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Serial No. 25

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SHIP-SHORE RADIO DIVISION - SEARCH RADAR SECTION

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18 February 1946

PROPOSED VERY LONG RANGE RADAR WITH HEIGHT FINDING

By A. A. Varela

FR-2759

\- Report R-2759 -

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* * *

Approved by:

R. C. Guthrie - Head, Search Radar Section

L. A. Gebhard - Superintendent,
Ship-Shore Radio Division

Commodore H. A. Schade, USN
Director, Naval Research Laboratory

Preliminary Pages .... a-c
Numbered Pages 12
Plates 5

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NRL Problem S1225X-S

[redacted] Serial No. 32

Navy Department - Office of Research and Inventions

NAVAL RESEARCH LABORATORY
Washington, D.C.

* * *

SHIP-SHORE RADIO DIVISION - SEARCH RADAR SECTION

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5338

PROPOSED VERY LONG RANGE RADAR WITH HEIGHT FINDING

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ABSTRACT

The fundamental design considerations are given for a radar capable of detecting a target of one square meter within a cylinder of space 300 nautical miles in radius and 50 miles up, and providing range, bearing, and elevation information at a rate of every four seconds. It is concluded that this performance would be best accomplished by a system having eight separate beams tilted progressively upward and with the lower beams derived in groups of three from single reflectors 18 x 35 ft. Factors entering into choice of frequency are analyzed and it is concluded that 1300 mcs. is most desirable.

The power requirements are calculated and found to be about 7 megawatts peak for each of the beams and about 400 KW average power for the entire system. Presentation of information is discussed and it is shown that an elevation accuracy of 10' is conceivably possible at the lower angles.

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INTRODUCTION:

Problem S1225X-S established by the Bureau of Ships calls for development of a radar system capable of detecting, and supplying range, azimuth, and elevation information at four second intervals on any likely target within a radius of 300 miles and up to 50 miles. In development of the design set forth in this paper the utilization of the radar information has been kept in view with the intent that the system be capable of supplying sufficiently accurate target data to directly guide counter missiles.

From consideration of present small long range missiles such as the V-2 bomb and the Baka plane it has been concluded that the minimum target to be expected will have an effective echo area of at least one square meter referred to an isotrope.

1. BASIC PARAMETERS

Since such basic factors as frequency, pulse power, pulse length and antenna beam width are inter-related it is first necessary to consider practical limits and their bearing on these factors.

1-1. Scanning Time Limitations With full range of 300 n. miles the two-way propagation time is .00366 second and if 80% maximum duty factor is assumed for the sweep circuits the maximum repetition rate is 220 per second. If the antenna rotation period is 4 seconds then the number of pulses on a target per revolution per degree beam width is

$$N = \frac{4 \times 220}{360} = 2.44/\text{rev.}/\text{degree} \qquad (1)$$

Sensitivity of a radar system decreases as number of pulses on target decreases as a result of two separate effects:

(a) Integration factor on minimum observable signal. It has been determined here and at other laboratories that minimum detectable signal power varies approximately inversely as the half power of the number of pulses and applies whether the number is varied by change of repetition rate or by change of arc length within normal limits.

(b) Loss in effective antenna gain due to antenna movement during signal transit time. If during the time required for the echo to return to the antenna the beam has turned an appreciable part of its width then full antenna gain will not be realized on maximum range signals. This loss varies with exact azimuth position of the target and is most severe when the antenna is aligned on target during transmission and hence off during reception, or vice versa.

These losses, omitting the effect of increased gain due to the sharper beam, are shown as a function of antenna beam width on Plate I and plainly put an economic limit on decreasing beam width.

1-2. Maximum Range vs. Beam Width If pulse power, receiver sensitivity, and target echoing area are assumed constant then maximum detection range R_o is given by

$$R_o \propto (G\lambda)^{\frac{1}{2}} \qquad (2)$$

where $G =$ antenna power gain
$\lambda =$ wave length

Since antenna gain is inversely proportional to the product of the beam widths in the electric and magnetic planes we may conclude

$$R_o \propto \left[\frac{\lambda}{\theta_V \, \theta_H}\right]^{\frac{1}{2}} \qquad (3)$$

Vertical beam width θ_V is determined by the high angle coverage requirements and cannot be taken as a variable. On the other hand the horizontal dimension of the antenna is ultimately limited by mechanical considerations so that horizontal beam width may decrease in proportion to decrease in wave length. Hence from eqtn. (3) with θ_V constant and all other factors neglected maximum range will not vary with frequency. However from the considerations of Par. 1-2 it is apparent that maximum range will decrease with frequency due to narrowing of horizontal beam width.

For low side lobes the relation between beam width (3 db pts) and antenna aperture (D) may be taken

$$\theta = \frac{70\,\lambda}{D} \text{ degrees} \qquad (4)$$

Considering the high turning rate of 15 r.p.m. it does not appear feasible to plan on a horizontal antenna dimension greater than forty feet. Beam widths obtainable for various frequencies are then as follows:

f (mcs.)	θ (degrees)
600	2.86
1200	1.43
2000	.86
3000	.57

[redacted]

From this table and the data of Plate 1 the scanning loss is plotted as a function of frequency in Plate 2. Curves for 7.5 and 10 as well as 15 r.p.m. antenna rotation are plotted to show the relative effect.

These curves present considerable inducement for choice of a low frequency and show that, at least for the case of one antenna continuously revolving at 15 r.p.m., the loss at S band is prohibitive. Other factors must be considered however. The vertical dimension of the antenna must increase linearly with wave length, wave-guides and r.f. plumbing may become excessively large, azimuth accuracy and discrimination decrease, and jamming and interception become more feasible. Before making more definite conclusions as to frequency it appears desirable to examine general characters of possible systems.

2. POSSIBLE SYSTEM TYPES

For achieving the required solid coverage out to 300 miles and up to 50 miles with height finding several different methods are presented. It is taken as a requirement that any target within this cylinder of space surrounding the radar must be presented on each sweep of the beam without the gaps or nulls characteristic of present search radars. The various proposals are set forth below with letter designations and are subsequently analyzed with reference to the letters.

A. A single beam sufficiently broad and distorted (Csc^2) in the vertical plane and tilted up so as to nearly eliminate lobing from surface reflection.

B. A vertically broad horizontally polarized beam with a second less broad vertically polarized beam on slightly different frequencies. Low frequency.

C. A series of vertically narrow beams separately fed and tilted progressively upward so as to overlap and provide essentially solid coverage.

D. Vertical Scanning with one or more beams.

2-1. The Single Beam System(A) Such a system is incapable of giving height information and is extremely uneconomic in the use of power. It is presented here as a basis for comparison. Free space propagation applies. Although the beam would be distorted in the vertical plane it appears that an equivalent width of at least 15° is required.

2-2. Dual Polarized Beam System with Surface Reflection (B) Here it is proposed to make use of the factor of 2 on range obtained from surface reflection. The most likely method of gap filling appears in the use of both vertical and horizontal polarization, but this is

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effective only if the frequency is below about 300 mcs. This method of gap filling is well discussed in Reference (1) and the Canadian ZPI System using elliptical polarization at 150 mcs. is described in Reference (2). The minimum vertical width of the horizontally polarized beam for the required coverage is about 28° with 10 db first side lobes or shoulders. For gain comparison purposes the equivalent beam width may be taken as 30°. For vertical polarization in the neighborhood of 200 mcs. the reflection coefficient is about 0.5 (Ref. (3)) hence for the same peak range as with the horizontally polarized beam a beam width of $(1.5/2)^2 \times 30^\circ = 17^\circ$ must be used. Appreciable gaps will then be present at angles above 10° and for true gap filling a third split beam must be added. Equal power would be fed to each of the beams and since for a given maximum range with other parameters being constant the transmitter power varies as the square of the antenna beam width we can conclude that the total power requirement of the system as described will be roughly three-quarters that of system A.

Target vertical angle might be determined with such a system by deriving an e.m.f. from the increase in echo pulse length over transmitted pulse length due to the difference in reflected and direct paths. Techniques for accomplishing this have not been developed and present severe difficulties.

2-3. Stacked Beam System (C) Here it is proposed to utilize a series of independent beams tilted progressively upward and becoming broader as the coverage requirements permit. The economic merit of this scheme is demonstrated if we assume any vertical angle sector θ in which full coverage to a given range is desired. Now if n stacked beams are used instead of a single beam, the range depends on the power in one beam, i.e., P/n (P being the total power) as well as on the width of one beam, i.e., θ/n, according to the formula

$$R_o \propto \frac{(P/n)^{\frac{1}{4}}}{(\theta/n)^{\frac{1}{2}}} = \frac{(nP)^{\frac{1}{4}}}{\theta^{\frac{1}{2}}} ;$$

thus if θ and R_o are constant, then $P \propto \frac{1}{n}$. That is, the total power required is inversely proportional to the number of stacked beams employed, arising simply from the fact that while the number of transmitters increases directly as the number of beams used the antenna gain, which is squared for the system, also increases directly and hence the power required in each beam varies inversely as the square of the number of beams.

The most desirable number of beams must result from a compromise between complexity and antenna size on the one hand and average power and quality of information on the other. Eight beams appears as a likely compromise and with 3 db pattern crossover the lower

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beams would then be about 2°.

2-4. Vertical Scanning System (D) In order to avoid excessive scanning loss there should be at least two pulses during the interval in which the angular vertical deflection of the beam is equal to its width. Also the vertical scan cycle must be accomplished in the interval in which the horizontal angular deflection of the beam is equal to its width in this plane. If the vertical scanning angle is 70° and horizontal beam width is taken as the dependent variable we have

$$\theta_H = \frac{70}{\theta_v} \times \frac{2}{220} \times \cancel{\frac{4}{360}} \; \frac{360}{4} \qquad (7)$$

Then if θ_v is made 2° θ_H must be 28.4° if only one beam is used and the total power would then be $(28.4/1.43)^2 \times 1/8 = 49 \times$ that required by the eight beam system (C) on 1200 mcs., and this without taking account of a greater scanning loss. Both azimuth sensitivity and total power might be improved by using a large number of beams shooting in different directions with the rotation speed, i.e., azimuth scanning speed, proportionately reduced. The individual antennae might then scan azimuth sectors only and the entire system would not have to rotate. But if θ_H is reduced to 1.43° for comparison with system C then some 20 antennae are required and the relative total power is $20/8 = 2\frac{1}{2}$ times. However, on this basis the scanning system would have an upward range of 300 instead of 50 miles. Reduction of transmitter power as the beams swing upward does not appear feasible but economy of both power and number of antennae might be obtained by employing non-linear vertical scan, the angular velocity increasing with vertical angle. The vertical angle accuracy and discrimination would then degenerate with high angles as in the case of system C. The ratio of range being $300/50 = 6$ permits loss of sensitivity equivalent to a power reduction of 32 db. The worst case occurs when the antenna is pointed directly on target at the instant of transmission and is consequently off target by the deflection angle α at instant of reception, or vice versa. The deflection angle for the interval .00366 sec. may then be the 32 db point on the antenna pattern. This angle will of course depend on the particular pattern but an assumption of twice the beam width appears reasonable with a widely tapered illumination. Hence at high angles the deflection velocity may be about four times that at low angles, and with a 2° beam these velocities would be about 1092°/sec and 273°/sec. Taking the mean and allowing an arbitrary factor of 1.2 for reversal time gives .27 seconds for the scanning cycle or a rate of 220 per minute, which is impracticably high for such a large structure.

2-5. Summary on System Type

From the foregoing rather rough analyses it appears that a stacked beam system is the best choice of the types considered since it gives better height information without ambiguities and

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requires much less total power than the other fixed beam systems and since it appears much more feasible mechanically than a scanning beam system.

2-6. F.M. vs. Pulse Modulation

Since the foregoing conclusions are based on time-space distribution of energy they should apply equally well for F.M. as for pulse modulation. The Armstrong F.M. system derives an advantage over the pulse system from its greater ability to integrate effectively over a long period of time, but when a rapid scan is required, as in this case, the advantage is completely lost. To avoid scanning loss the modulation cycle can be no longer than the repetition period of the pulse system and for the same range discrimination the time during which echo energy passes to the FM receiver can be no longer than the pulse length in the pulse system. Accordingly the same receiver band width is required in either system and for the same system sensitivity the same peak transmitter power is required. But the average power required by the FM system will then be roughly 150 times as great, and this factor can be reduced only by increasing scanning time or range resolution.

2-7. Antenna Arrangement

The stacked beam system requires relatively little transmitter power because it utilizes to full advantage a very large antenna area. Provision of separate antennae for each of the beams would result in a mechanical monstrosity and the system is feasible only because several beams may be obtained from one reflector by using vertically off-set feeds. Reference (4) shows that with a parabolic reflector off-set of feed up to somewhat more than one beam width will not produce appreciable degeneration of the beam shape. The coverage of one possible eight beam system is shown in Plate 3, a target on which the peak range of the lower beams is 300 miles is assumed and all parameters other than antenna gain are taken to be equal for the eight channels. Cross-over of the lower beams is at the 2 db field strength points. The beam widths and elevation and displacement angles are as follows

Beam Number	Width	Elev. L	Displ. L
1	2.5°	1°	
2	2.5	3	2°
3	2.5	5	2
4	2.5	7	2
5	3.0	9.2	2.2
6	4.9	13	3.8
7	11.5	20	7
8	35	35	15

[redacted]

Another pattern, obtained with eight beams of the same unit sensitivity as above but with crossover of the lower beams at the three db points is given by Plate 4. Better high angle coverage is shown but the signal depression areas are more severe. The beam widths, elevation, and displacement angles for this case are:

Beam Number	Width	Elev.	Displ.
1	2.5°	1.25°	
2	2.5	3.75	2.5°
3	2.5	6.25	2.5
4	3.1	9.0	2.75
5	4.9	12.5	3.5
6	8.8	19.3	6.8
7	20.4	30	10.7
8	46	52	22

Since the displacement angles do not exceed the beam widths in any instance it should be electrically feasible to derive the first three beams from one reflector and the second three from a second reflector.

2-8. Frequency Assuming an eight beam system with a vertical width of the lower beams 2.5 degrees and the first three and second three beams obtained from single reflectors then for a frequency of 1300 mcs. the vertical aperture of these reflectors must be about 18 feet. To obtain the same coverage with a frequency of 3000 mcs. a compromise between antenna gain and scanning loss, as indicated in Section 1-2, must be worked out and the reflectors might be 16 x 22 feet. But the number of beams required would then be sixteen or seventeen and the power required for each would be the same as for the eight beam system at 1300 mcs. Since the maximum power that can be generated in a magnetron or other tube or transmitted by a wave guide increases roughly as the square of the wave length it is apparent that increasing frequency is decidedly unprofitable. On the other hand decreasing frequency below the assumed 1300 mcs. does not appear so unattractive. Operation at 650 mcs. with the same maximum range, power, etc. per beam and the same horizontal antenna aperture should give a 2.5 db reduction in scanning loss (Plate 2). The vertical aperture required is therefore 1½ times or 27 feet and the lower beam widths would be 3.3° vertically. Six beams might then be used instead of eight so a 25% reduction in total power is obtained. Balanced against this, however, in addition to the increased antenna size, is the bulkiness of 650 mcs. wave guide, and fittings, the mechanical difficulty, if not impossibility of providing the multiple antenna feeds, the loss in azimuth accuracy and discrimination, greater vulnerability to jamming, and some likelihood of lower effective reflecting area with small targets.

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It is therefore concluded with some reservations that the present band of 1150 to 1350 megacycles is most desirable for the proposed system.

3. THE PROPOSED SYSTEM

The foregoing discussion has led to the conclusion that the system should operate in the 1150 to 1350 megacycle band with eight, or perhaps nine, stacked beams, the lower beam widths being about 2.5° vertically and 1.5° horizontally. It remains to establish the power required for the specified performance and the means by which the radar information is to be presented and employed.

3-1. Pulse Power Requirements Anticipated power requirements and range coverage can best be established by extrapolation from experimental results obtained with the Marine Corps AN/TPS-1B system (Reference 5). This system has an antenna aperture 4 x 15 feet, pulse power of about 700 KW, pulse length of 2 microseconds, repetition rate of 200 per second, and receiver noise factor of about 13 db. In the trials at the NRL Chesapeake Bay Station a peak range of 195 n. miles was obtained with a B-24 target plane. If the reflecting area of this plane is taken as 57 square meters a very good check between theoretical and actual performance is obtained.

Compared with the AN/TPS-1B, the proposed system thus far has an advantage in antenna gain of $(18 \times 35)/(4 \times 15) = 10.5$ times in power or 10.2 db. In terms of system power gain this gives 20.4 db. Since the minimum target has been taken to be one square meter, compared with a B-24 this represents a power loss of 57 times or -17 db, and since sea reflection was present in the AN/TPS-1B tests whereas the proposed system must operate under free space conditions, the latter has a 12 db disadvantage on this score. Also in the CBA tests a narrow sector scan was used and this should give about 1 db advantage on effective antenna gain and perhaps 3 db on integration compared to the porposed system with continuous rotation at 15 r.p.m. In the proposed system it appears reasonable to expect that improvements in crystals or tubes will result in at least a 3 db improvement in receiver noise factor and by use of non-coherent c.w. injection possibly another 3 db can be realized (Reference 7). If a ten microsecond pulse proves feasible an advantage of 7 db should be had from this with perhaps 1 db gain from improved pulse length to writing speed ratio. Summing all these factors gives $20 + 3 + 3 + 7 + 1 - 17 - 12 - 1 - 4 = 0$ db between the systems for the same transmitter peak power but with a B-24 target over water on the one hand and one square meter in free space on the other. But in order to have substantially solid coverage out to 300 miles the proposed system should have a peak range of 350 miles with eight beams or perhaps 330 with nine beams. This introduces a factor of $(350/195)^4 = 10.4$ in power and hence with a 10 microsecond pulse the pulse power required is about 7 megawatts for each of the eight

[redacted]

beams. The HP 10 V magnetron developed by Radiation Laboratories (Reference 6) gave 2.5 megawatts peak and 1250 watts average power at 3000 mcs. Since the maximum power obtainable with a given type of tube is in general proportional to the square of the wavelength 13 megawatts peak power on L band appears possible. However, the duty cycle proposed with 7 megawatts is .0022 giving 15.4 KW average power. Scaling the HP 10V would result in 6.6 KW average power output so both anode and cathode cooling may present severe problems. In delivering the power to the antenna it is proposed to use 1% frequency separation between the channels with feed through $6\frac{1}{2}$ inch rectangular wave guide and appropriate filters and transducers into a common $8\frac{1}{2}$ inch cylindrical wave guide with TM_{01} propagation. The rotary joint will be in the cylindrical guide and redistribution through another set of filters to the individual antenna feeds will take place on the other end. The peak power capacity of the rectangular guide without pressurization is over 50 megawatts and that of the cylindrical guide is at least 46 megawatts. Simultaneous pulsing of the transmitters presents the possibility of 8^2 x 7 = 450 megawatt peaks in the cylindrical guide. However, by reason of mutual coupling the magnetrons should start in phase and in this case this extreme peak will not occur within the pulse interval. Lesser, but still excessive peaks may well occur, but if this proves an obstacle the pulses can be staggered in time. The filters present a more serious break-down problem which requires study, and pressurizing with corona suppressors will undoubtedly be necessary.

3-2. Average Power Requirements

With 15.4 KW average power per beam the total average r.f. power for the eight beams is 123 KW. Assuming a magnetron efficiency of 50% and a power supply modulator efficiency of 75% the input power jumps to 330 KW. Adding to this 50 KW for blowers, receivers, and auxiliaries and 10 KW for rotation and stabilization of the antenna a total power requirement of about 400 KW is obtained. This figure is of course an extremely rough approximation and is presented only to indicate the order of magnitude to be anticipated.

3-3. Presentation and Use of Data

The performance and power calculations in Section 3-1 are based on the assumption that for primary detection of targets the eight beams will feed individual P.P.I. scopes and will not be mixed. This seems desirable to avoid too great concentration of information. It is planned then to have eight P.P.I.'s, each showing only one vertical angle sector. These would be provided with one or more rough range and azimuth gates and upon detection of a target the operator would immediately gate the signal and this operation would put it also on an auxiliary B scope with another operator. This second operator would then track the target

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and supply the range and azimuth information to an automatic computer which would in turn train a guide beam for a counter missile. Information from the two adjoining beams would also be fed into an interpolating circuit which would supply elevation angle information to the computer and would provide automatic switching of the B scope with progression of the target through the separate beams. The overall picture might be presented by photo cell or television camera pick-up of the primary P.P.I.'s and video insertion of identifying data could be provided by use of crayon marks on plexiglass screens with edge lighting. The video information from the eight channels would then be mixed and projected on a large central C.I.C. screen. The signal noise ratio of this master would be 4.5 db below the individual scopes because of combined noise, but weak signals might still be shown by the video insertion marks.

3-4. Height Accuracy

It is not planned to give height directly but rather elevation angle as this is much more convenient and is the information required by the computer and counter missile trainer. As indicated in the above section accurate elevation angle information will be obtained by comparison of the signal strength in the adjoining beams. Plate 5 shows a plot of typical 2.50° antenna patterns with overlap at the 2 db points so as to correspond with the lower beams of Plate 3. In view of the very wide dynamic range desired it is probably best to interpolate by ratio of signal strength. The change in ratio for 15' steps has been plotted along the abscissa of Plate 5 and is between 4 and 5 db. Hence with sufficiently strong signals an accuracy of better than 10' might be achieved. At high angles the accuracy would be considerably less and dependent largely on the actual beam patterns. If the antenna reflectors are mounted back to back or as the sides of a rectangle as is certainly very desirable from the structural standpoint it will be necessary to hold over the interpolation operation for one second when the beams involved are in different quadrants. This should be possible but will result in considerable error for high velocity targets due to the target movement in this interval. Possibly a correction could be introduced by the computer from the rate information.

3-5. I.F.F. It does not appear possible to provide i.f.f. antenna feed in the system as described; certainly not until the frequency and other characteristics of the i.f. system are known. It is thought that a practical solution to this problem is the use of slave antennae.

4. CONCLUSION

It is concluded that it is feasible to develop a radar system capable of giving accurate range, azimuth, and elevation information at a rate of fifteen times a minute on any target having an effective reflecting area of one square meter or more within 300 miles range

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and 50 miles height. Whether it is feasible to make such a system ship-borne has not been considered. Although the system proposed does not call for radically different components or techniques both the peak and the average powers involved are of higher orders of magnitude than in any system heretofore developed and the problems of generating and utilizing these powers are both difficult and long term. An advantage of the proposed multi-beam system is that step-by-step construction and test is possible.

[redacted]

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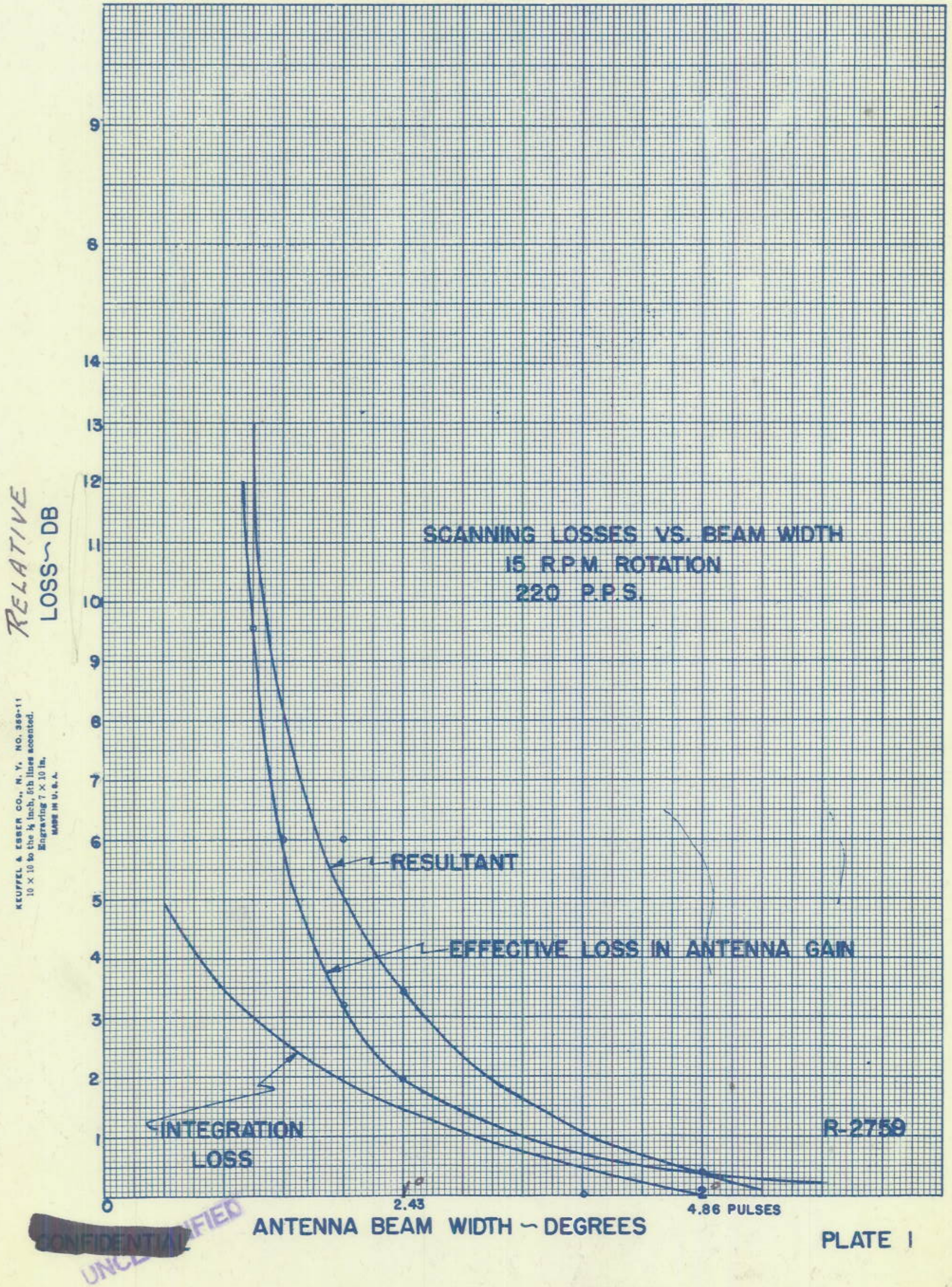
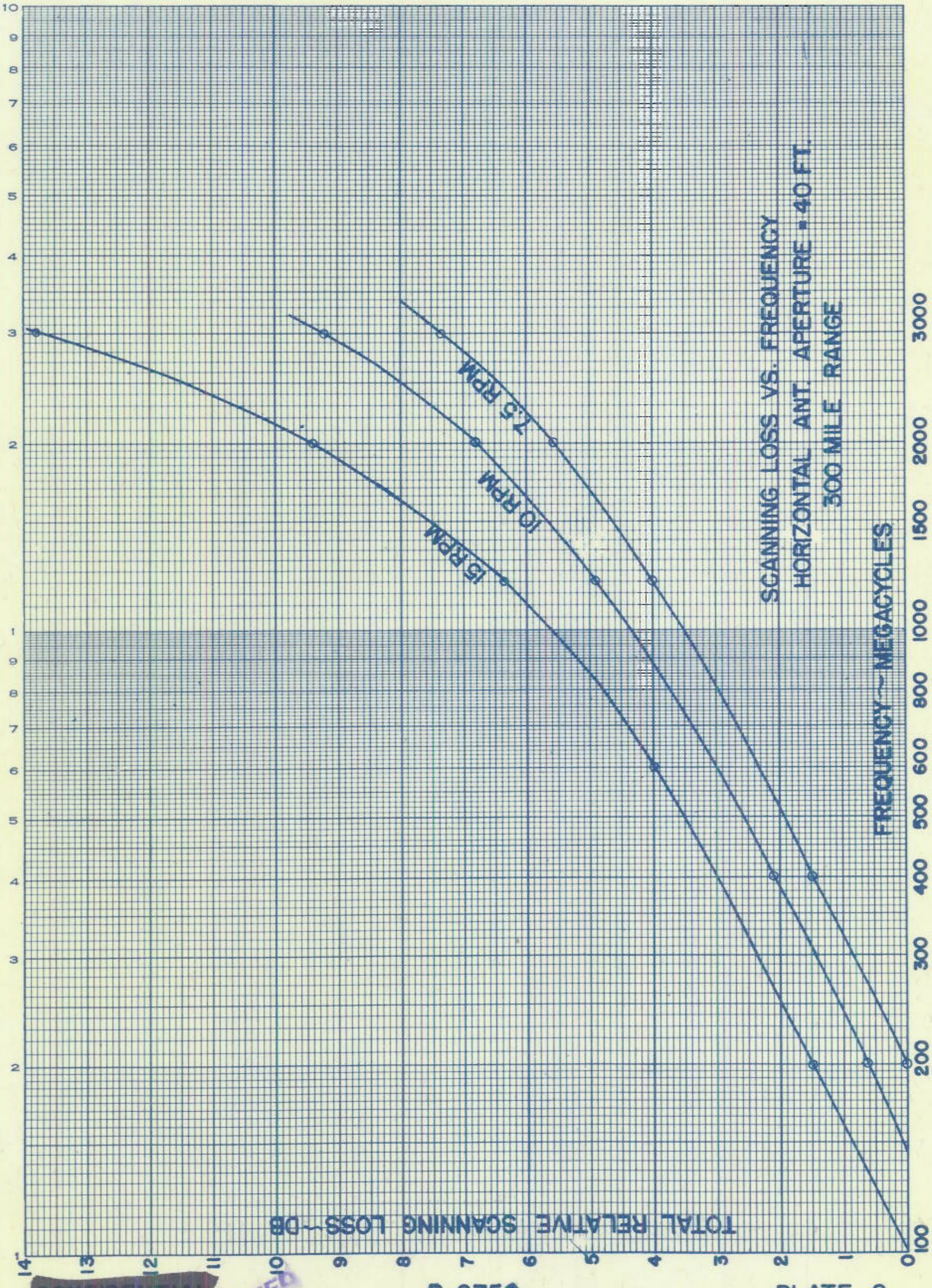


SCANNING LOSSES VS. BEAM WIDTH
15 R.P.M. ROTATION
220 P.P.S.

PLATE I



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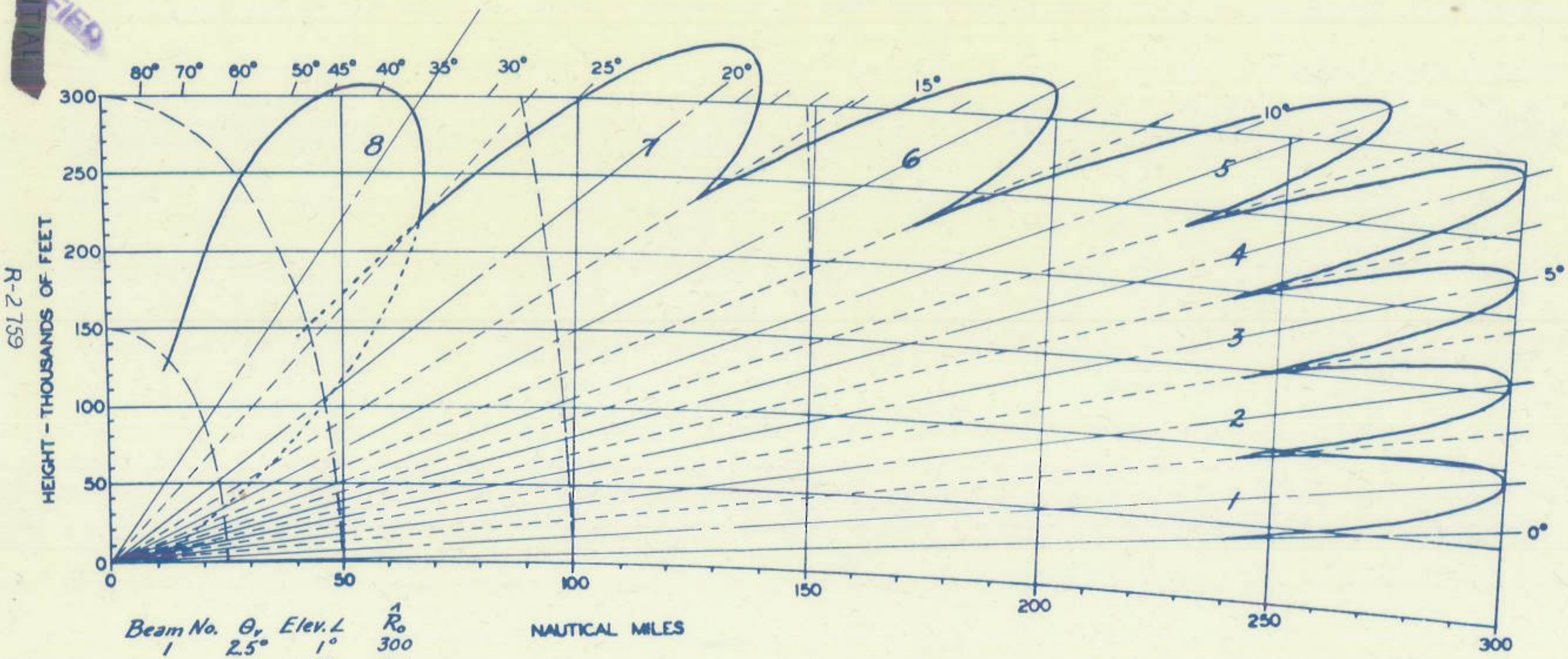

Beam No.	θ_r	Elev. ∠	$\hat{R}_o$
1	2.5°	1°	300
2	2.5	3°	300
3	2.5	5	300
4	2.5	7	300
5	3.0	9.2	270
6	4.9	13	200
7	11.5	20	140
8	35	35	80

EIGHT BEAM SYSTEM ~ 2 DB OVERLAP

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PLATE 3

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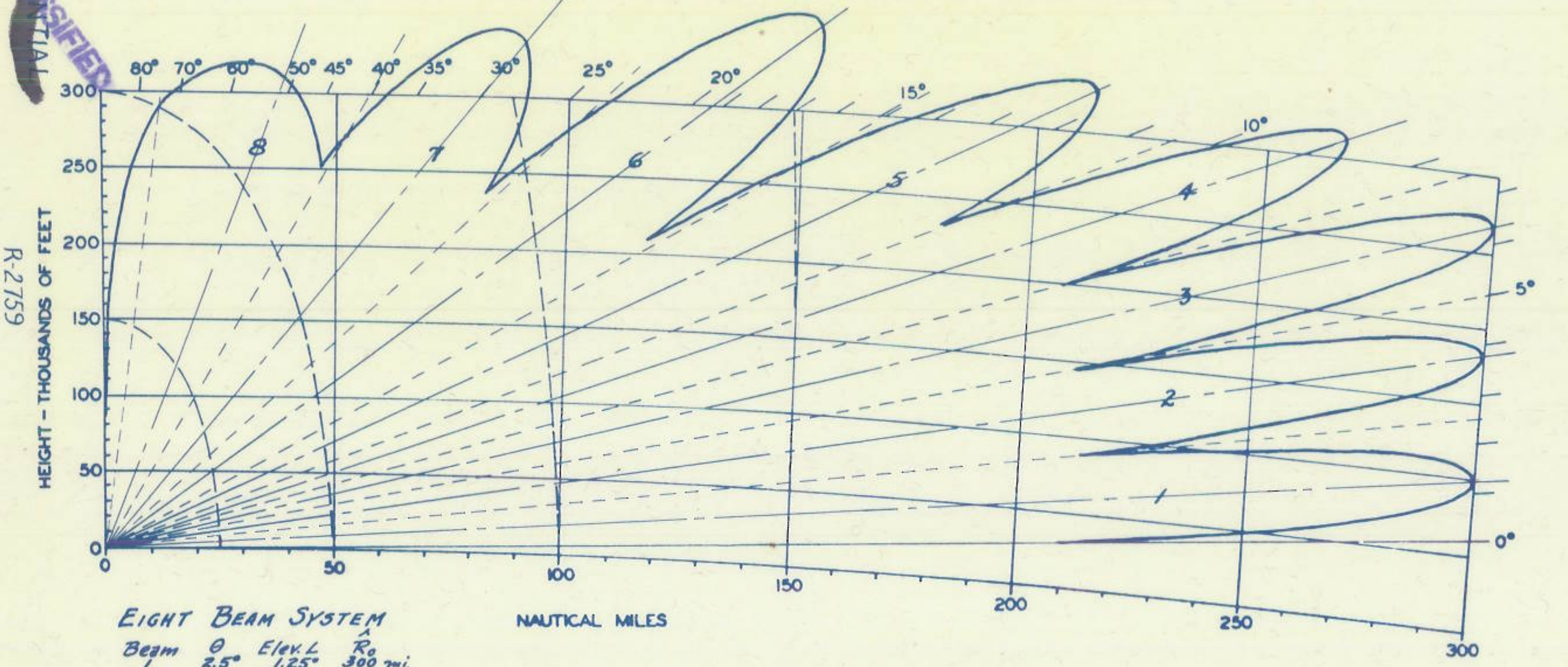

EIGHT BEAM SYSTEM

Beam	θ	Elev. ∠	$\hat{R}_o$
1	2.5°	1.25°	300 mi.
2	2.5	3.75	300
3	2.5	6.25	300
4	3.1	9.0	270
5	4.9	12.5	215
6	8.8	19.3	160
7	20.4	30	105
8	46.0	52	70

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PLATE 4

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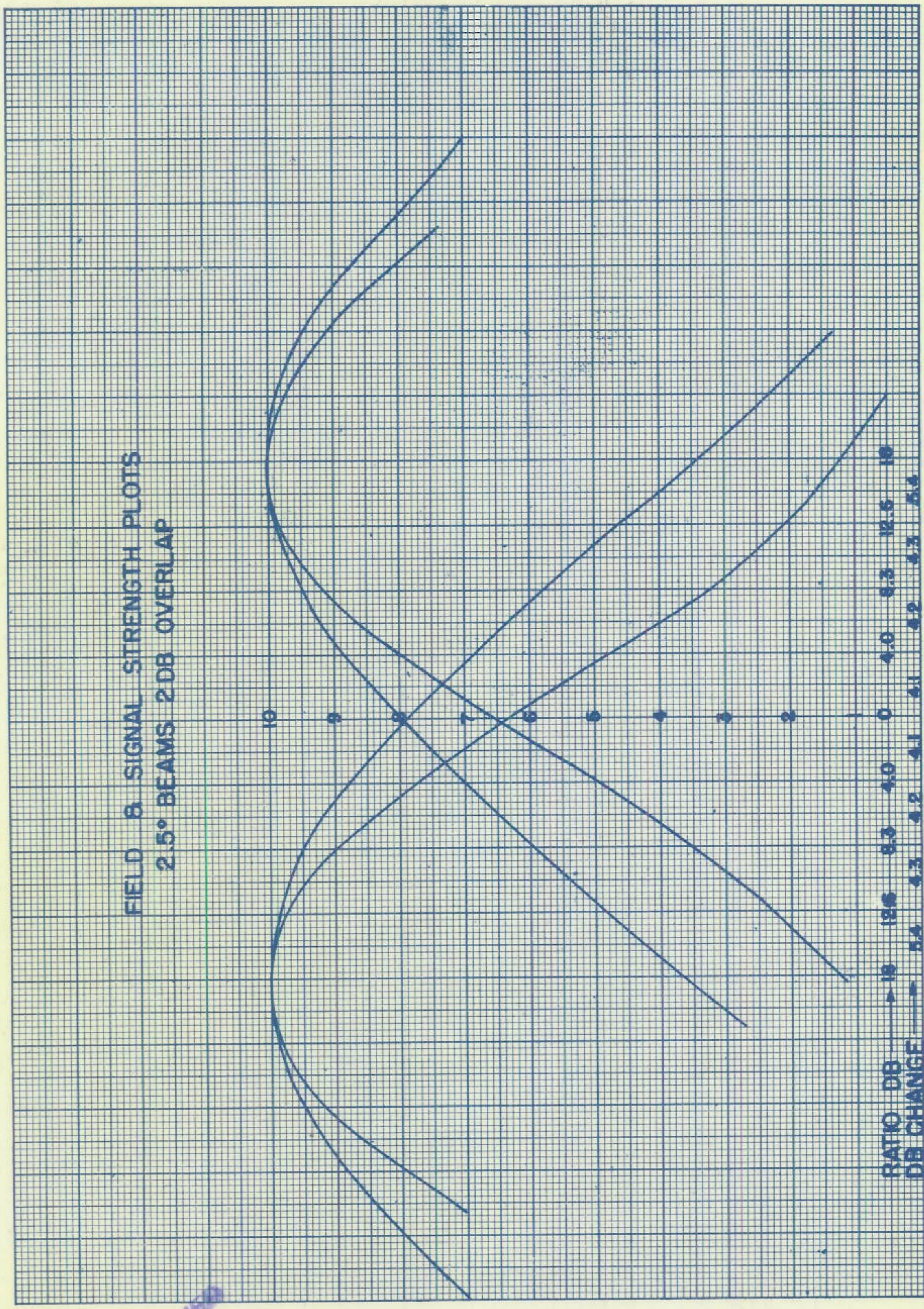

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