DECLASSIFIED

UNCLASSIFIED

[redacted]

NRL REPORT 3815

FR-3815

A LOW-FREQUENCY RADAR OF MODERN DESIGN

DECLASSIFIED by NRL Contract
Declassification Team
Date: 1 Feb 2017
Reviewer's name(s): H. Do, P. Hanna
Declassification authority: NAVY DECLASS GUIDE / NAVY DECLASS MANUAL, 11 DEC 2012, OP SERIES

DISTRIBUTION STATEMENT A APPLIES.
Further distribution authorized by UNLIMITED only.

NAVAL RESEARCH LABORATORY

WASHINGTON, D.C.

[redacted]

UNCLASSIFIED

[redacted]

DECLASSIFIED

[redacted] UNCLASSIFIED DECLASSIFIED

NRL REPORT 3815

UNCLASSIFIED

A LOW-FREQUENCY RADAR OF MODERN DESIGN

W. F. Main and W. S. Alderson

May 29, 1951

UNCLASSIFIED

UNCLASSIFIED

Approved by:

R. C. Guthrie, Head, Search Radar Branch
L. A. Gebhard, Superintendent, Radio Division II

NAVAL RESEARCH LABORATORY

CAPTAIN F. R. FURTH, USN, DIRECTOR

WASHINGTON, D.C.

UNCLASSIFIED

[redacted] DECLASSIFIED

DISTRIBUTION

OpNav	
Attn: Code Op-374	1
Attn: Code Op-42	2
Attn: Code Op-421G	5
ONR	
Attn: Code 470	2
BuShips	
Attn: Code 820	10
CO & Dir., USNEL	2
Attn: Code 470	1
CDR, USNOTS	
Attn: Reports Unit	2
Supt., USNPGS	1
CDR, NATC, Patuxent River, Md.	
Attn: Electronics Tests	1
CDR, NADC	1
Wright-Patterson AFB	
Attn: BAU-CADO	1
Attn: CADO-E1	2
Attn: Ch., Electronics Subdiv., MCREEO-2	1
Attn: Code MCREEP	1
Attn: Eng. Div., Project RAND	1
Ch. of Staff, USAF	1
CG, SCEL	
Attn: SCEL Liaison Office	3
OCSigO	
Attn: Ch. Eng. & Tech. Div., SIGTM-S	1

UNCLASSIFIED

CONTENTS

[redacted]

DECLASSIFIED

ABSTRACT

Since the latter portion of World War II, the major air-search radar systems have been operated at a frequency of 1300 Mc. Fleet evaluation studies of these radars indicated that systems operating at this high frequency failed to detect high-altitude targets dur ng periods of abnormal propagation, while the old low-frequency radars were not affected.

A new radar system with an antenna small enough to permit installation on destroyers is to be constructed to operate at a frequency of 420-450 Mc. Tubes are available for this radar which will permit a transmitter peak power of 1.5 megawatts and a receiver noise figure of 5 decibels.

The theoretical performance of this radar has been studied in terms of the cumulative probability of detection for a radially flying target. For a one-square-meter target at 50,000 feet, the 0.9 cumulative probability of detection is reached at a range of about 250 miles. These studies showed that there is a severe loss in detection range if the radar is operating only a few decibels below optimum. As an aid in maintaining the radar near peak performance, test equipment for the measurement of radar performance will be installed as an integral part of the system.

PROBLEM STATUS

This is an interim report, work is continuing.

AUTHORIZATION

R02-55D
NE 050-515
BuShips S-1560

Manuscript submitted fcr publication: March 13, 1951

[redacted]

DECLASSIFIED

[redacted]

DECLASSIFIED

UNCLASSIFIED

A LOW-FREQUENCY RADAR OF MODERN DESIGN

INTRODUCTION

Starting about the latter part of World War II, the radio frequency for Naval primary air-search radar systems was shifted from 200 to 1300 Mc. The AN/SPS-6 series (1944) of radar equipments was designed for operation at this frequency in shipboard installations. Evaluation studies of these systems were made by the Operational Development Force (OpDevFor) (1-6).

On the whole, the performance of the AN/SPS-6B was said to be good; however, a serious fault was reported by OpDevFor for the 1300-Mc systems. Surface trapping was quite often noted, as evidenced by the long-range detection of surface targets, and during these instances, it was reported to be impossible to detect high-altitude aircraft. In addition, the echo-return from storms was of such amplitude that it was not possible to track aircraft through the storm area.

It was further noted that the SK-2, at 200 Mc, was unaffected during periods when the 1300-Mc radars were reported to be disabled owing to abnormal propagation conditions. The Operations Evaluation Group of the Office of the Chief of Naval Operations recommended that consideration be given to the study of propagation conditions which resulted in this behavior. Since the SC-SK series of radars is obsolescent, they also recommended that a new low-frequency radar system be developed (7).

On 21 September 1950, Problem Number R02-55D was initiated at the Naval Research Laboratory under Bureau of Ships sponsorship for a study of the characteristics of the low-frequency spectrum to determine an optimum frequency for use with an air-search radar, with particular attention to the problem of selecting a frequency which will be least affected by abnormal atmospheric conditions. Also called for is the construction and shipboard test of a radar which will operate at this optimum frequency.

This new radar will be used to determine the capabilities of a low-frequency radar of modern design. Comparisons will be made between the performance of this system and the performance of the higher frequency systems. In order that this set may eventually be used on ships of the DD class, the Bureau of Ships has placed rather stringent limits on the maximum top-side size and weight. The maximum turning radius and weight of the antenna shall not be appreciably greater than those of the AN/SPS-6B — 8.5 feet and 1000 pounds. Reliability and simplicity are to be stressed, and at the same time the design is to be one which will afford the maximum reliable range permitted by present-day components and techniques.

[redacted]

DECLASSIFIED

CHOICE OF FREQUENCY

Background

During World War II, the majority of air-search radars were operated with radio frequencies of around 200 Mc, but in the latter portion of the war, emphasis was placed upon the development of 3000-Mc radars for this same purpose. This shift from the low to the high frequency was proposed to eliminate many of the disadvantages of operation in the lower bands. Due to the limitation of physical size of the antennas, the minimum horizontal beamwidth which can be achieved at the low frequencies is about 16 degrees. With such low azimuth resolution, operator confusion frequently occurs when a number of targets are visible in an area. In addition, the maximum of th first lobe due to sea-reflection interference is at an angle of about 0.6 degree above the horizon for normal antenna heights. This prevents the detection of low-altitude aircraft until they have closed to a short range (but it also reduces the echo return from sea clutter). Further, the fade zones — or nulls in the interference pattern — are of such great extent that the amount of data obtained on a target may be low, since it is possible for an aircraft to remain in a null area for a great number of miles.

All of these faults may be corrected by simply increasing the operating frequency of the radar. For a given physical size of the antenna, the resolution increases as the frequency increases. The maximum of the first lobe of the interference pattern approaches the horizon, permitting the detection of low-altitude aircraft at greater ranges. The higher angle maxima are close together, so the aircraft cannot remain in a null for an appreciable time.

Another factor also favors the choice of the higher frequencies. For the transmission of power to the antenna in the low-frequency systems, pressurized-gas or dielectric-filled coaxial line is used, and neither of these is wholly satisfactory. Gas-tight seals are difficult to obtain and maintain in the pressurized line. The dielectric-filled cable produces excessive attenuation, and connections to it are difficult to make. In addition, neither type of line is capable of handling the increasingly higher powers which are necessary for long-range radars. In the microwave region, the use of waveguide for power transmission is practical. For a shipboard system, the installation of the waveguide is simple, the maintenance problem is practically nonexistent, and very great power may be transmitted.

Microwave frequencies had not been used for air-search radars early in the war period because of the limited power which could be generated. During the latter part of the war, magnetron tubes were made available which were capable of generating microwave power at a high average and a high peak level.

During 1945, a study was conducted by NRL in an attempt to determine the optimum frequency for use with a height-finding air-search radar (8). When all of the factors were weighed and summed, the curve of "excellence" vs. frequency had a broad maximum with a center near 1300 Mc. There was a radar set available which operated at this frequency—the Marine Corps AN/TPS-1B. Operational tests of this equipment had been made at the Chesapeake Bay Annex of this Laboratory, and the results tended to confirm the superiority of this frequency (9). This NRL study and additional studies made at other laboratories indicated a general superiority of the 1300-Mc band for air-search radar. As a result, the subsequent major developmental long-range radar equipments have been designed to operate at this frequency.

Recent developments in magnetron tubes have indicated that it is possible to obtain r-f power output of the order of ten megawatts at this frequency, and waveguide to transmit this power is of reasonable size. Receiver components have been built which show that it is possible to obtain receiver noise figures of less then ten decibels.

If it is necessary to obtain a certain azimuth resolution (which determines the antenna beamwidth), and the antenna diameter is restricted to a maximum of 40 feet, this restriction, taken with the previously mentioned developments, indicates that a long-range search radar which is constructed to operate near 1300 Mc will surpass a radar built in any other frequency region. As the frequency is raised progressively above 1300 Mc, various losses increase, and it becomes more difficult to obtain high transmitter power. As the frequency is progressively lowered, the restrictions on the physical size of the antenna limit the performance by loss of resolution, and the lowered frequency causes a loss of coverage in regions near the horizon and a loss owing to the increased time that a target may remain in a null zone. In addition, the impractical size of low-frequency waveguide dictates the use of other means for the transmission of power which then limits the maximum power which may be transmitted.

The Westinghouse Manufacturing Company developed the SR-3, a shipboard radar which operated at 1300 Mc. Unfortunately, in an effort to decrease the top-side weight, the antenna aperture was made small, and the results from this set were far from satisfactory (10). A redesign of the system and the antenna resulted eventually in the AN/SPS-6, -6A, and -6B. These sets differed from each other only in the shape of the antennas. The first employed a simple paraboloid possessing a vertical beamwidth of 10 degrees; the second and third, cut dishes producing vertical beamwidths of 20 and 30 degrees, respectively. Evaluation studies were made of these sets by the Operational Development Force (1-6).

As has been stated, the performance of the AN/SPS-6B was good, on the whole. It was noted, however, that during times of abnormal propagation, high-altitude targets were not detected. At the same time, the SK-2, at 200 Mc, was able to track the high-altitude aircraft with no reduction in performance. This apparent disadvantage of the high frequency system would outweigh any advantage which it might possess.

Abnormal Propagation

A search of the literature was made to see if light could be thrown on this problem, with particular reference to any report which would indicate whether this fault had been noticed in any other system, and to what extent abnormal propagation affected the performance of radar systems.

Soon after the Fleet installations of radar systems, it was noticed that during certain periods surface targets were detected at abnormally long ranges.* As the very high frequencies came into use, the effects of anomalous propagation became more pronounced. A great many theoretical and experimental studies were made in an attempt to determine the meteorological conditions which resulted in trapping (11-14). It was established that the trapping was a function of frequency — as the frequency increased, the probability of trapping increased. However, trapping, as evidenced by the increase of detection range on surface targets, has been observed at the lowest frequencies which have been employed in radar systems. As an example, with 200-Mc ground radar overlooking the Indian Ocean, the British reported ranges of up to 1500 miles on ship targets (14). Data recorded from radar sets on 200 and 3000 Mc in the New Zealand area indicate that abnormal ranges are obtainable during a great percentage of the year.

* Within two months of the permanent installation of 200-Mc radar systems in the U.S. Fleet (October 1940), the USS YORKTOWN reported detection of a destroyer target at 70 miles and the California mountains at 450 miles.

In general, abnormal propagation will occur at least a portion of the time with any radar set, regardless of the frequency. From the limited amount of data available, the frequency which will be least affected by abnormal atmospheric conditions will be the lowest frequency. This observation is not universal, however, for there are reports from certain areas in which trapping occurs for a great percentage of the time regardless of the frequency.

In the foregoing discussion, it has been tacitly assumed that during periods of surface trapping the majority of the energy available from the radar set has been diverted to follow the surface of the earth, and thus, the high-altitude coverage would suffer. This premise is vigorously contested by the propagation experts. It has been categorically stated that this is not true — that any loss in high-altitude coverage must be due to faulty radar performance and not atmospheric conditions (11-13). Extensive theoretical and experimental propagation studies have indicated that energy is trapped from the portions of the beam below one degree at a maximum, and generally from only the lower one-half degree. The energy which is radiated at angles higher than this is not affected, and therefore the high-altitude coverage of a radar should be unaffected during atmospheric conditions which result in trapping.

As has been stated, the reports by the Operational Development Force on evaluation studies made on the AN/SPS-6 series of radar sets do not agree with this. A preliminary investigation conducted by NRL tended to support the data obtained by OpDevFor (15). A sufficient amount of data has not been obtained to afford a good statistical sample, however, and it has been recommended that a complete investigation be conducted to obtain the required data.

This phenomenon — the loss of high-altitude coverage during periods of trapping — has been noticed by others. In an attempt to verify this behavior, the British conducted a lengthy series of experiments at Malta (16) using A.M.E.S. radar equipments Types 14 and 13 (10 cm) and Type 5 (200 Mc). The radar systems were carefully adjusted and calibrated before and after each flight to insure optimum performance conditions. Aircraft flights were conducted with a Lancaster bomber at altitudes of 500, 7000, 12,000, and 17,000 feet. Photographs were obtained of the PPI screens, and the amplitude of the target echo was recorded by pip-matching with a calibrated, pulsed signal generator. A large quantity of information was obtained, and the results indicated that "the radiation pattern above the low-level duct remains substantially unchanged." This is in agreement with the propagation theory.

There is reason for concern in view of these conflicting reports. The data gathered by OpDevFor indicates that the 200-Mc equipments were not affected by these abnormal weather conditions which trapped the energy from the 1300-Mc radars, so a course is open for the development of a new low-frequency system. The work on this system is to be carried on simultaneously with the investigations into the loss of high-altitude coverage by the 1300-Mc systems.

A possible explanation for the behavior of the 1300-Mc equipments is that, since the antenna is cut to produce a cosecant-squared pattern, the energy which is radiated at high angles is marginal even for an optimum adjustment of the radar. If the performance were below optimum, there would be insufficient energy radiated at these angles to enable high-altitude detection.

Choice of Low Frequency

At the time that this low-frequency radar was proposed, the only band which was available for use with a high-powered radar was the band 420-450 Mc. A service radio altimeter operates in this band, and it will be several years before the band is completely open for radar use. Permission has been recently granted for the operation of a radar in the additional frequency band 190-225 Mc. The lower portion of this band, 190-216 Mc, is to be used on a noninterference basis with television stations. This report will cover a radar which will operate in the band 420-450 Mc only; a later report will discuss the performance of a radar to operate in the frequency band 190-225 Mc.

It is known that there is nothing fundamentally wrong with the 420-450 Mc band, for there have already been radar equipments constructed which operated at, or near, these frequencies. The SR-2, built by RCA, operated in the band 550-660 Mc, and NRL constructed the SR-1(XBF-1) which operated in the band 400-425 Mc. An experimental radar operating between 420 and 450 Mc will be built and tested. It is thought that a radar system of high performance and reliability can be constructed to operate in this band.

The Operations Evaluation Group of the Office of the Chief of Naval Operation (OEG) has stated that the SR-2 has appreciably greater low-angle coverage than the SK-2, with little or no decrease in performance at the higher angles (17). The 420-450 Mc radar should exhibit much the same performance on low-flying targets.

Limited operational tests were conducted on the SR-1(XBF-1) which indicated that the performance was about seven decibels lower than anticipated; a B-24 target at 20,000 feet was detected at about 140 nautical miles (18). No attempt was made to determine the reason for the low performance level since the radar was abandoned by the Navy. However, the effect of the operator, writing speed losses, and scanning losses were not considered in the design calculations for this radar. It is also believed that a possible reason for the low performance is the fact that the receiver was not stable during the tests.

PREDICTION OF SYSTEM PERFORMANCE

OEG Method

In the design of radar equipment, use is made of the well-known radar range equation. In an effort to obtain a more complete description of the detection capabilities of a radar system, the Operations Evaluation Group has made a series of statistical studies of the received target-echo signal strengths for various types of targets on existing radar equipments. This group takes into account the fact that the target echoing area is not a constant value (as assumed in the more conventional form of the radar range equation) but rather one that fluctuates in a random manner. In addition, OEG takes into consideration the fact that the operator is not perfect—there is a possibility that the operator will fail to observe a blip when it is sufficiently large to be apparent upon the oscilloscope. Both the fluctuating echo signal strength (so-called "scintillation") and the effect of the operator have been treated in a statistical manner, and the method for the determination of maximum reliable detection ranges has been specified.

For their studies, OEG constructs an experimental blip-scan curve from radar data obtained during a measurement composed of a great number of radial target runs during which the operator knows the position of the target. The blip-scan ratio, Ψ, is the probability that the echo will, during a given scan past a target, exceed the threshold signal value* for the receiver. This blip-scan ratio is multiplied by what OEG terms the "operator factor," P_o, which enters because under normal search conditions the operator is unaware of the target position. The operator factor, considered by OEG to be a constant, is the probability that the operator will see the target blip if it exceeds the threshold signal

* For a definition of threshold signal, see Reference 20 or Reference 21.

level and is presented upon the oscilloscope. The product of these two factors, then, is the probability that the echo from a randomly positioned target will be detected on a single particular scan, or look.

If $P_o\Psi$ represents the probability of success on a given look, the difference between this term and unity represents the probability of failure to detect the target on that look. The cumulative probability of failure may be obtained by computing the product of the successive probabilities of failure. The difference between this quantity and unity will be the cumulative probability of success — or detection — and if it is plotted against range, a curve results which will enable one to determine the cumulative probability of detection at any range for a particular radar.

To determine the value of P_o, a second measurement is made, again composed of a great number of radial target runs. These runs are made under actual searching procedure during which time the operator is unaware of the target position. Under these conditions, the curve for probability of detection may be constructed from the actual ranges at which the target was detected. A value of operator factor is then chosen which will permit the experimentally determined values of Ψ to fit the actual operational performance. The operator factor, seen to be a curve-fitting constant, has had values ranging from very low to as great as unity, depending on the type of radar. For high-frequency radar sets with good azimuth resolution, the target blip is small and is often confused with receiver noise, weather return, and false echoes; for these sets, the value of P_o is small. For the low-frequency radars the oscilloscope is relatively free from interfering blips, and, with low azimuth resolution, the target blip is a long arc; the value of P_o for these sets is generally high — often as large as unity.

In order to fit the operational results to the constructed curve, OEG considers conditions which it calls the "single-blip" case and the "double-blip" case. The single-blip condition results when the operator is immediately able to identify a blip as a target. If it is necessary to obtain a confirming blip on the next scan in order to identify a target positively, the double-blip condition exists. The probability, Ψ', that the target echo will exceed the threshold value on two successive scans is the product of the two successive values of Ψ. The value of the double-blip Ψ' may be multiplied by an appropriate operator factor, and, from this product, a curve may be constructed for the cumulative probability of detection for the double-blip case.

The low-frequency radars, with low azimuth resolution and an oscilloscope presentation free from interference are generally in the single-blip category. The high-frequency radars — where the reverse is true — are generally in the double-blip class.

Target Characteristics

The use of the radar range equation requires the assignment of a particular radar cross section, or effective area, to the target. Actually, a radar target — with dimensions greater than the wavelength of the illuminating radar — may be regarded as a group of separate reflecting areas. An aircraft in flight does not present a constant aspect to the radar but rather, because of yawing and pitching, an aspect which varies continuously in a random fashion. This random motion of the aircraft target varies the magnitudes and positions of the reflecting areas with respect to the radar, and to each other, and thus varies the strength of the received signal in a random manner. For a propeller-driven aircraft, the relative position of the propeller also influences the signal strength. In general, the signal strength varies about some median value. These signal-strength fluctuations (scintillations) have been measured for various aircraft targets by measuring the variation in pulse amplitude from pulse to pulse (19).

In order to predict the performance of a radar, however, a knowledge of the magnitude of scintillation from scan to scan is necessary. This scintillation curve (Figure 1) has been obtained by two methods. For the first, an experimental curve was constructed at this Laboratory for a two-plane target from the limited amount of raw radar data available in portions of OEG and OpDevFor reports. For the second, a curve was constructed mathematically (Rayleigh distribution) by making certain assumptions about the nature of the target and the character of the reflected pulses. The derivation of this second curve is contained in Appendix I.

Radar Characteristics

Also needed for predicting the performance of the radar is a knowledge of the system parameters. Recent component developments have indicated that the following characteristics may be achieved, and these will be assumed for the proposed system:

P_t = Peak Transmitter Power = 1.5 megawatts

F = Pulse Repetition Frequency = 300 pulses per second

τ = Pulse Length = 5 microseconds

B = Receiver Bandwidth = $1/\tau$ = 200 kilocycles

NF = Receiver Noise Figure = 5 db over kTB

G = Antenna Gain = 100, or 20 db over an isotrope

θ_h = Horizontal Beamwidth $\doteqdot$ 10 degrees

θ_v = Vertical Beamwidth $\doteqdot$ 36 degrees

λ = Wavelength = 69.8 cm

Indicator: PPI

Polarization: Horizontal

The scan rate for the system is one of the varied parameters; the choice of this factor will be given in the next section.

Performance Calculations

Since a PPI indicator is to be used for the 420-450 Mc radar, the visibility factor must be computed. This factor and scan loss were obtained by extrapolation from experimentally determined curves (20, 21). The target was chosen to have a radar area of one square meter, which is assumed to be the median value of the scintillation.

From the radar characteristics, visibility factor, scan loss, and the median value of the radar area, a range was computed by use of the radar range equation. This range is the range at which the blip-scan ratio is 0.5. Using the Universal Lobe-Pattern Nomograph (Appendix II), lobes were constructed on a range vs. expanded-height chart.

Using the experimental scintillation characteristic given in Figure 1, the ratios of the range R_o for 0.5 blip-scan ratio to the ranges of the other blip-scan ratios were obtained in 0.1 increments. The lobe structures corresponding to these blip-scan ratios were also drawn in on the chart. This chart, a sample of which is given in Figure 2, consists of a set of lobe patterns, each of which corresponds to a particular blip-scan ratio, Ψ.

Now, if a target velocity of 500 knots is assumed, a set of points may be constructed on a particular altitude line; the distance between adjacent points is the product of the target velocity and the scan time. In other words, each point represents the target position at the time that the antenna is pointing at it. Further, to each point of position may be connected a particular blip-scan ratio, Ψ, depending upon the position of the point with respect to the blip-scan lobe structure. Progressing from point to point along the constant altitude line, a tabulation of the successive blip-scan ratios may be obtained. By assuming values for the operator factor, P_o, a cumulative-probability-of-detection curve for the particular altitude may be constructed.

It is felt that the frequency of the 420-450 Mc radar is sufficiently low and the beamwidth sufficiently large to allow it to be classed with the "low-frequency radars"; i.e., it would be characterized by a high operator factor and would most likely be in the single-blip class. However, curves have been constructed for both the single- and double-blip cases with operator factors of 0.25 and 0.5. It is felt that the most likely values for detection ranges are obtained with the single-blip case and an operator factor of 0.5.

Cumulative-probability-of-detection curves have been computed for antenna rotation speeds of 5, 10, and 15 rpm, and various target altitudes. The altitude increment was 10,000 feet, and heights up to 50,000 feet were considered. The curves of the results are contained in Figures (3) through (28).

Additional sets of curves were obtained by considering the performance of the radar to be down from the optimum value by factors of 7 and 12 decibels. This was done to estimate the degradation of performance that might occur through faulty adjustment and maintenance. The assumed degradation values were chosen arbitrarily, but losses of this order of magnitude are typical for Fleet operation.

All of the curves referred to thus far were constructed on the basis of the experimentally determined scintillation characteristic.

Now, using the calculated scintillation characteristic (blip-scan curve) given in Figure 1, an antenna speed of 10 rpm, an operator factor of 0.5, and the single-blip case, a new set of cumulative probability curves was computed. Since the calculated characteristic differs from the experimental one mainly for low blip-scan ratios, it is seen that the use of this calculated blip-scan curve would tend to decrease the range for the 0.1 blip-scan ratio from that obtained using the experimental curve. For the radar operating at optimum performance, the use of the calculated blip-scan curve would affect the cumulative probability values at the highest altitudes only. For a P_o of 0.5, the target is detected in the first lobe; with P_o of 0.25, the target is detected in the second lobe. If the performance is assumed to be down several decibels, however, the use of the calculated curve will affect the values for nearly all altitude levels, so cumulative probability curves based on the calculated blip-scan curve were plotted for the 7-db-down and 12-db-down conditions only (Figures 29 and 30).

Discussion of Results

All probability-of-detection curves show that the range for 0.9 probability, for a target closing in range, increases when the antenna rotation speed is increased. It is known, however, that operator fatigue is experienced for antenna speeds greater than about 15 rpm, so the increase in range at this antenna rate might be affected by this factor. The range for 0.9 probability of detection for the antenna rate of 10 rpm is significantly superior to the corresponding range for a 5-rpm rate (see Figure 31, which is a composite of Figures 15, 16, and 17). The antenna speed for the 420-450 Mc radar has therefore been chosen to be 10 revolutions per minute.

The cumulative-probability-of-detection curves have been plotted for the different operator factors and are shown in Figures 3 through 28 with the antenna speed and altitude as parameters. In addition, the 0.9 probability contour has been shown for each of the conditions on the expanded-height vs. range charts of Figures 32 through 36. The ranges on the even 10,000-foot altitude lines are the calculated values; those on intermediate points are estimated.

It is seen that if the radar operates at peak performance, and the experimental scintillation characteristic of Figure 1 is valid, the altitude coverage is excellent. The range for a one-square-meter target at 50,000 feet is 250 miles, assuming an operator factor of 0.5 and the single-blip condition. For an operator factor of 0.25, this range drops to 240 miles. For the double-blip condition, the range for 0.9 probability of detection is about 200 miles for an operator factor of 0.5, and 180 miles for a P_o of 0.25.

For the conditions where the one-square-meter target is at 50,000 feet, the single blip applies, the performance is 7 decibels down from the optimum, and with an operator factor of 0.5, the range is about 200 miles. With an operator factor of 0.25, the range is about 185 miles for the single-blip case.

For the condition where the performance is down by a factor of 12 decibels from the optimum, with an operator factor of 0.5, the range for 0.9 probability is about 150 miles for the single-blip case and 110 miles for the double-blip. For an operator factor of 0.25, this range is about 100 miles for the single-blip case and 80 miles for the double-blip.

As has been stated, it is felt that the most probable value for operator factor is 0.5, and it is thought that the single-blip condition will apply. Under these circumstances, the curves of Figures 4, 16, 25, 29, 30, 32, and 36 would apply.

It is interesting to consider the performance of the 420-450 Mc radar with an antenna comparable in size to that employed with the SK radar. The SK antenna is roughly 17 feet square, or of an area slightly more than three times greater than that of the AN/SPS-6. An antenna this size would have a gain of about 25 db, or 5 db more than the antenna of the proposed system. This would amount to an improvement in system performance of 10 db and would permit the use of the predicted range curves on a target of an area of only 0.1 square meter!

As has also been stated, the performance of shipboard radar systems generally falls much below the figure which is obtained by calculation from the radar range equation. The serious loss in detection range when the performance of the set is several decibels below optimum is readily seen by a comparison of the sets of curves. The transmitter power of this radar will be the maximum which can be generated and transmitted with available components, and the receiver is to be operated at the minimum noise figure which can be attained. Even so, with modern, high-speed attacking aircraft, the maximum possible detection range will afford a warning time which is just barely adequate. In order to prevent — or at least minimize — deterioration in the performance of the radar, means for the measurement of receiver sensitivity and transmitter power will be included as an integral part of the radar.

DESIGN OF MAJOR COMPONENTS

Antenna

The Bureau of Ships has requested that the antenna be of a size and weight not appreciably greater than that of the AN/SPS-6B. At 420-450 Mc, this size will provide an antenna with a gain of about 100, or 20 decibels, over an isotrope. The horizontal beamwidth will be of the order of 10 degrees; the vertical beamwidth, of the order of 36 degrees. Preliminary calculations have indicated that the vertical aperture will have to be greater than five feet — that employed for the AN/SPS-6B — and this will give a smaller vertical beamwidth and a greater gain. The antenna will be designed and measured using a scaled, high-frequency model. The final antenna will then be constructed from the model dimensions.

It is hoped that the antenna pedestal of the AN/SPS-6 radar may be employed, but the mechanical design of this pedestal limits the size of the coaxial line through the azimuth rotary joint to 1-5/8 inches. Whether this is sufficiently large to transmit the high peak power is not yet known.

Transmitter

Eitel-McCullough, Inc., of San Bruno, California, has developed the XM tetrode transmitting tube, which, according to advice from the Company, will provide a peak pulse power of 1.5 megawatts with a duty factor of 0.15% at 450 Mc.

A contract has been issued by the Naval Electronics Laboratory, San Diego, California, to Eimac for the design and production of an experimental plate-keyed oscillator and modulator employing this tube. Tentative specifications for the transmitter-modulator have been furnished to NEL.

The pulse length and repetition frequency were chosen to employ the maximum permitted duty factor of the tube within the limitations on pulse rate imposed by the maximum radar range. This maximum duty factor will be obtained with pulse length of five microseconds and a PRF of 300. The latter value will permit a maximum oscilloscope range of 250 miles with a comfortable margin of dead time for indicator recovery.

Since it may later become desirable to add MTI to this system, rather severe limitations have been imposed on the transmitter-modulator. The time jitter from an external trigger is to be less than 0.03 microseconds, the incidental frequency modulation during the pulse is to be less than 100 kc, and the amplitude variation from pulse to pulse is to be less than 1 percent.

Receiver

The Western Electric coplanar triode, Type 416-A, will make possible a receiver noise figure of approximately five decibels at 450 Mc. The use of an r-f amplifier preceding the mixer will provide sufficient gain to make the i-f noise figure relatively unimportant. The very high gain-bandwidth figure of this triode will permit the use of a fixed-tuned r-f stage of a bandwidth equal to the tuning range of the transmitter. A sharp tuned circuit in the mixer will be required to decrease image response. This circuit and the local oscillator will be the only adjustments required for receiver tuning, and they may perhaps be ganged.

Performance Monitoring Equipment

The Operational Evaluation Group has stated that the performance for shipboard radars is, on the average, down 15 decibels from that calculated from the radar range equation. Previous studies (18) of the performance loss in the Fleet have given figures of 6-7 decibels under typical conditions of operation and maintenance. These figures have been observed to be a function of the size of ship on which the radar equipment is installed (e.g.,the figures of 6-7 db down is typical of a radar installation on a cruiser). The degradation of performance has been noticed to be less for the larger ships, where there are greater numbers of technicians. (It is also believed to be greater in peacetime than in wartime.) Of great importance, then, is some sort of method for the measurement of radar performance. This measurement should be simple, and should require a minimum of the operator's time. All equipment for the measurement should be an integral part of the radar. It has been noticed in the past that while equipment was available on the ships for the measurement of performance, little use was made of it, apparently because it was not always available right at the radar equipment.

It is proposed, therefore, that on the 420-450 Mc radar, there be provision for the measurement of transmitter power output and for the measurement of receiver sensitivity. It should be possible to arrange these instruments so that the operator could throw two or three switches, read from "go no-go" types of meters or indicators, and thus determine whether the radar performance is optimum.

CONCLUSIONS

If long-range detection is the major requirement of a radar, it may be economically obtained by the use of a low-frequency radar provided that the sensitivity of the set is great enough to assure detection in the first lobe. If the target is not detected in the first lobe, a serious loss of detection range occurs, since the lobes are generally wide spaced. The early low-frequency radar systems did not meet this requirement of adequate sensitivity.

The performance is, theoretically, very good for the 420-450 Mc radar under the conditions when the operator factor is 0.5 and the single-blip case applies. For optimum adjustment of the radar, a radially traveling one-square-meter target will be detected in the first lobe for all target altitudes up to 50,000 feet. Even with the operator factor as low as 0.25, the 0.9 cumulative probability of detection will be achieved in the first lobe, with but a slight reduction in range.

If, however, the radar performance is below optimum by just a few decibels, the target probably will not be detected in the first lobe. The actual reductions in detection ranges resulting from lowered performance are shown best in Figures 32 and 33.

It is imperative, then, to provide means for the measurement of the radar performance to insure that the system will operate at a level near the optimum. Simple means for the measurement of transmitter power and receiver sensitivity will be included with this radar for the measurement of the radar performance.

ACKNOWLEDGMENT

The authors wish to thank Mr. L. V. Blake and Mr. A. A. Varela for their helpful suggestions and discussions.

***

[redacted]

DECLASSIFIED

APPENDIX I
Scintillation Characteristics

The experimental blip-scan curve shown in Figure 1 was obtained from meager data. It was prepared from the small amount of raw radar data available in some of the OpDevFor reports. The data itself suffers from the obvious defect of being obtained under conditions which were not ideal. Further, the data is not given in a quantitative form, and it is difficult to account for the effect of the antenna pattern on the signal strength. For these reasons, the validity of the experimental curve may be questioned. With this in mind, a different approach to the problem was made.

This Laboratory has obtained pulse-to-pulse echo strength data on aircraft targets by the use of continuously tracking radars (19). Where the data were sufficient to accept the statistical results, the variation in amplitude of the pulse followed a Rayleigh distribution.

A Rayleigh distribution of echo amplitude is explained by assuming that the target consists of a large number of randomly moving point targets. The instantaneous variation in the received electric field at the radar would follow a Gaussian distribution. The variation of the pulse amplitudes would be the same as that of the envelope of this field which has a Rayleigh distribution (22).

The distribution (Rayleigh) of pulse amplitude, V, is defined by the probability density function

$$P_V(V) = \frac{2V}{V_1^2} e^{-\frac{V^2}{V_1^2}} \quad \text{for } V > 0$$
$$= 0 \quad \text{for } V < 0 \qquad (1)$$

The radar target area, σ, is proportional to the square of the pulse amplitude.

$$\sigma = k^2 V^2 . \qquad (2)$$

Since the probability density of σ is related to that of V in the following manner:

$$P_\sigma(\sigma) = \frac{P_V(V)}{\left|\frac{d\sigma}{dV}\right|}, \qquad (3)$$

$$P_\sigma(\sigma) = \frac{1}{\sigma_1} e^{-\frac{\sigma}{\sigma_1}} \quad \text{for } \sigma > 0$$
$$= 0 \quad \text{for } \sigma < 0 \qquad (4)$$

where $\sigma_1 = k^2 V_1^2$.

The method used in predicting radar performance consisted, essentially, of computing the target area necessary for the radar to receive a minimum detectable signal for each point in space. Once the target characteristics were known, it was possible to calculate the probability of the instantaneous aircraft radar area exceeding this threshold

[redacted]

DECLASSIFIED

value — in other words, the probability of the aircraft presenting a recognizable blip on the radar scope. The cumulative probability of detecting a target flying toward the radar on a radial course was then determined numerically as stated in the body of this report.

The probability that the target area will be larger than σ is

$$\psi(\sigma) = 1 - \int_0^{\sigma} P_{\sigma}(\sigma)\, d\sigma .$$

Using $P_{\sigma}(\sigma)$ as given in Equation (4),

$$\psi(\sigma) = e^{-\frac{\sigma}{\sigma_1}} \qquad (5)$$

The median area of the target, σ_{50}, is defined as being the area which is exceeded 50 percent of the time, or

$$\psi(\sigma_{50}) = \frac{1}{2} = e^{-\frac{\sigma_{50}}{\sigma_1}}$$

$$\text{or} \quad \sigma_{50} = \sigma_1 \ln 2 ,$$

and Equation (5) becomes

$$\psi(\sigma) = 2^{-\frac{\sigma}{\sigma_{50}}} \qquad (6)$$

This equation is shown in Figure 1 plotted against a db scale. The reference is such that db = 10 log σ/σ_{50}.

Since a single blip on a radar scope represents the sum of a number of pulses, it is necessary to find the variation in effective σ rather than the pulse-to-pulse variation of σ. This requires a knowledge of the correlation of the pulses as a function of time and a knowledge of what determines the minimum detectable signal when the echo amplitude varies from pulse to pulse.

From general observations on A scopes, it appears that for low-frequency radars there is practically no variation in pulse amplitude during the illumination time of a single scan. Furthermore, there is practically no correlation from scan to scan. It is therefore assumed that there is no variation in pulse amplitude during the illumination time and that the Rayleigh curve represents the distribution of amplitudes from scan to scan.

***

APPENDIX II

Universal Lobe Pattern Nomograph

The radar equation for a flat earth is well known.

$$S_r = \frac{16 P_t G^2 \sigma \lambda^2}{(4\pi)^3 \; R^4} \sin^4 \left(\frac{2\pi h_1 h_2}{\lambda R} \right), \tag{7}$$

where S_r = Peak echo power received

P_t = Peak power transmitted

G = Gain of antenna over an isotrope

σ = Target area

λ = Wavelength

R = Range of target

h_1 = Height of antenna

h_2 = Height of target

The flat earth equation may be used for a curved earth by assuming that the plane of reflection is the radio horizon. (A reflection coefficient of unity is assumed, and is valid for horizontal polarization over water.) The effect of refraction may be compensated by using an earth with a radius 4/3 the true radius of the earth (13). This is a reasonably good approximation when the height of the target above the horizon is large compared to the antenna height.

Equation (7) may be used to find the contours showing constant probabilities of the target presenting a blip strong enough to be seen. First, minimum detectable signal, S_{min}, is calculated for the radar from its parameters (20). Then, using curves such as those in Figure 1 and a value of σ_{50}, it is possible to find a value of target area, σ_p, that will have the probability, P, of being exceeded. Inserting these into Equation (7) it is found that

$$\frac{R}{R_o} = \left| \sin \left[\frac{h_2/H_o}{R/R_o} \right] \right| = \left| \sin \phi \right| \tag{8}$$

where

$$R_o = \left[\frac{16 P_t G^2 \sigma_p \lambda^2}{(4\pi)^3 \; S_{min}} \right]^{\frac{1}{4}}$$

and

$$H_o = \frac{\lambda R_o}{4 h_1}.$$

Equation (8) then shows the locus of all points, (R, h_2), where P is the probability that the target presents a blip that is detectable.

When ϕ is equal to $(2n-1)\frac{\pi}{2}$ (where n is any positive integer), $\sin \phi = 1$, and

$$\frac{h_2}{R} = \frac{H_o}{R_o} (2n-1)\frac{\pi}{2} . \tag{9}$$

When h_2 and R satisfy Equation (9) they are said to lie on the maximum of the n^{th} lobe. Since ϕ is linear with respect to h_2, it is clear that all values of h_2 that satisfy Equation (8) (at a given range) lie at equal height increments, Δh, from the maximum of the lobes. This means it is only necessary to plot the lower half of the first lobe, since the other lobes and the top half of the lower lobe may be obtained from it as shown in the diagram below.

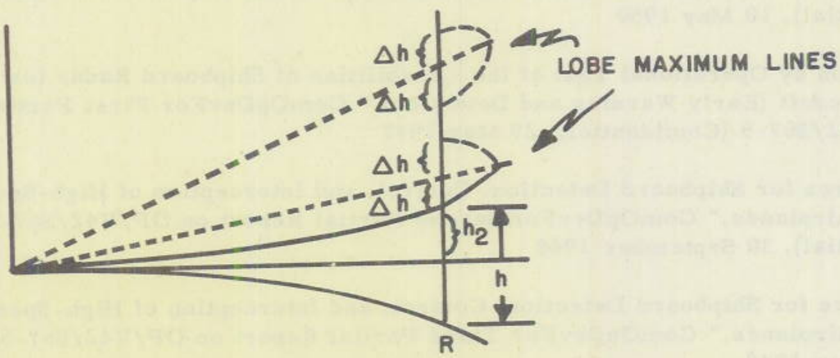

Figure 37 is a nomogram for finding points on the lower half of the first lobe. First calculate H_o and R_o and express these in any desirable units. Suppose H_o = 5000 feet and R_o = 170 miles. Choose one of the two fives on scale A and draw a line to point H_o on scale C. The intersection of this line with line B determines the height pivot-point. The lower five was chosen in the diagram and when the pivot-point so determined is used, scale A covers heights from 1000 to 100,000 feet. Draw a line from 1.7 on range scale F to R_o on scale D. The intersection of this line with line E determines the range pivot-point. When this pivot-point is used, scale F covers ranges from 100 to 1,000 miles. To find the value of h_2 that corresponds to a given R, draw a line from R on scale F (assumed to be 120 miles in this problem) through the range pivot-point to scale D. Then the diagonal lines are followed to scale C. A line is drawn from this point on scale C through the height pivot to the value of h_2 on scale A (1760 feet).

It is possible to use the chart for values of range less than 100 miles by finding another pivot-point. This is done by drawing a line from 1.7 on scale F to $0.1R_o$ on scale D. The intersection of this line with line E determines the new range pivot-point. When this pivot-point is used, the range scale varies from 10 to 100 miles. The illustration shows how to find the height corresponding to a range of 70 miles. It is necessary to find a new height pivot-point – this time by ruling a line from 5 on scale A to $0.1H_o$ on scale C, thus changing scale A to cover heights from 100 to 10,000 feet. The value of height corresponding to a range of 70 miles is shown as 555 feet.

***

[redacted]

REFERENCES

1. "Evaluation of AN/SPS-6 Radar," ComOpDevFor Final Report on OP/S137/S67-5 (Confidential), 10 March 1949

2. "Evaluation of AN/SPS-6A Radar," ComOpDevFor First Partial Report on OP/S141/S67-5 (Confidential), 22 August 1949

3. "Evaluation of AN/SPS-6B Radar," ComOpDevFor Final Report on OP/S142/S67-5 (Confidential), 10 May 1950

4. "Evaluation by Operational Test of the Capabilities of Shipboard Radar for the Control of Jet Aircraft (Early Warning and Detection)," ComOpDevFor First Partial Report on OP/V42/S67-5 (Confidential), 29 May 1947

5. "Procedures for Shipboard Detection, Control, and Interception of High-Speed, High-Altitude Airplanes," ComOpDevFor Second Partial Report on OP/V42/S67-5 (Revised) (Confidential), 30 September 1948

6. "Procedure for Shipboard Detection, Control, and Interception of High-Speed, High-Altitude Airplanes," ComOpDevFor Third Partial Report on OP/V42/S67-5, 7 November 1949

7. Lamar, E. S., "Long Wave Early Warning Radar," CNO, OEG Study 402 (Confidential), 21 September 1949

8. Varela, A. A., "Proposed Very Long Range Radar with Height Finding," NRL Report R-2759 (Restricted), 18 February 1946

9. "Operational Tests on TPS-1B," NRL Conf. Ltr. C-S67-5(536) to BuShips, 11 August 1944

10. Kingsbury, R. S., "Performance of SR-3 Radar Against Air Targets — An Analysis of ComOpDevFor Data," CNO, OEG Study 359 (Confidential), 7 June 1948

11. "Historical and Technical Survey," Summary Technical Report of NDRC, Vol. 1, 1946

12. "Wave Propagation Experiments," Summary Technical Report of NDRC CP, Vol. 2, 1946

13. "Propagation of Radio Waves," Summary Technical Report of NDRC CP, Vol. 3, 1946

14. "Meteorological Factors in Radio-Wave Propagation," Report of a Conference held on 8 April 1946 by the Physical Society and the Royal Meteorological Society

[redacted]

15. "Effects of Anomalous Propagation at Various Radar Frequencies," NRL Conf. Ltr. C-3460-52A/50 to BuShips, 16 August 1950

16. "An Investigation into the Effect of Anomalous Propagation on the High Altitude Coverage of Ground Radar Using AMES Types 13, 14, and 5," TRE Report T2112

17. "Airsearch Coverage Tests of SR-2 and SK-2 Radars," CNO, OEG Study 253, 5 March 1946

18. Varela, A. A., Chambers, T. H., and Lance, H. W., NRL Report R-2559, 1 June 1945

19. "Quantitative Measurements of Radar Echoes from Aircraft," NRL Conf. Ltr. C-3460-73A/50 emh to CNO, 24 October 1950

20. Ashby, R. M., Josephson, V., and Sydoriak, S., "Signal Threshold Studies," NRL Report R-3007, December 1946

21. Lawson, J. L., and Uhlenbeck, G. E., "Threshold Signals," Radiation Laboratory Series Vol. 24, McGraw-Hill, 1950

22. Landon, V. D., "The Distribution of Amplitude With Time in Fluctuation Noise," Proc. IRE, 30: 425-429, 1942

***

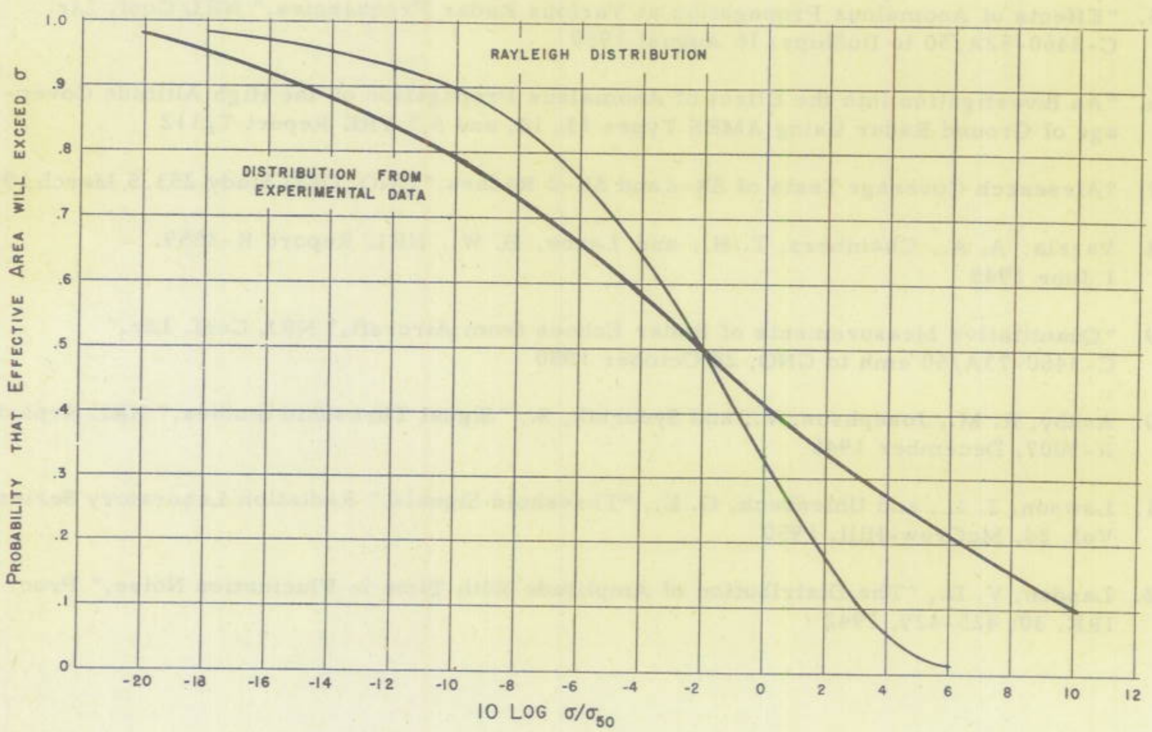

Figure 1 - Scan-to-scan scintillation characteristics

[redacted]

DECLASSIFIED

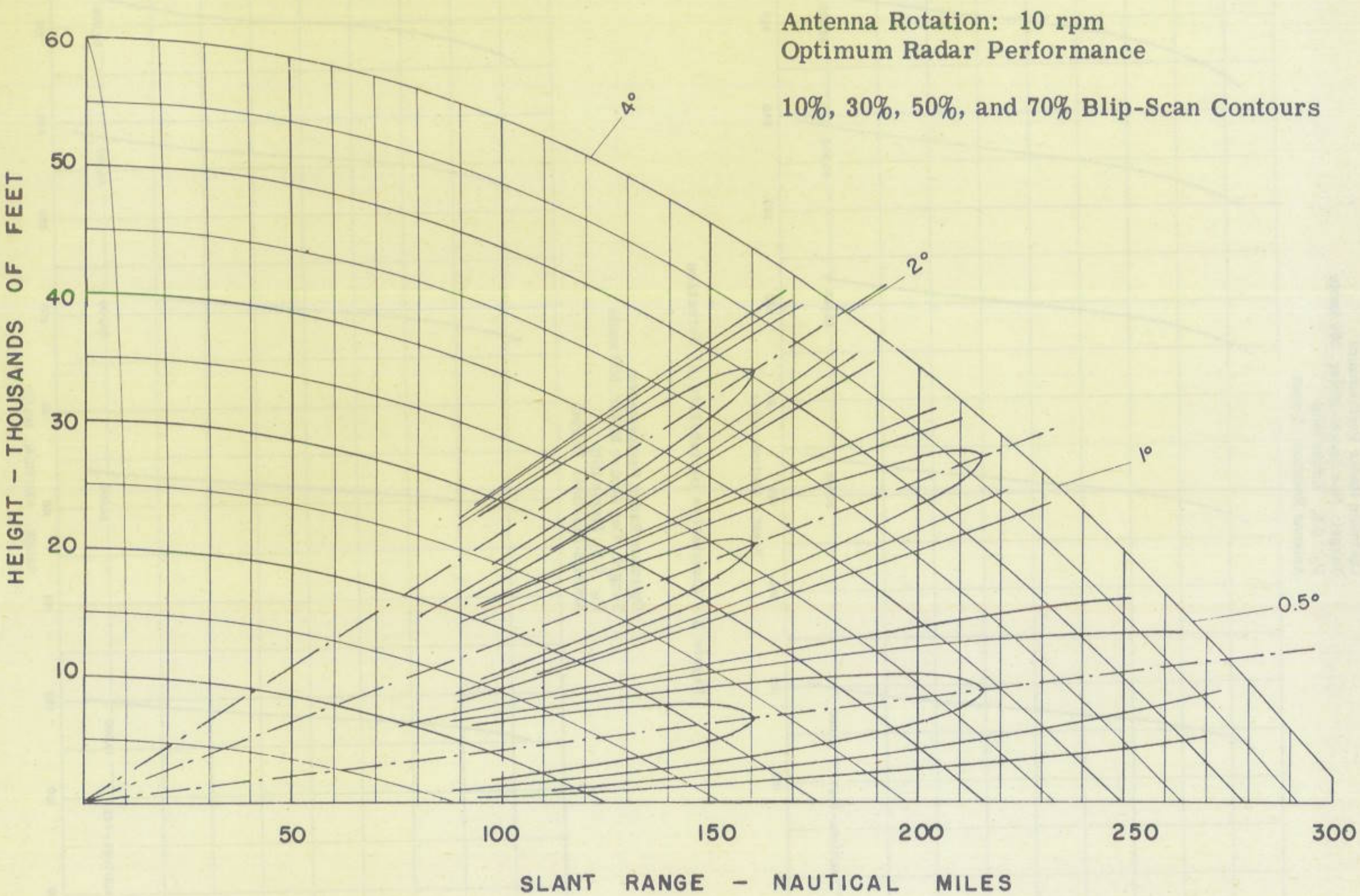

Figure 2 - Sample blip-scan lobe patterns

[redacted]

NAVAL RESEARCH LABORATORY

DECLASSIFIED

Optimum Radar Performance
Target: One Square Meter, 500 knots
P_0: 0.5; Single Blip
Antenna Rotation: 5 rpm

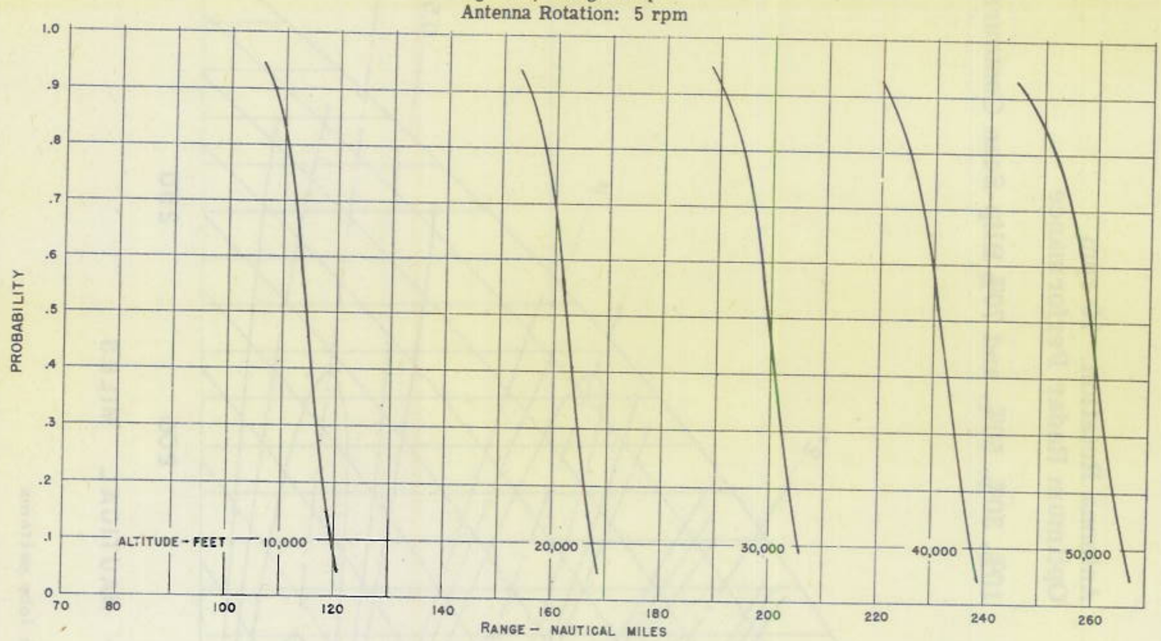

Figure 3 - Cumulative probability of detection

Optimum Radar Performance
Target: One Square Meter, 500 knots
P_0: 0.5; Single Blip
Antenna Rotation: 10 rpm

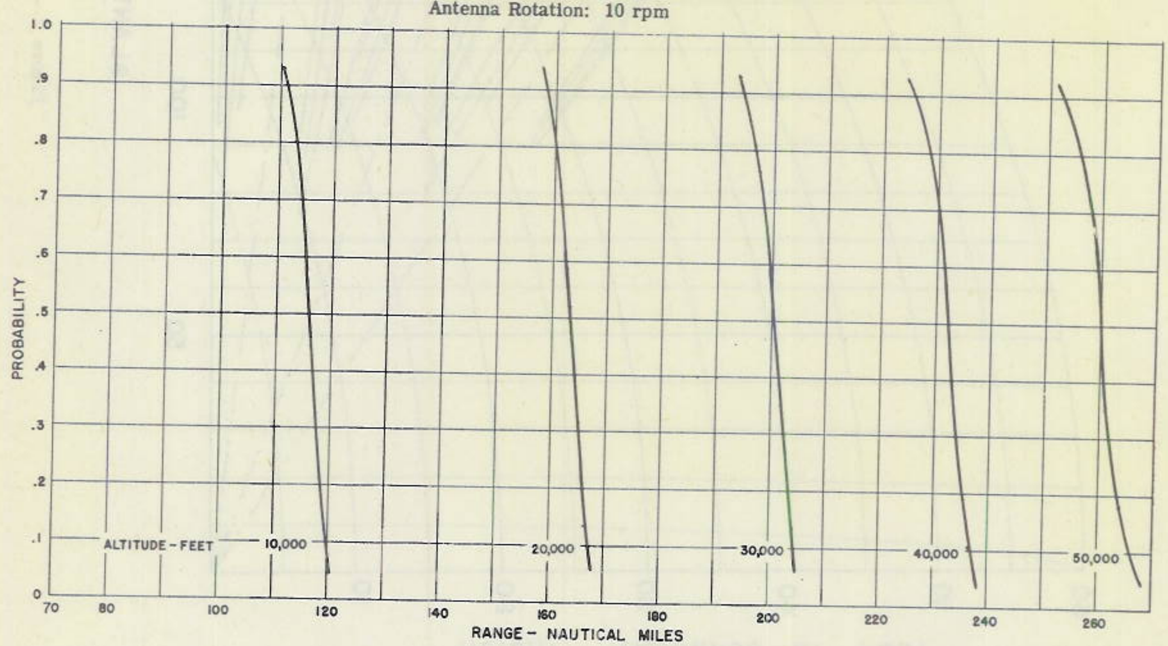

Figure 4 - Cumulative probability of detection

Optimum Radar Performance
Target: One Square Meter, 500 knots
P_0: 0.5; Single Blip
Antenna Rotation: 15 rpm

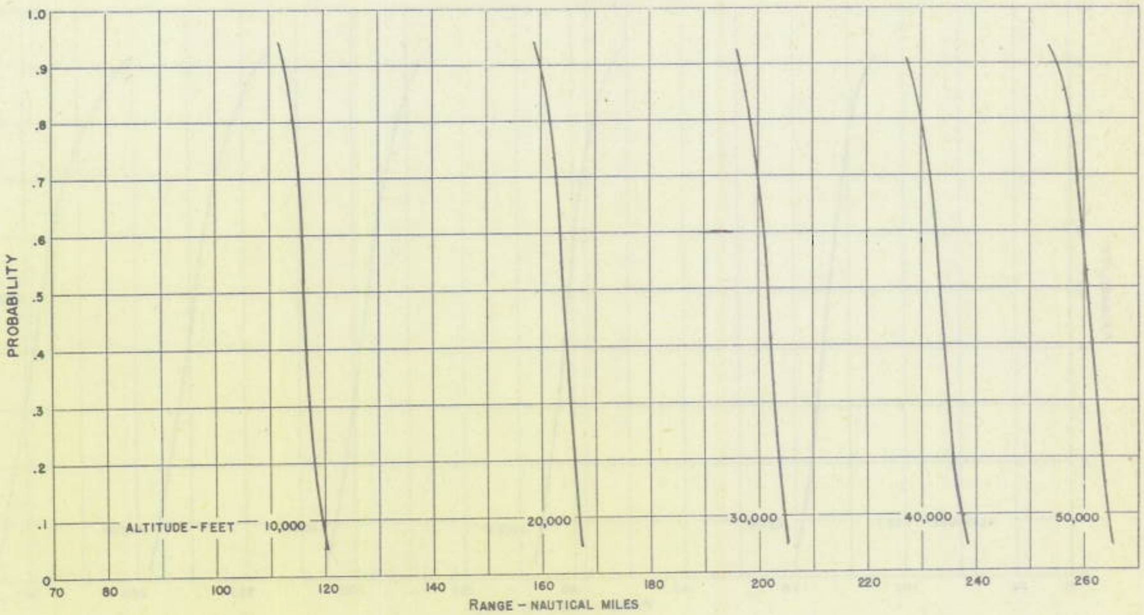

Figure 5 - Cumulative probability of detection

Optimum Radar Performance
Target: One Square Meter, 500 Knots
P_0: 0.25 Single Blip
Antenna Rotation: 5 rpm

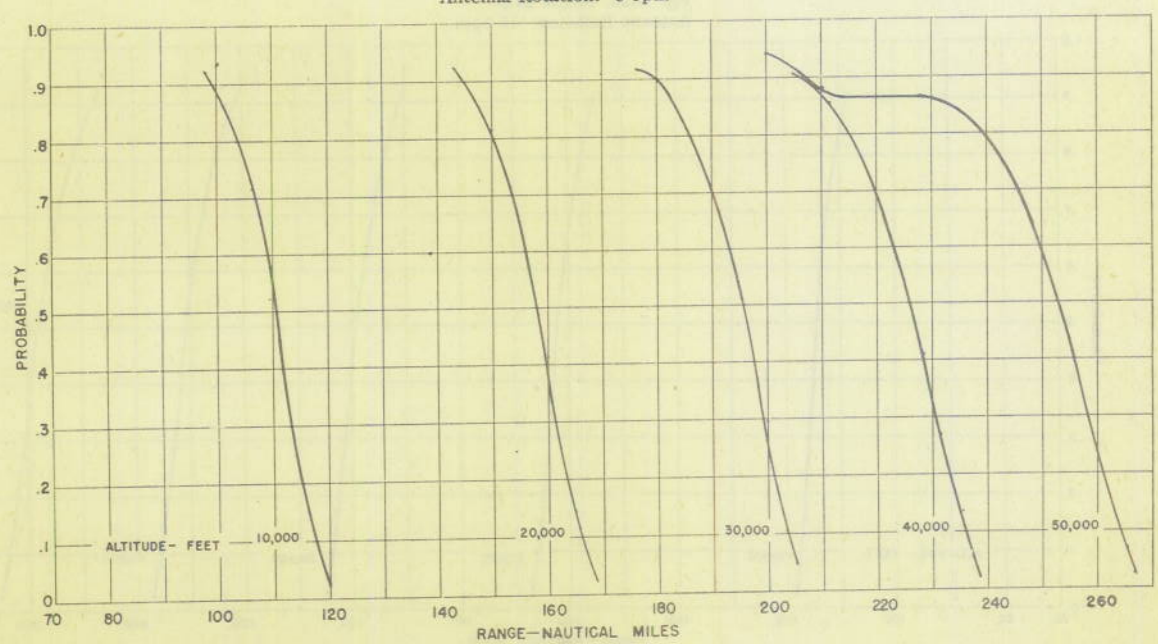

Figure 6 - Cumulative probability of detection

Optimum Radar Performance
Target: One Square Meter, 500 Knots
P_0: 0.25; Single Blip
Antenna Rotation: 10 rpm

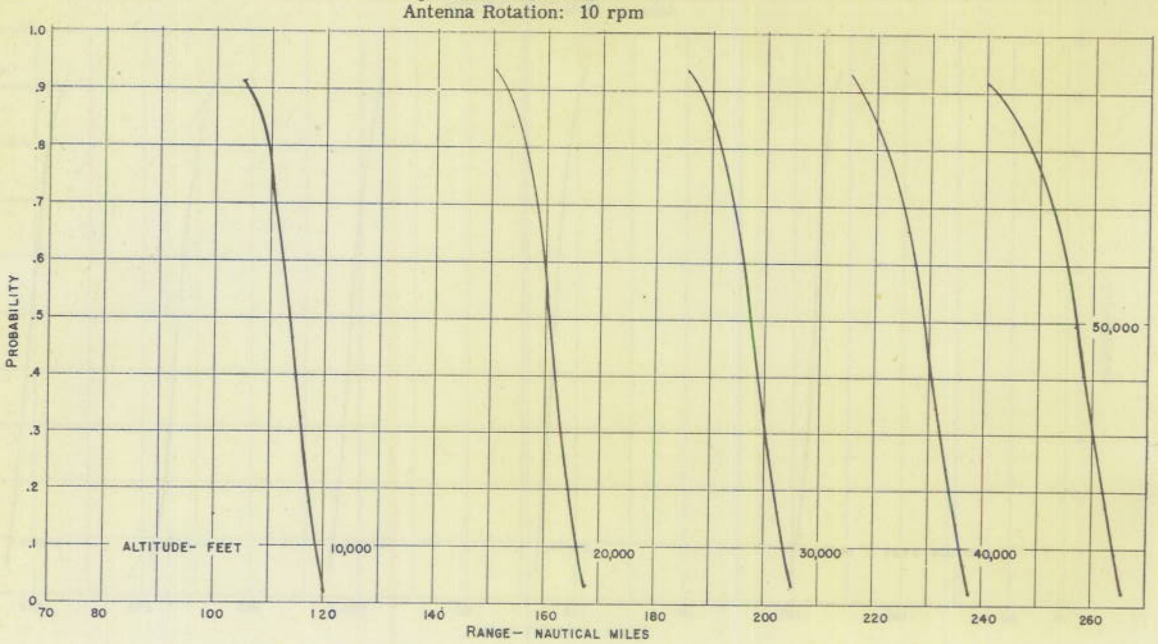

Figure 7 - Cumulative probability of detection

Optimum Radar Performance
Target: One Square Meter, 500 Knots
P_0: 0.25; Single Blip
Antenna Rotation: 15 rpm

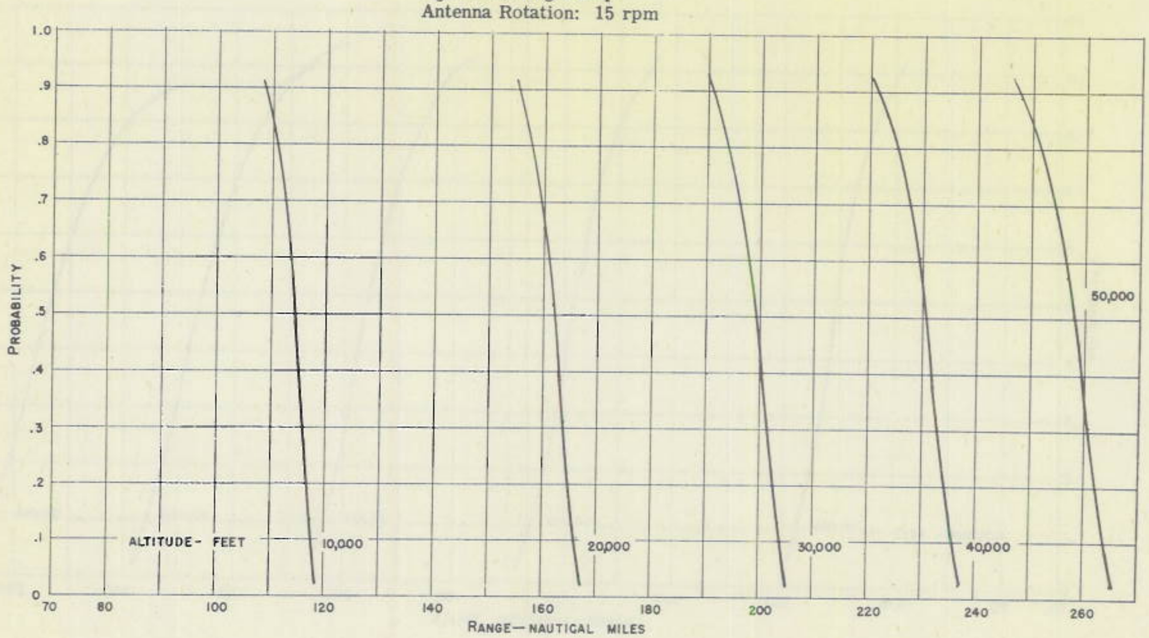

Figure 8 - Cumulative probability of detection

[redacted]

[redacted]

Optimum Radar Performance
Target: One Square Meter, 500 Knots
P_O: 0.5; Double Blip
Antenna Rotation: 5 rpm

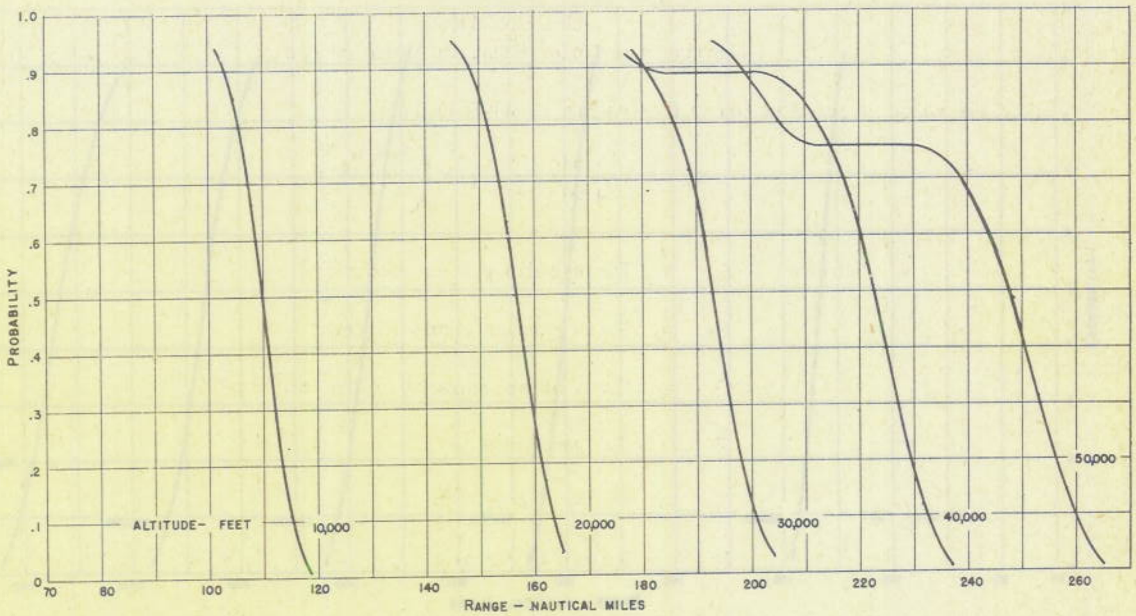

Figure 9 - Cumulative probability of detection

Optimum Radar Performance
Target: One Square Meter, 500 Knots
P_O: 0.5; Double Blip
Antenna Rotation: 10 rpm

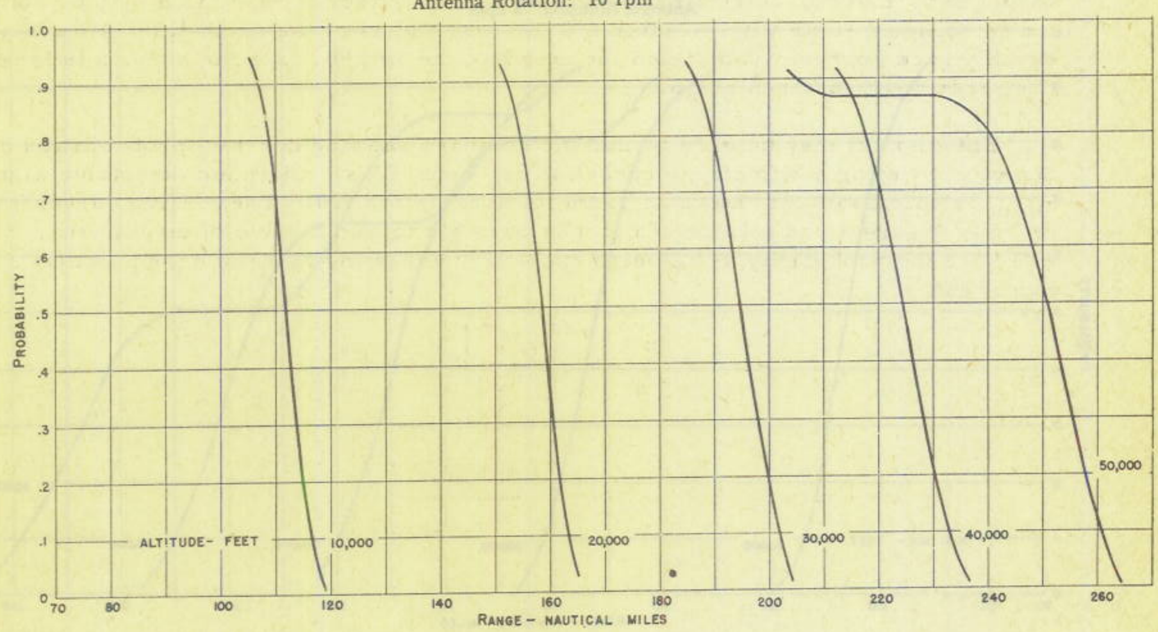

Figure 10 - Cumulative probability of detection

[redacted]

Optimum Radar Performance
Target: One Square Meter, 500 Knots
P_0: 0.5; Double Blip
Antenna Rotation: 15 rpm

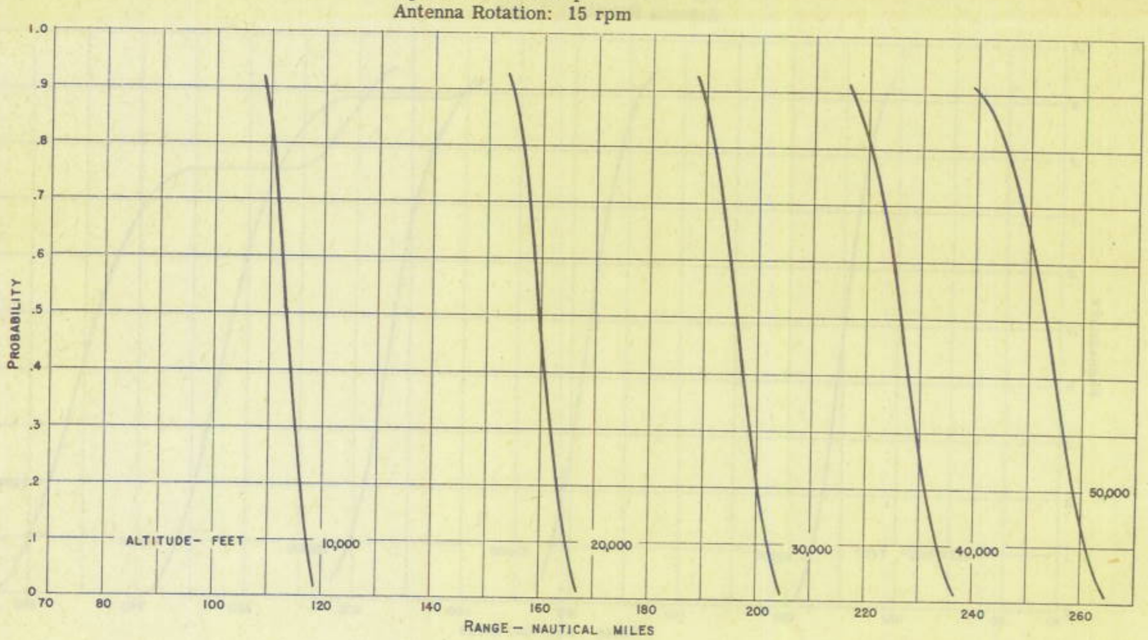

Figure 11 - Cumulative probability of detection

Optimum Radar Performance
Target: One Square Meter, 500 Knots
P_0: 0.25; Double Blip
Antenna Rotation: 5 rpm

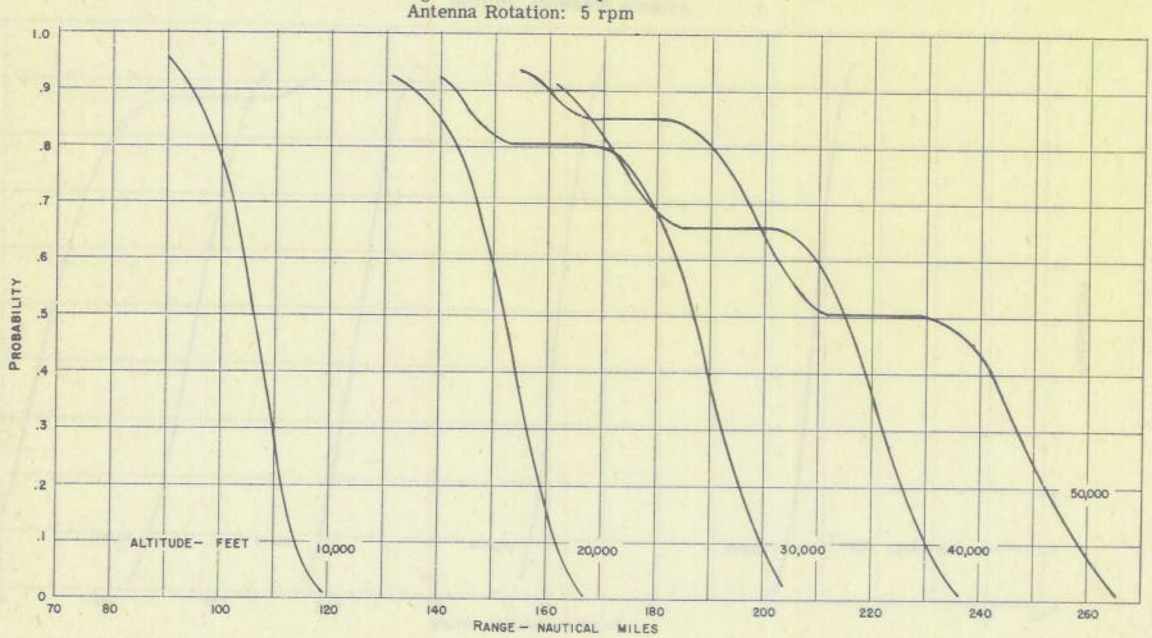

Figure 12 - Cumulative probability of detection

Optimum Radar Performance
Target: One Square Meter, 500 Knots
P_0: 0.25; Double Blip
Antenna Rotation: 10 rpm

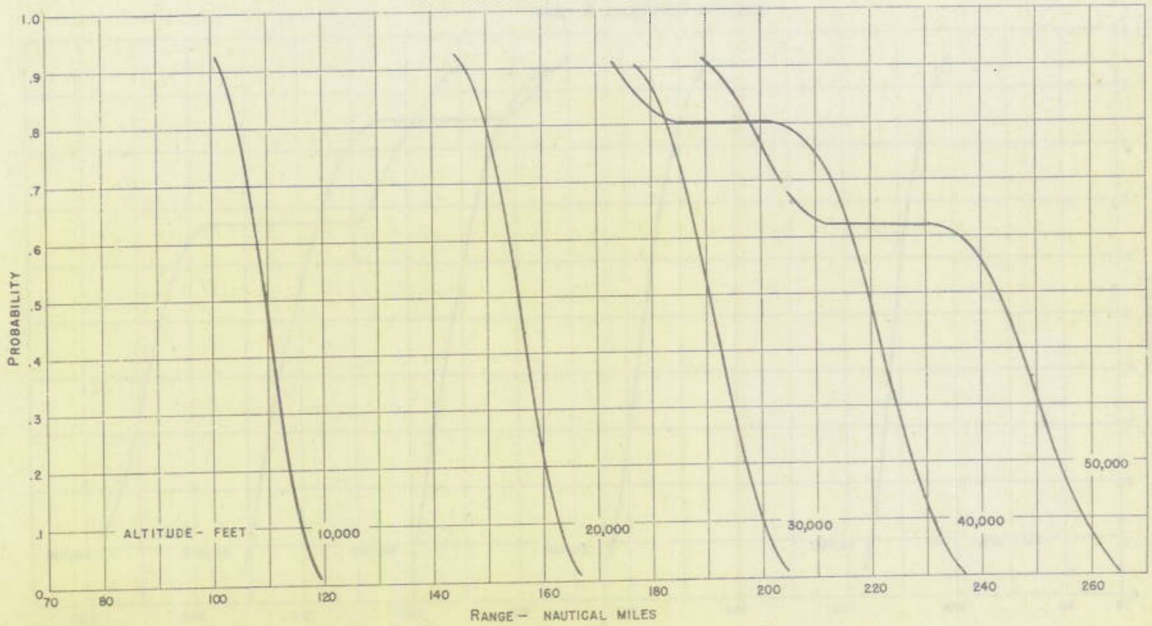

Figure 13 - Cumulative probability of detection

Optimum Radar Performance
Target: One Square Meter, 500 Knots
P_0: 0.25, Double Blip
Antenna Rotation: 15 rpm

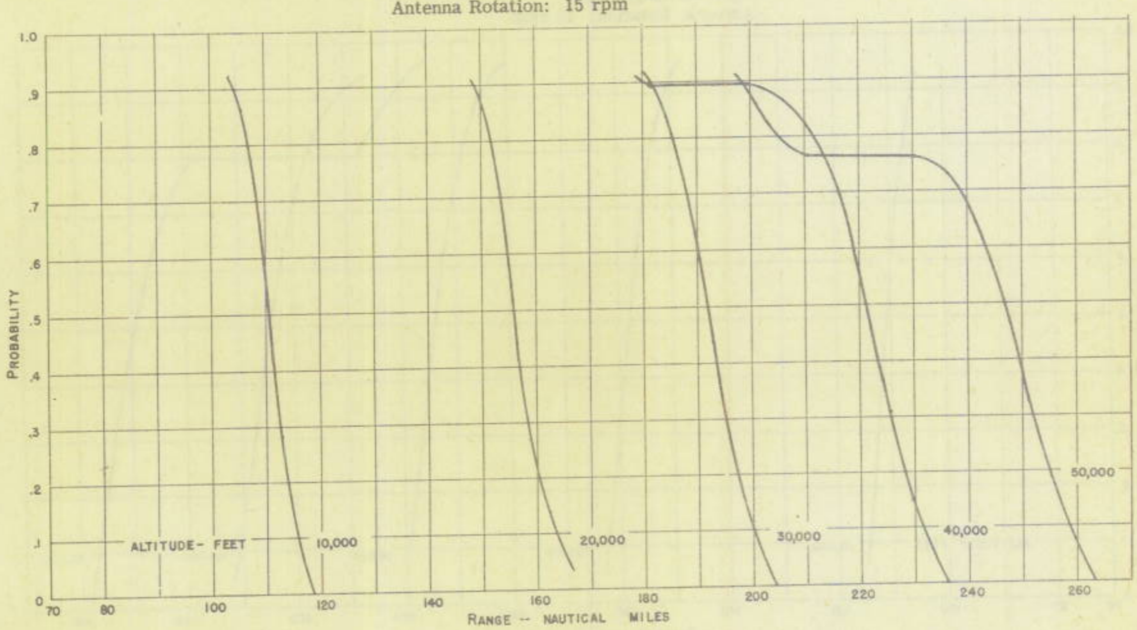

Figure 14 - Cumulative probability of detection

Radar 7 db Below Optimum
Target: One Square Meter, 500 Knots
P_0: 0.5; Single Blip
Antenna Rotation: 5 rpm

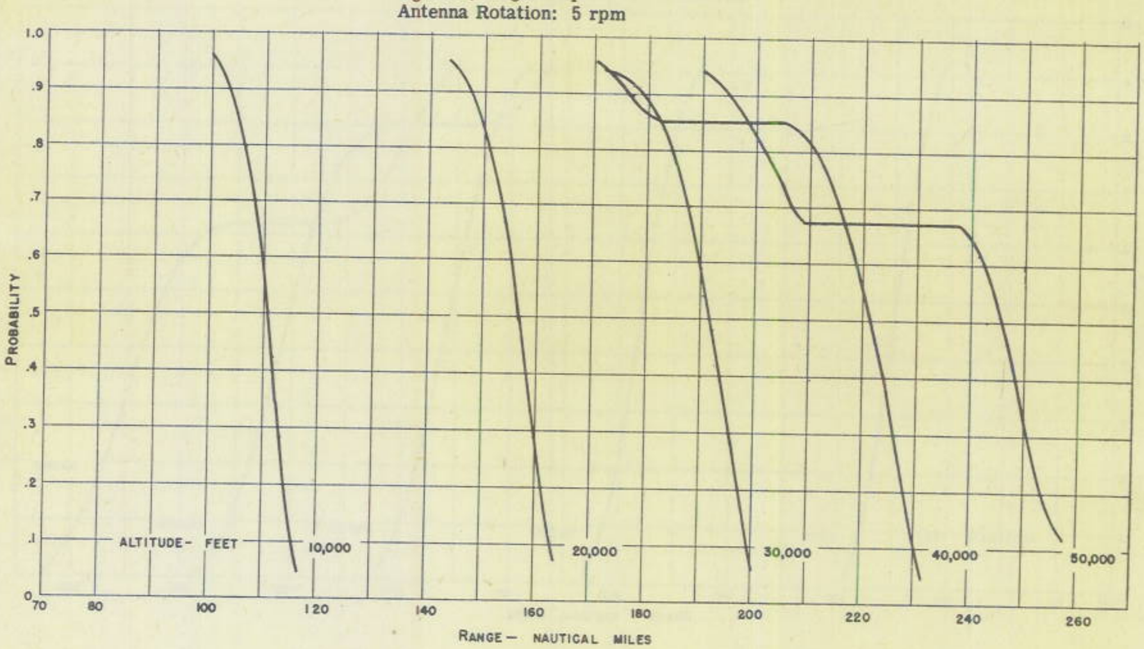

Figure 15 - Cumulative probability of detection

Radar 7 db Below Optimum
Target: One Square Meter, 500 Knots
P_0: 0.5; Single Blip
Antenna Rotation: 10 rpm

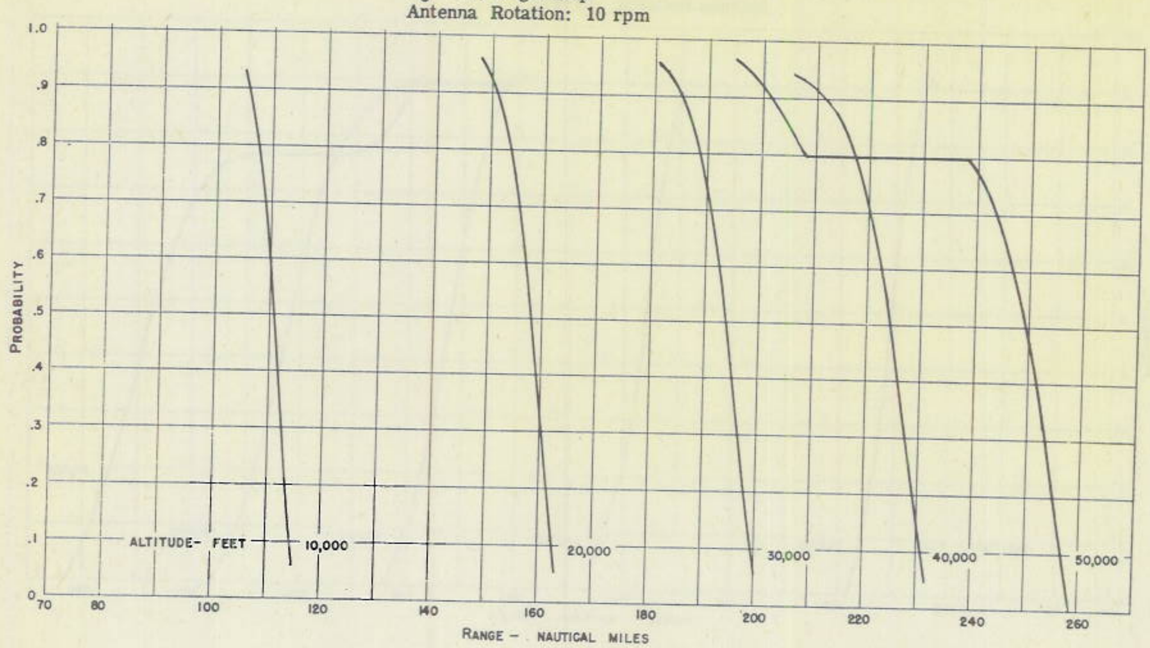

Figure 16 - Cumulative probability of detection

[redacted]

Radar 7 db Below Optimum
Target: One Square Meter, 500 Knots
P_0: 0.5; Single Blip
Antenna Rotation: 15 rpm

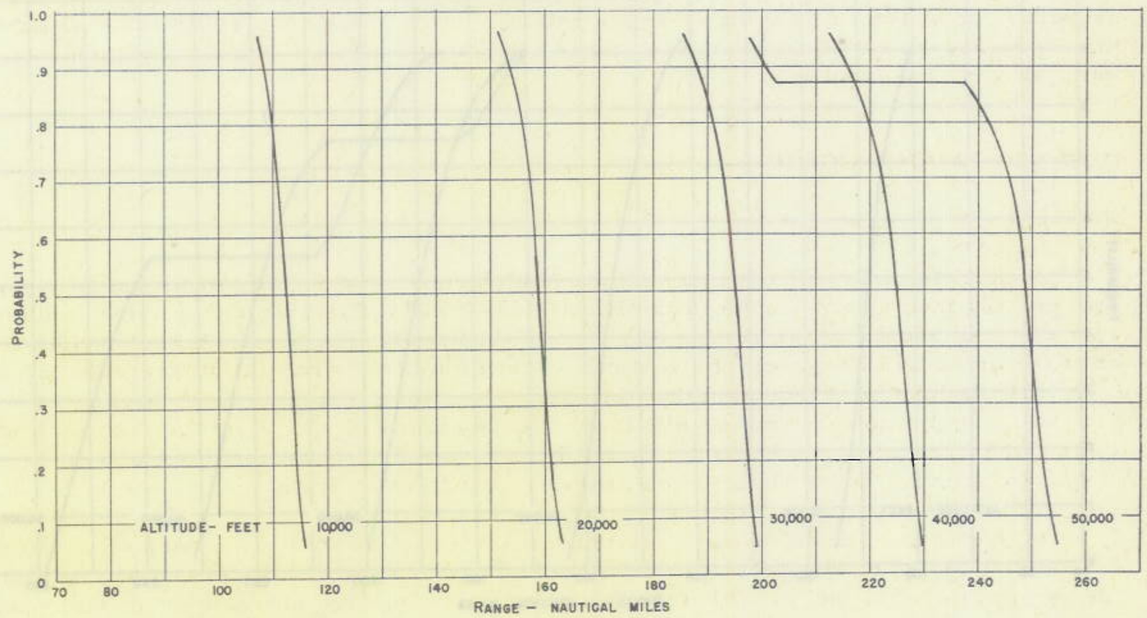

Figure 17 - Cumulative probability of detection

Radar 7 db Below Optimum
Target: One Square Meter, 500 Knots
P_0: 0.25; Single Blip
Antenna Rotation: 5 rpm

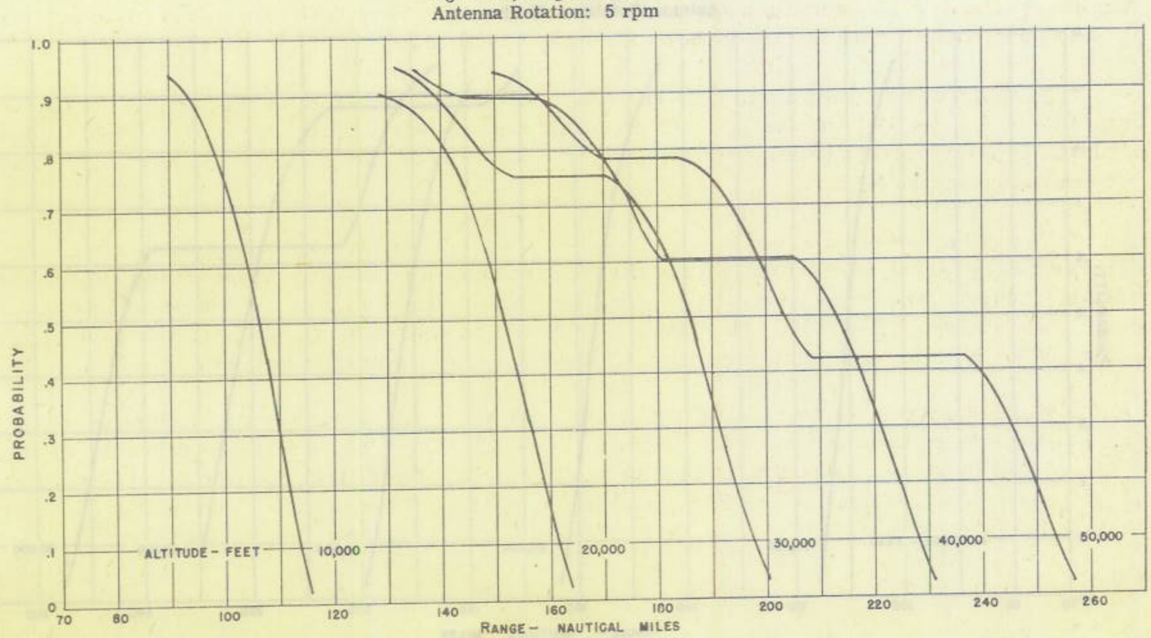

Figure 18 - Cumulative probability of detection

[redacted]

Radar 7 db Below Optimum
Target: One Square Meter, 500 Knots
P_0: 0.25; Single Blip
Antenna Rotation: 10 rpm

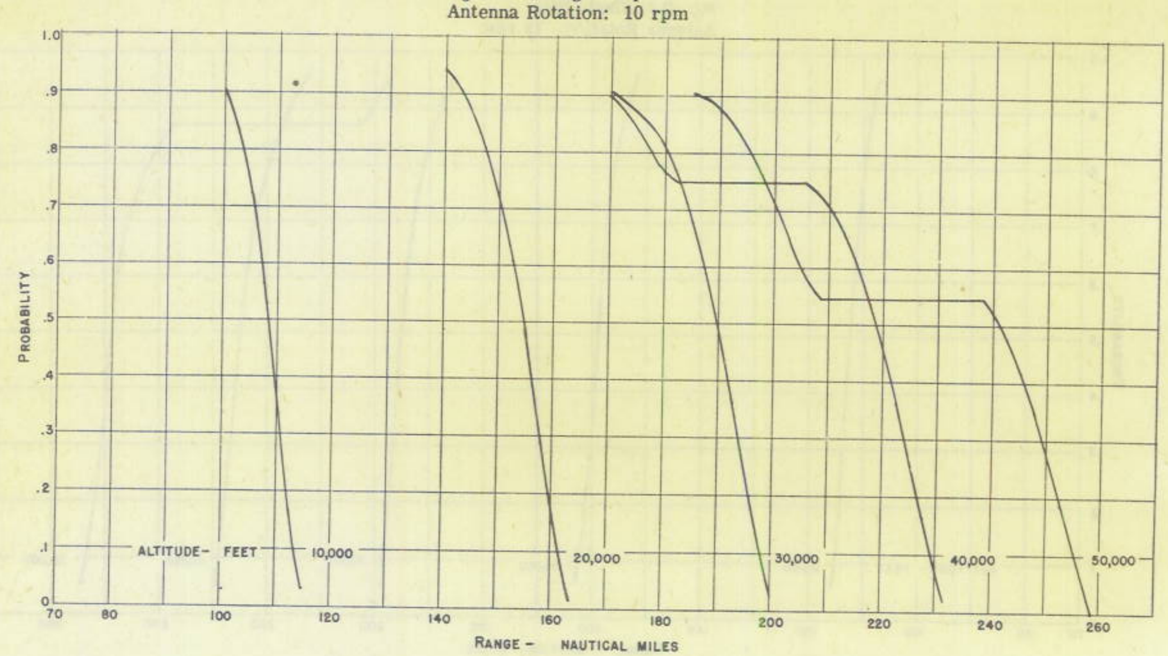

Figure 19 - Cumulative probability of detection

Radar 7 db Below Optimum
Target: One Square Meter, 500 Knots
P_0: 0.25; Single Blip
Antenna Rotation: 15 rpm

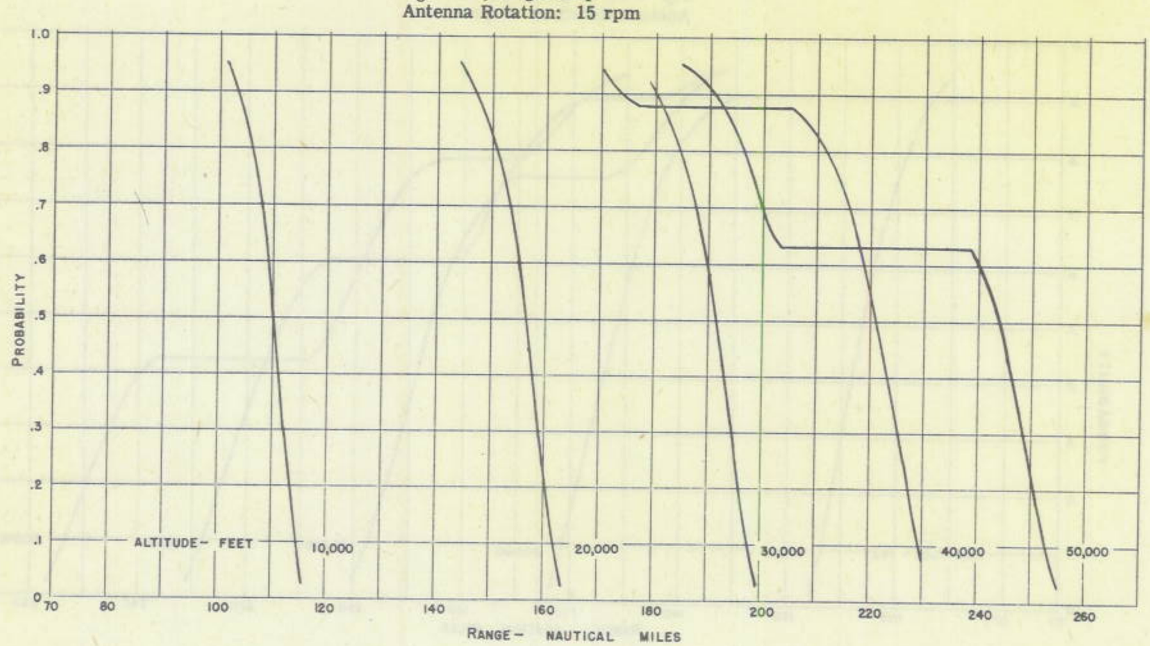

Figure 20 - Cumulative probability of detection

Radar 7 db Below Optimum
Target: One Square Meter, 500 Knots
P_O: 0.5; Double Blip
Antenna Rotation: 5 rpm

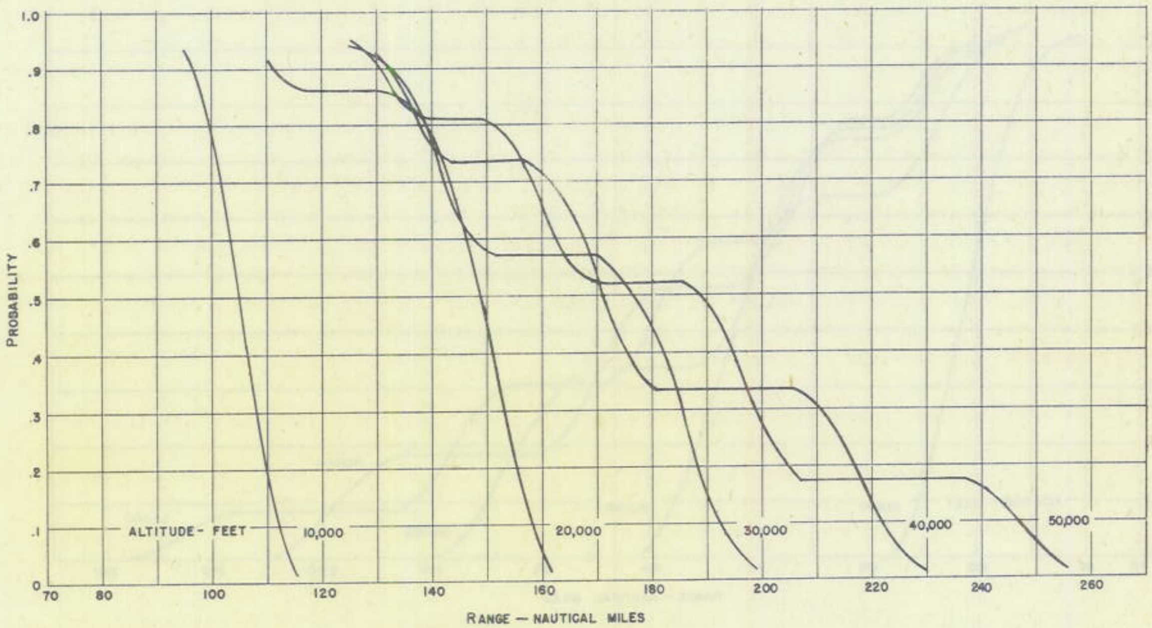

Figure 21 - Cumulative probability of detection

Radar 7 db Below Optimum
Target: One Square Meter, 500 Knots
P_O: 0.5; Double Blip
Antenna Rotation: 15 rpm

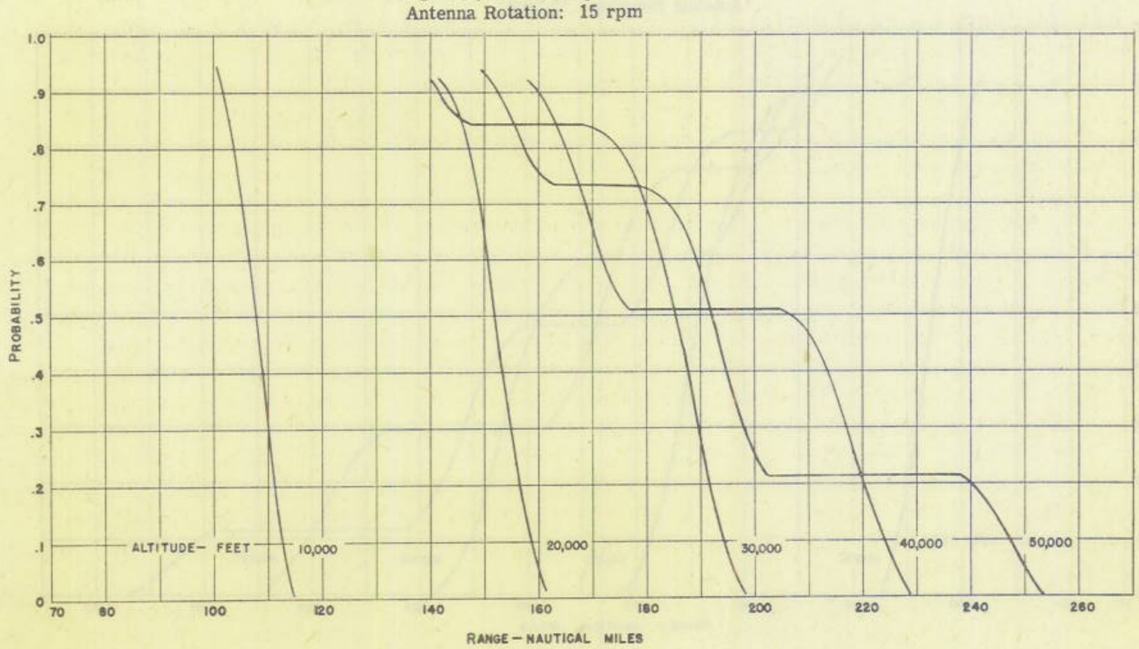

Figure 22 - Cumulative probability of detection

[redacted]

Radar 7 db Below Optimum
Target: One Square Meter, 500 Knots
P_0: 0.25; Double Blip
Antenna Rotation: 5 rpm

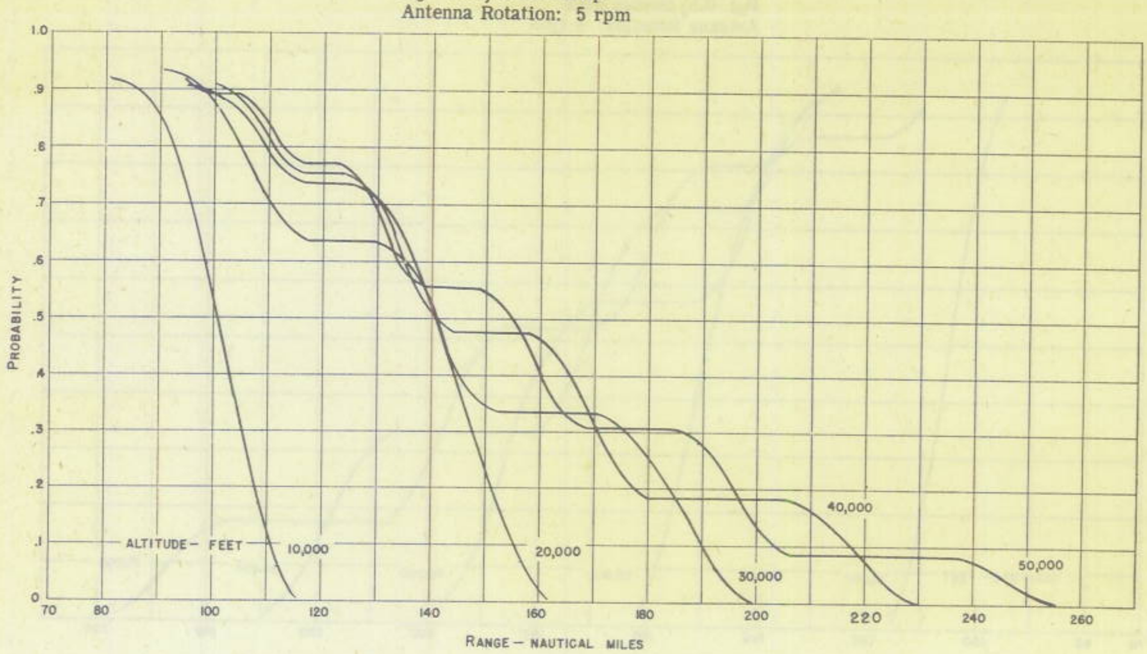

Figure 23 - Cumulative probability of detection

Radar 7 db Below Optimum
Target: One Square Meter, 500 Knots
P_0: 0.25; Double Blip
Antenna Rotation: 15 rpm

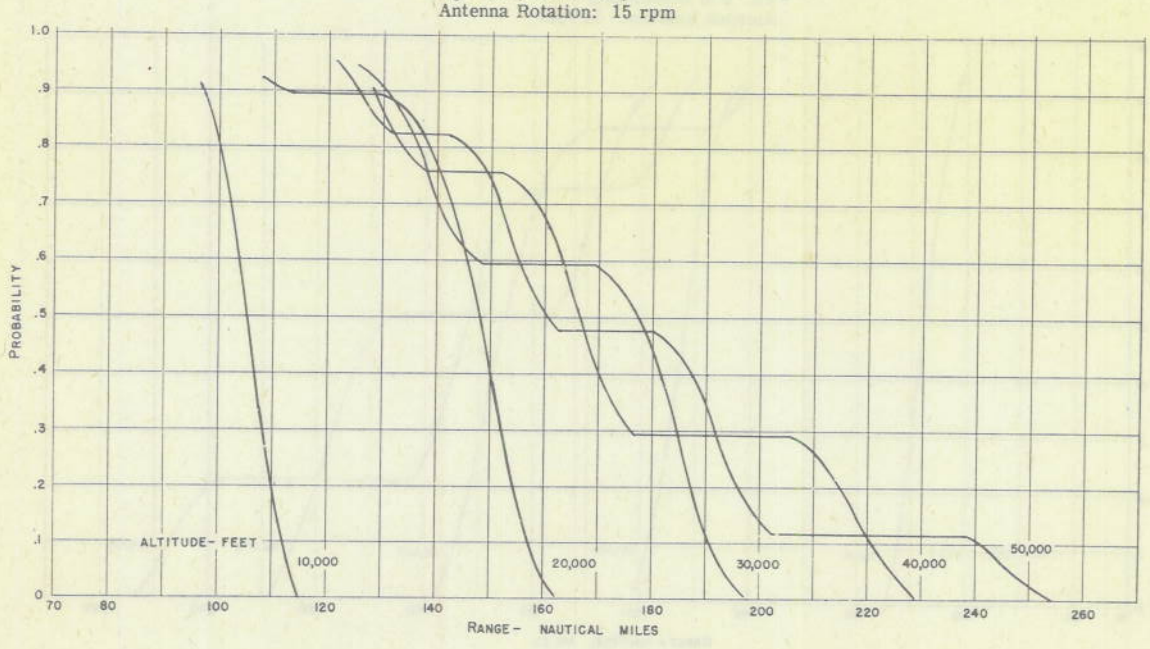

Figure 24 - Cumulative probability of detection

Radar 12 db Below Optimum
Target: One Square Meter, 500 Knots
P_O: 0.5; Single Blip
Antenna Rotation: 10 rpm

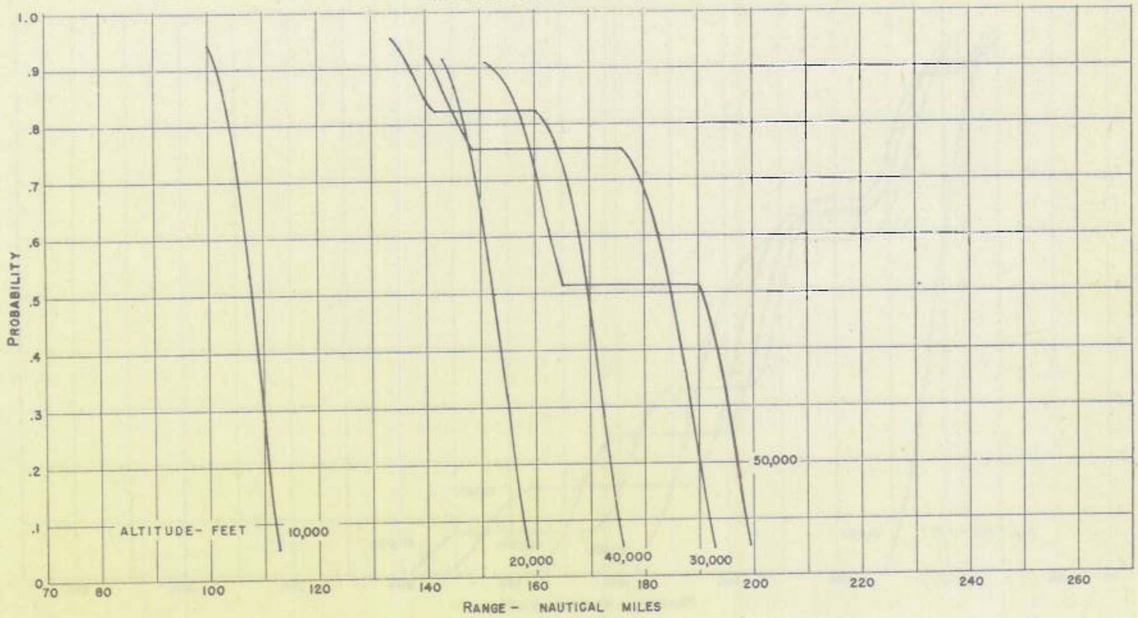

Figure 25 - Cumulative probability of detection

Radar 12 db Below Optimum
Target: One Square Meter, 500 Knots
P_O: 0.25; Single Blip
Antenna Rotation: 10 rpm

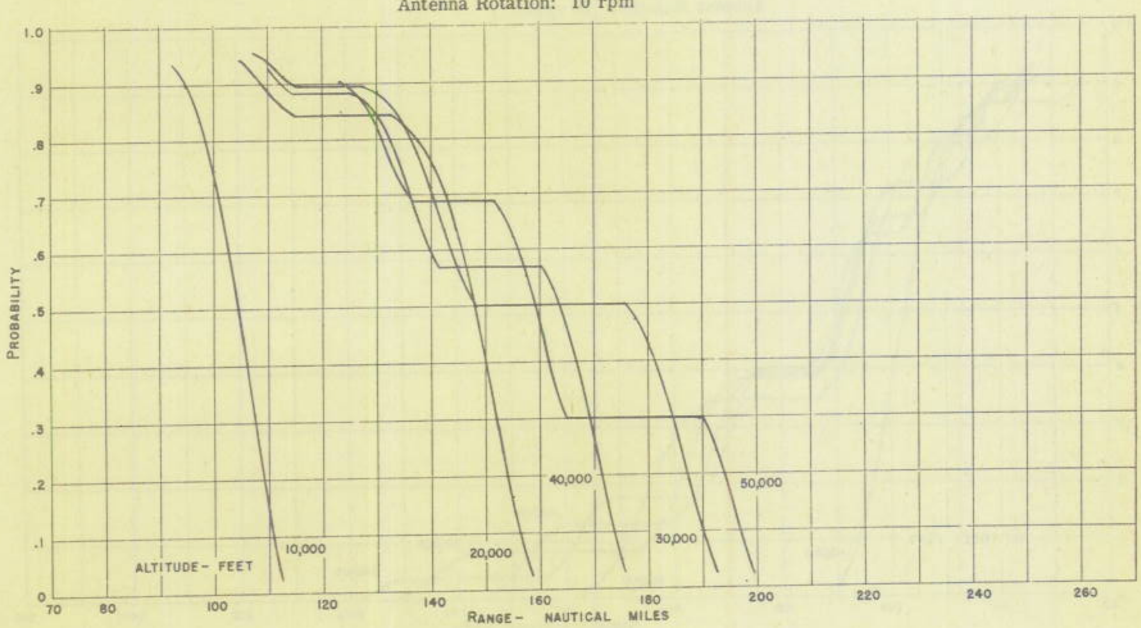

Figure 26 - Cumulative probability of detection

Radar 12 db Below Optimum
Target: One Square Meter, 500 Knots
P_0: 0.5; Double Blip
Antenna Rotation: 10 rpm

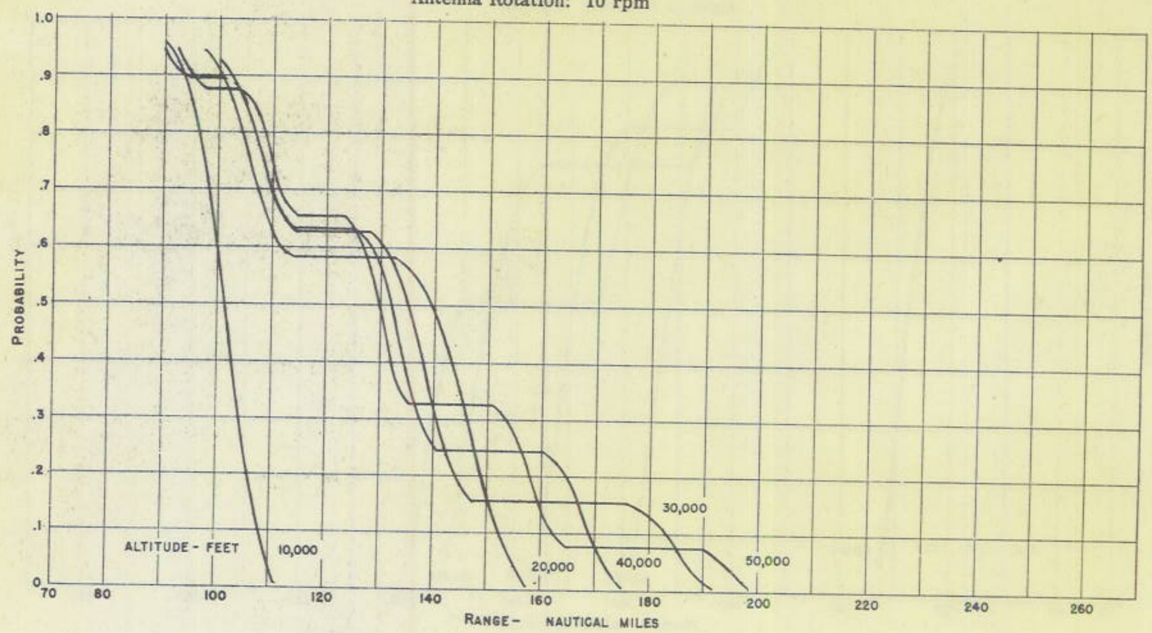

Figure 27 - Cumulative probability of detection

Radar 12 db Below Optimum
Target: One Square Meter, 500 Knots
P_0: 0.25; Double Blip
Antenna Rotation: 10 rpm

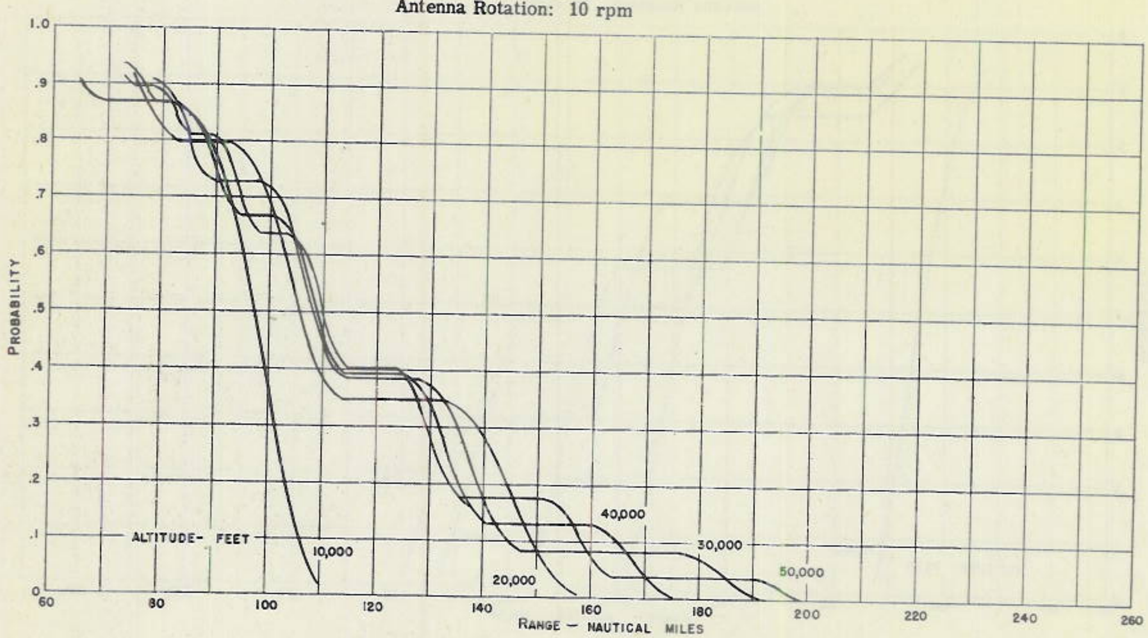

Figure 28 - Cumulative probability of detection

Radar 7 db Below Optimum
Target: One Square Meter, 500 Knots, Rayleigh Distribution
P_0: 0.5; Single Blip
Antenna Rotation: 10 rpm

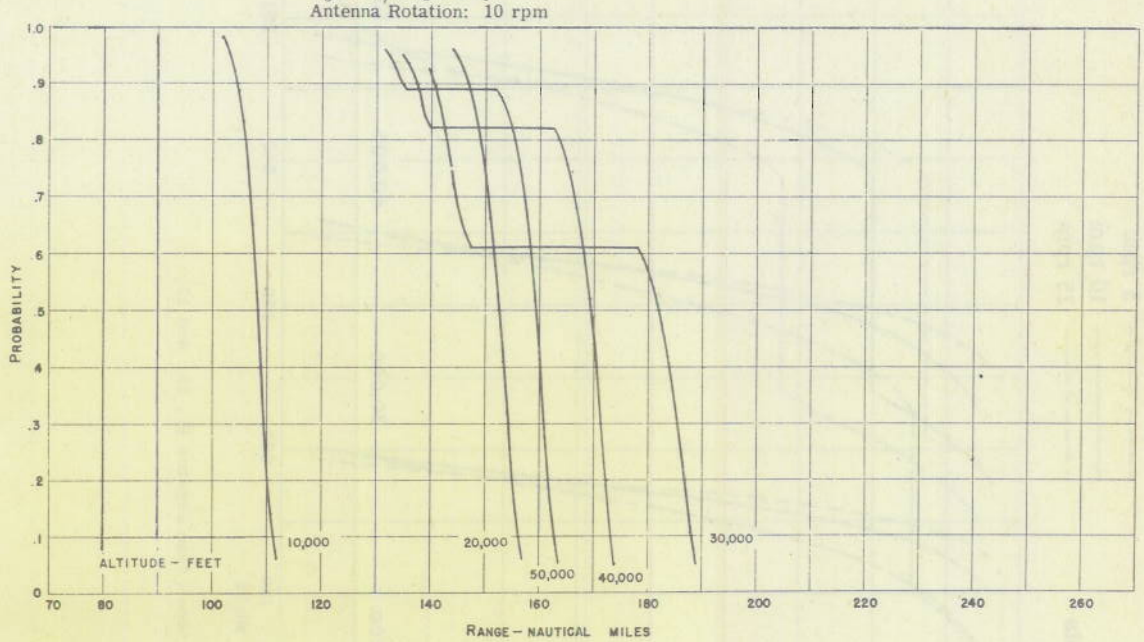

Figure 29 - Cumulative probability of detection

Radar 12 db Below Optimum
Target: One Square Meter, 500 Knots, Rayleigh Distribution
P_0: 0.5; Single Blip
Antenna Rotation: 10 rpm

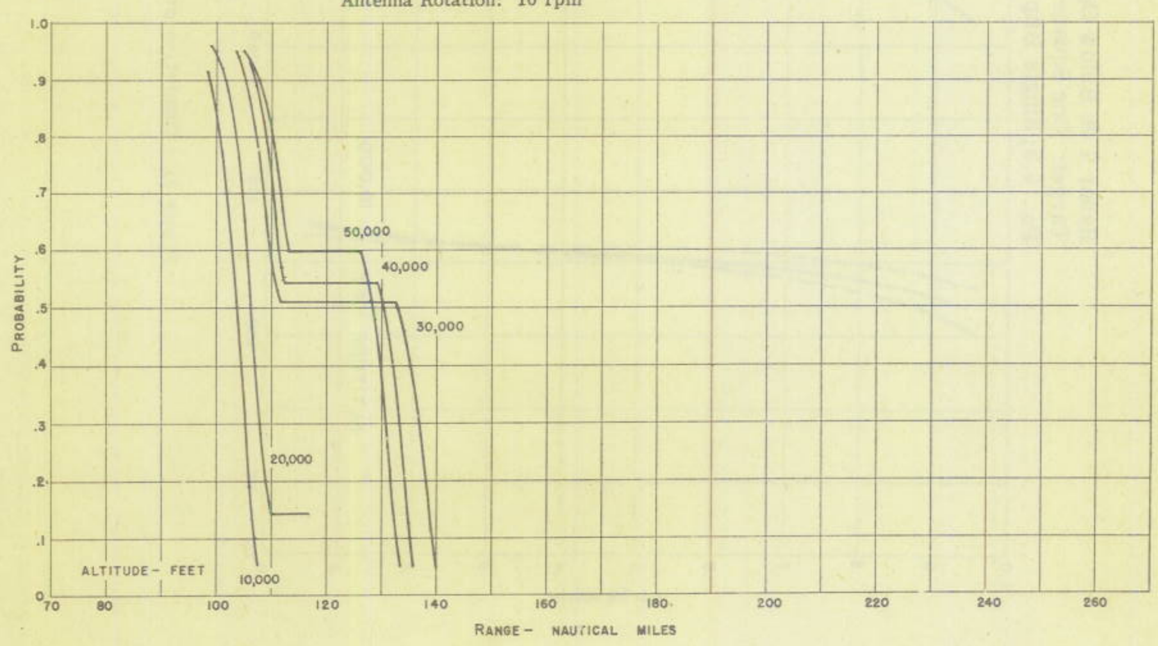

Figure 30 - Cumulative probability of detection

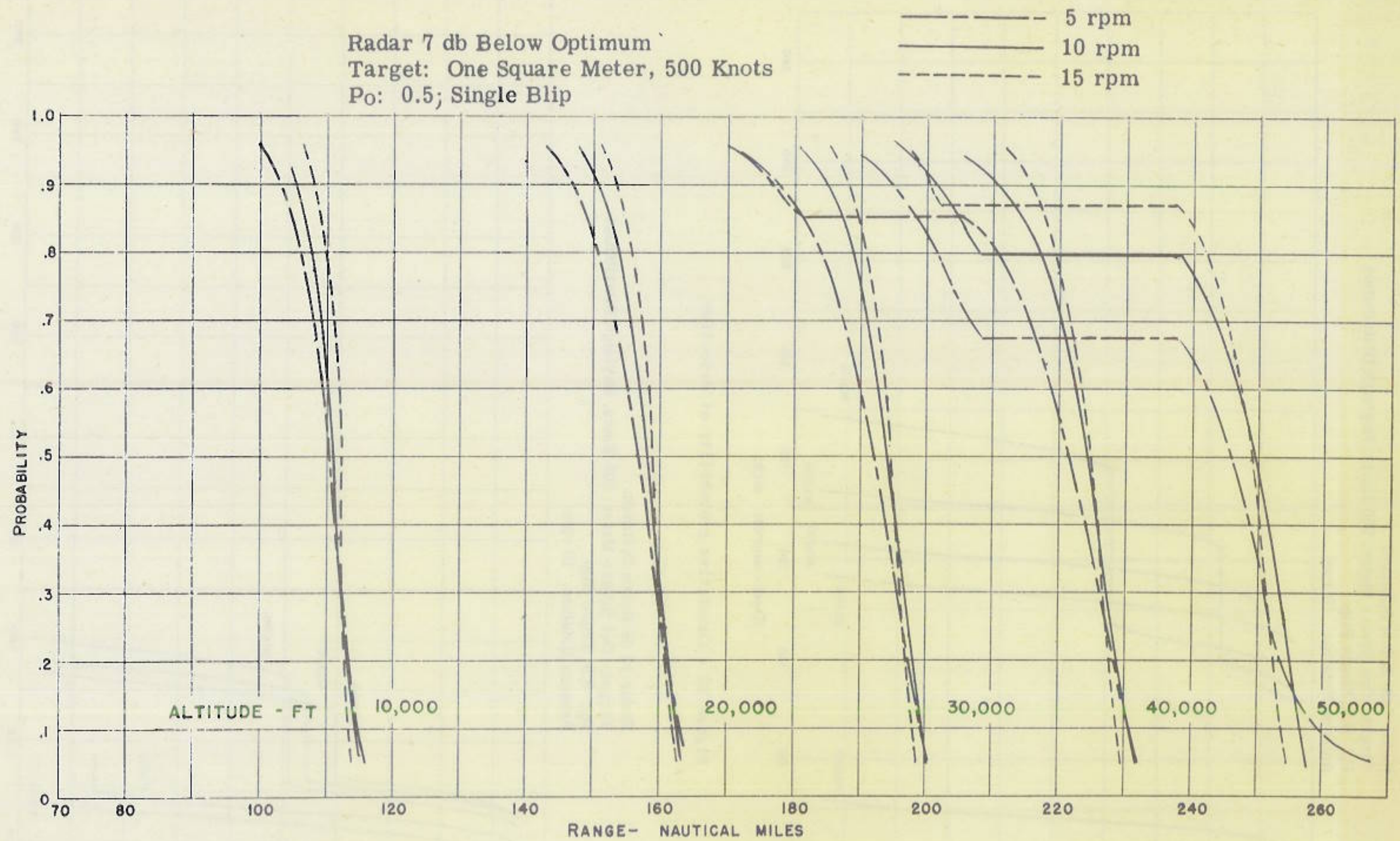

Figure 31 - Cumulative probability of detection (from Figures 15, 16, and 17)

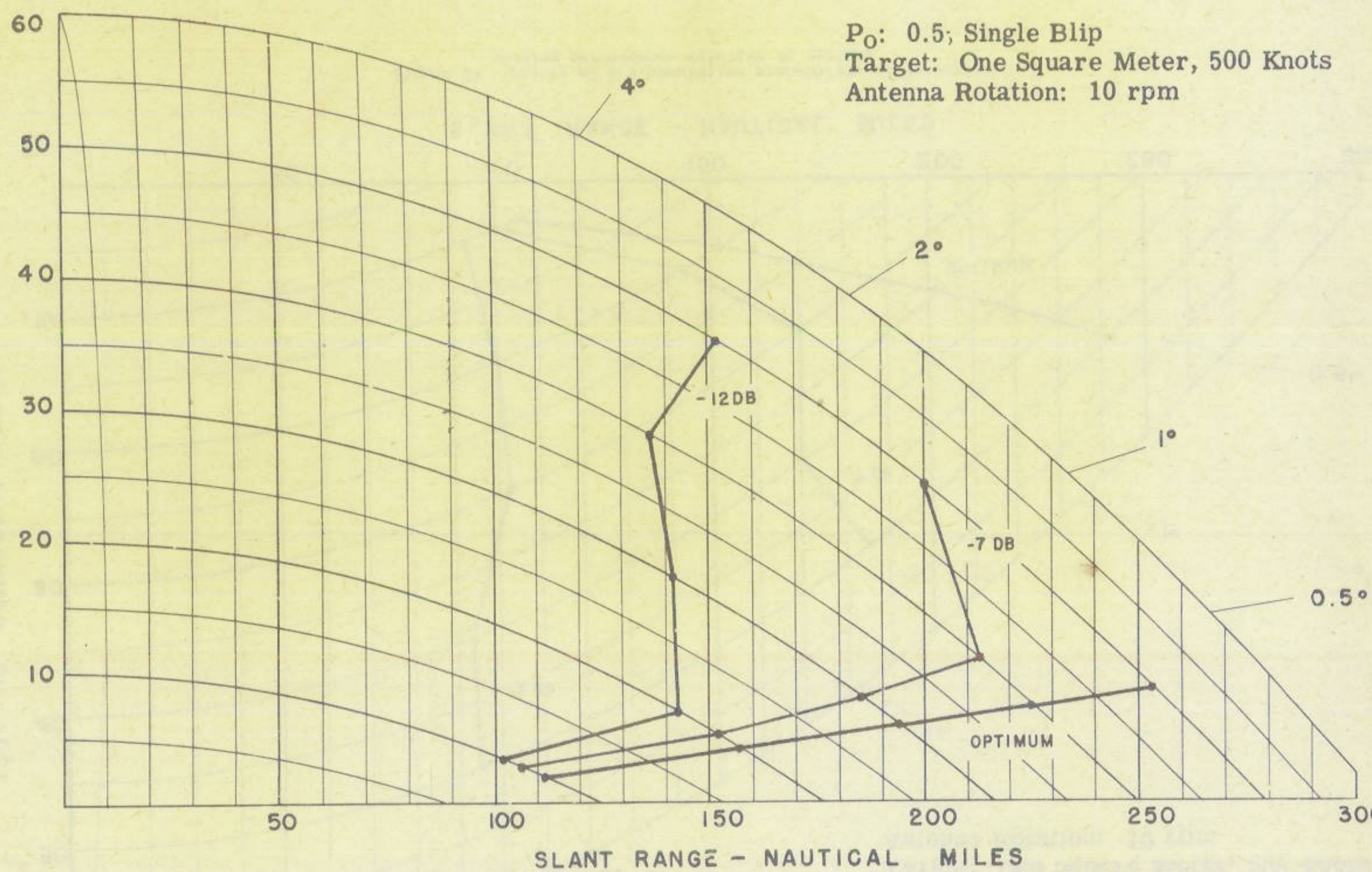

Figure 32 - Points of 0.9 cumulative probability of detection showing performance relative to optimum

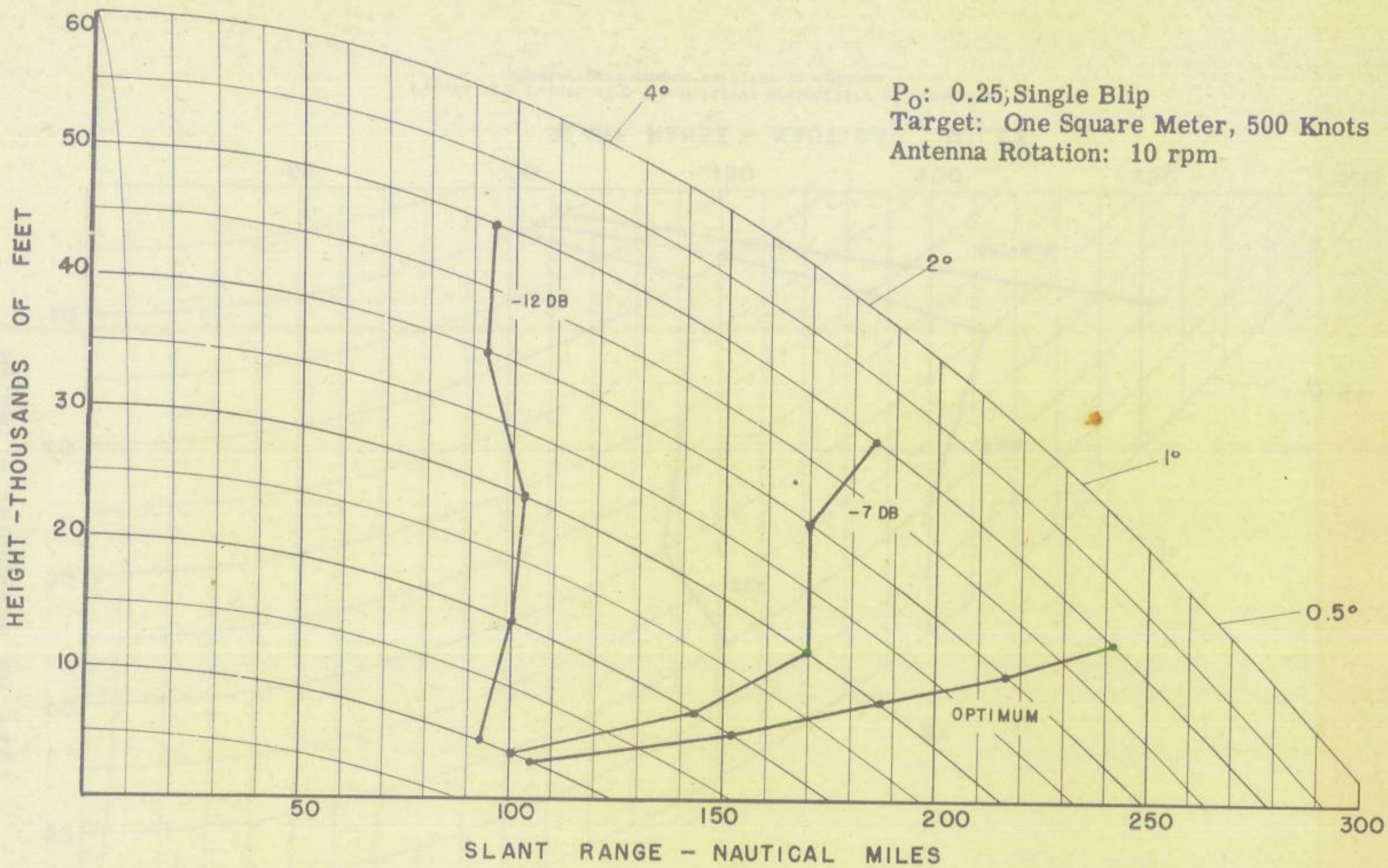

Figure 33 - Points of 0.9 cumulative probability of detection showing performance relative to optimum

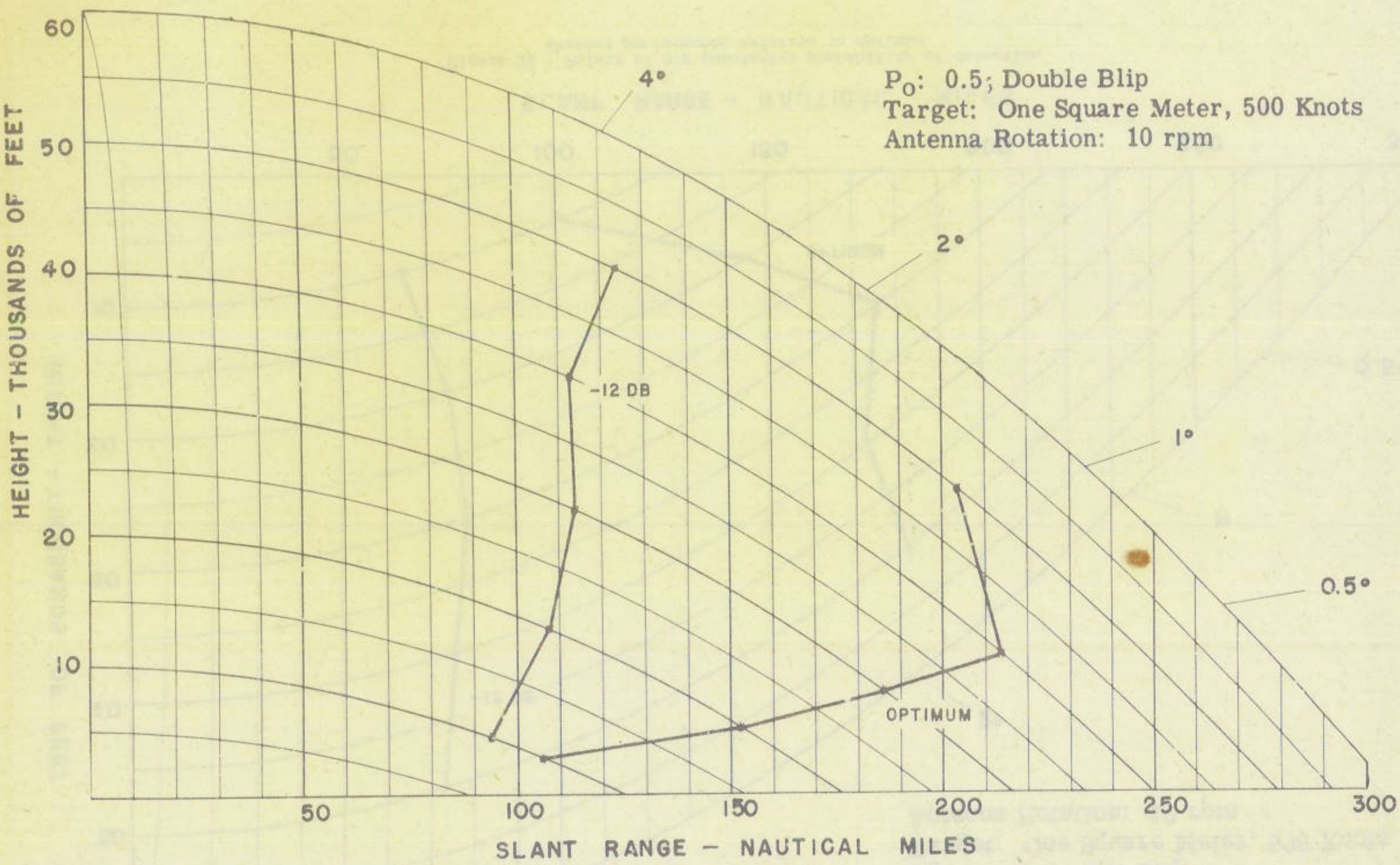

Figure 34 - Points of 0.9 cumulative probability of detection showing performance relative to optimum

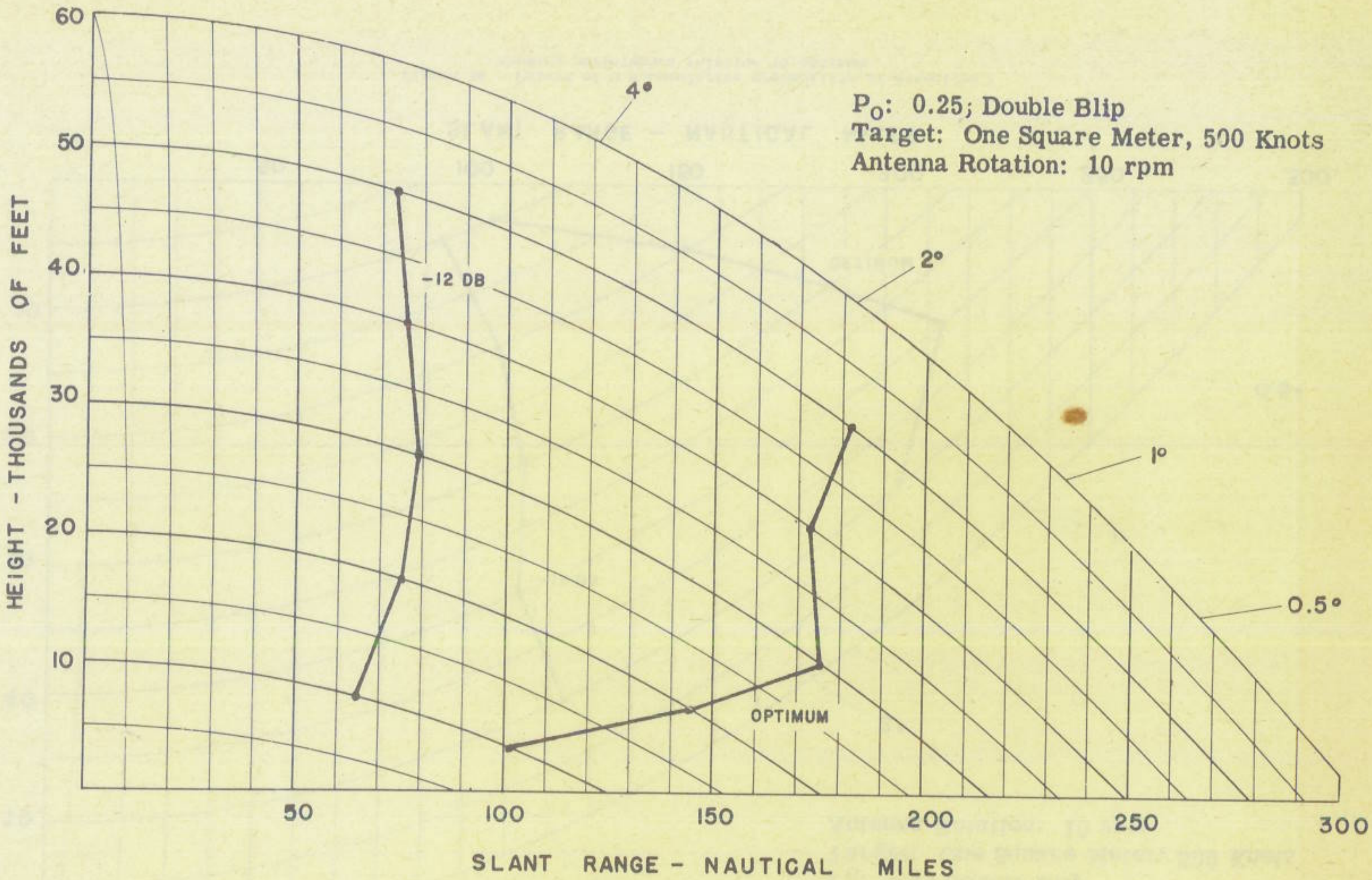

Figure 35 - Points of 0.9 cumulative probability of detection showing performance relative to optimum

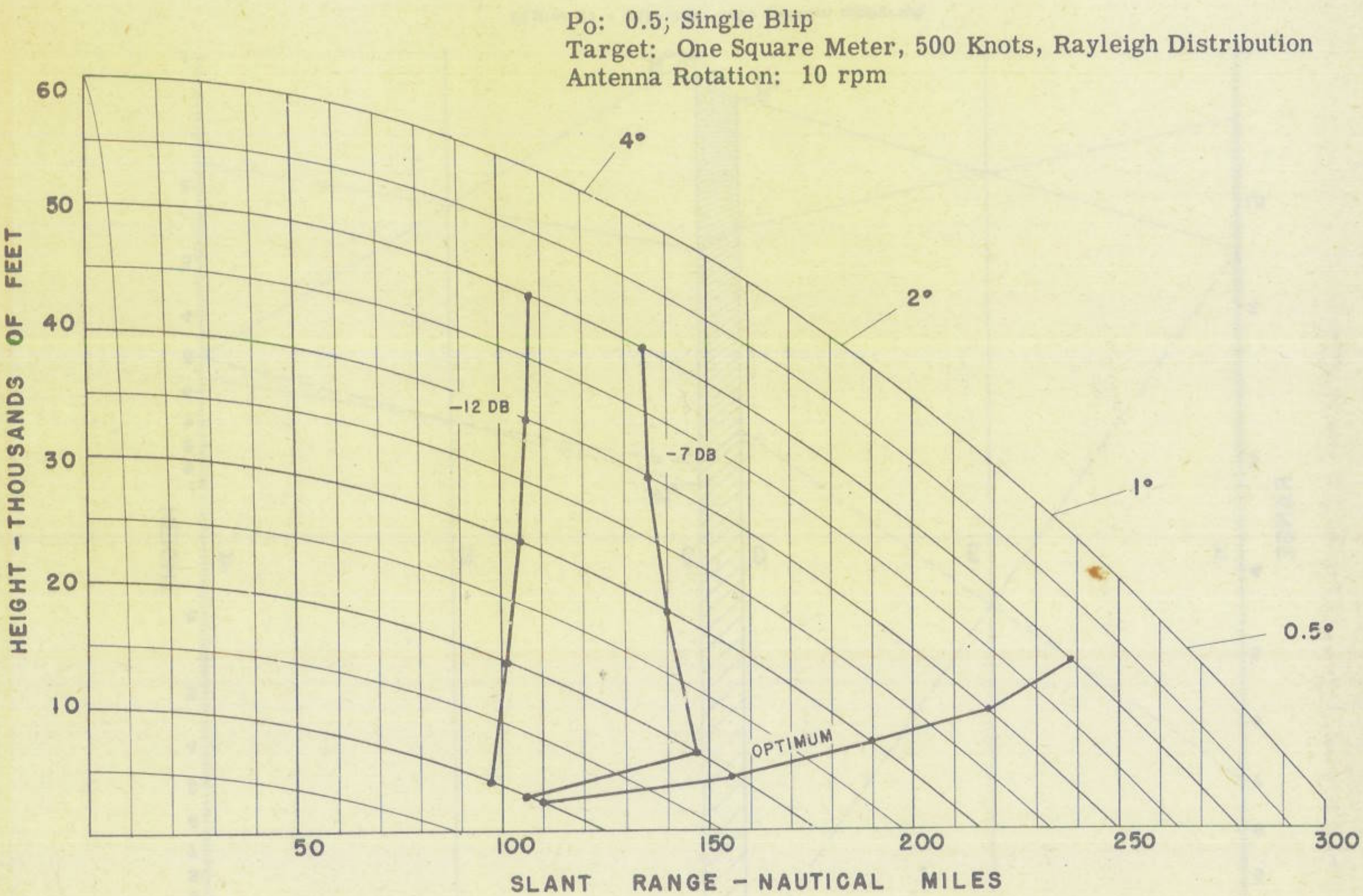

Figure 36 - Points of 0.9 cumulative probability of detection showing performance relative to optimum

 [redacted]

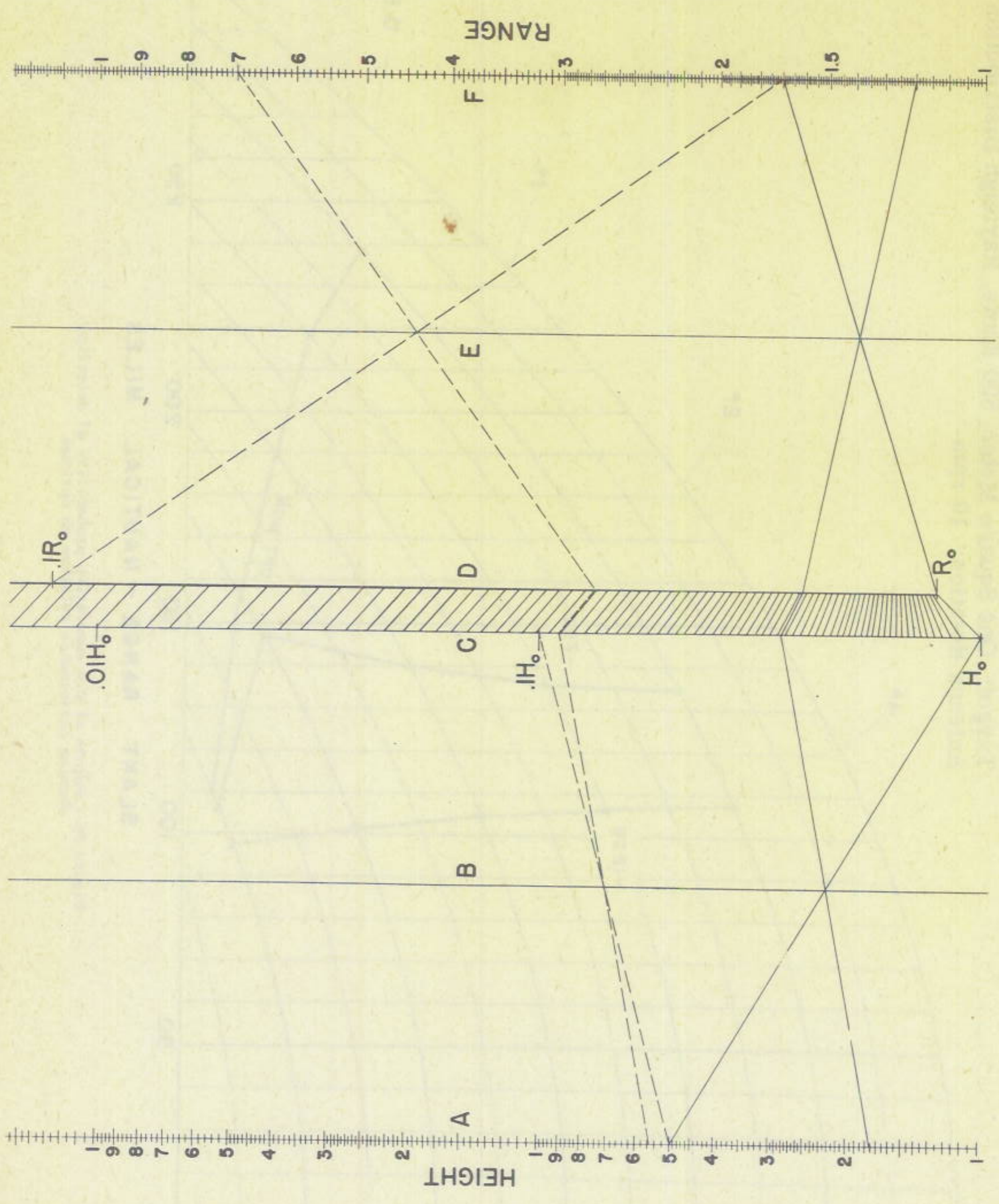

Figure 37 - Universal lobe pattern nomograph

[redacted]

NAVY-DPPO PRNC. WASH., D.C.