the omnidirectional antenna and a sensitivity of -85 dbm, has a higher probability of intercept under all conditions than a DF crystal video receiver which has -50 dbm sensitivity. The latter receiver has the obvious advantage of simplicity while the former has the usual advantages of a rf-tunable superheterodyne receiver such as: good image rejection, minimization of spurious responses, good signal reproduction and signal resolution, and better sensitivity, so that chance intercepts at extended ranges are possible.

Since it is contemplated that most future radars will operate on an intermittent basis, it is necessary to increase the receiver sensitivity so that intercepts in the scatter region will be assured within one rotation of the radar antenna. This requirement is necessary if a countermeasures intercept system is to have an appreciable advantage in range over a search radar. It is difficult to obtain the necessary improvement in sensitivity for the AN/WLR-1, but the order of sensitivity needed for a crystal video receiver can be approached by utilizing a traveling-wave tube as a rf amplifier. A DF crystal video receiver with a sensitivity of -75 dbm will intercept signals from an AN/APS-20 in the normal scatter region after one rotation of the radar antenna when the radar antenna height is 130 feet. This receiver has the added advantage of being capable of determining bearing information in the scatter zone, but has the inherent disadvantage of any wide-open system of signal clutter in a high-density signal area.

An effective radar countermeasures receiver should be capable of intercepting signals in the scatter zone after a few rotations of the radar antenna together with giving high signal resolution and good signal reproduction. Since these features cannot be efficiently incorporated in a receiver system which utilizes either rf-tunable superheterodyne or crystal video techniques exclusively, a countermeasures receiver system should consist of both a highly sensitive DF crystal video receiver and the AN/WLR-1 receiver. The individual receivers could be used in conjunction with each other or independently, depending upon the operation conditions. This is assuming, of course, that present TWT design techniques are adequate to permit a practical design of a DF crystal video receiver.

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ACKNOWLEDGMENT

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