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25 May 1942

NRL Report No. R-1878
BuShips Prob. B1-R and B8-2R

NAVY DEPARTMENT

FR-1878

Declassified by NRL Report No. 3085

Report on

Coupling between Antennas

at Intermediate Frequencies

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WASHINGTON, D. C.

Number of Pages: Text - 42 Tables - 2 Plates - 39.

Authorization: Bureau of Ships Problems B1-R and B8-2R.

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Radio Materiel School, Bellevue, D.C. (10)
Radio and Sound Lab., San Diego (1)

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TABLE OF CONTENTS

AUTHORIZATION.	Page	1
INTRODUCTORY		1
THEORY		2
Coupling between Two Vertical Antennas. . . .		2
Coupling between Two Partially Shielded Vertical Antennas with Slanting Top Sections.		9
Conditions for Maximum and Minimum Radiation Resistance		11
Measurement of the Coupling Impedance or $R_m - j X_m$.		12
Examples.		15
EXPERIMENTAL WORK.		21
Antenna Constants		23
Field Strength Measurements		23
Antenna Current Measurements.		24
RESULTS.		25
Antenna Constants		25
Antenna Currents.		27
Field Strength.		32
APPLICATIONS		35
SUMMARY.		38

APPENDICES

Comparison of Theoretical and Experimental Values of the Coupling Reactance between Antenna 2 and Antenna 1	Table	1
The Measured Values of X_m with and without a Vertical Ground Wire between the Coupled Antennas.		2
Diagram for coupled vertical antennas.	Plate	1
Diagram for coupled antenna system		2
Diagram for coupled antenna system consisting of 160-foot verticals spaced 30 feet.		3
Diagram for coupled antenna system consisting of 50 and 150-foot verticals spaced 30 feet . .		4
Ratio of antenna-2 to antenna-1 currents as function of frequency for coupled antenna system shown in Plate 3. Resonance frequency of antenna-2 system - 207 kc, ...		5
Phase lead of antenna-2 current relative to antenna-1 current as function of frequency for coupled antenna system shown in Plate 3. Resonance frequency of antenna-2 system - 207 kc.		6

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Resistance and radiation resistance of antenna-1 system as function of frequency for coupled antenna system shown in Plate 3. . . . . Plate 7
Radiation efficiency of transmitter antenna system shown in Plate 3 as function of frequency. 8
Resistance and radiation resistance of antenna-1 system as function of frequency for coupled antenna system shown in Plate 4. 9
Radiation efficiency of transmitter-antenna system shown in Plate 4 as function of frequency. 10
Radiated power as function of frequency for TBL-2 transmitter. 11
Resistance and capacity of antenna-1 system as function of frequency for coupled antenna system consisting of 160-foot verticals spaced 30 feet 12
Resistance and capacity of antenna-1 system as function of frequeney for coupled antenna system consisting of 160-foot verticals spaced 30 feet 13
Resistance and capacity of antenna-1 system as function of frequency for coupled antenna system consisting of 160-foot verticals spaced 10 feet 14
Resistance and capacity of antenna-1 system as function of frequency for coupled antenna system consisting of 160-foot verticals spaced 10 feet and with a 160-foot ground wire between them. 15
Resistance and capacity of antenna-1 system as function of frequency for coupled antenna system consisting of 60-foot verticals spaced 30 feet. 16
Resistance and capacity of antenna-1 system as function of frequency for coupled antenna system consisting of 60-foot verticals spaced 10 feet 17
Resistance and capacity of antenna-1 system as function of frequency for coupled antenna system consisting of 60-foot verticals spaced 10 feet and with a grounded 60-foot vertical between them. 18
Resistance and capacity of antenna-1 system as function of frequency for coupled antenna system consisting of 60-foot verticals spaced 5 feet. 19

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DECLASSIFIED

Resistance and capacity of antenna-1 system as function of frequency for coupled antenna system consisting of 60-foot verticals spaced 5 feet and with a grounded 60-foot vertical between them. . . . . Plate 20
Antenna and antenna-system currents as function of frequency for coupled antenna system consisting of 160-foot vertical antennas spaced 30 feet. Resonance frequency of antenna-2 system - 207 kc 21
Ratio of antenna-2 to antenna-1 measured currents as function of frequency for coupled antenna system shown in Plate 3. Resonance frequency of antenna-2 system - 207 kc. 22
Antenna-1 current as function of frecuency for antenna system shown in Plate 3 23
Antenna and antenna-system currents as function of frequency for coupled antenna system consisting of 160-foot vertical antennas spaced 10 feet. Resonance frequency of antenna-2 system - 207 kc 24
Antenna and antenna-system currents as function of frequency for coupled antenna system consisting of 160-foot vertical antennas spaced 10 feet and with a grounded 160-foot vertical between the antennas. Resonance frequency of antenna-2 system - 207 kc. 25
Antenna and antenna-system currents as function of frequency for coupled antenna system consisting of 60-foot vertical antennas spaced 30 feet. Resonance frequency of antenna-2 system - 237 kc 26
Antenna and antenna-system currents as function of frequency for coupled antenna system consisting of 60-foot vertical antennas spaced 10 feet. Resonance frequency of antenna-2 system - 237 kc 27
Antenna and antenna-system currents as function of frequency for coupled antenna system consisting of 60-foot vertical antennas spaced 10 feet and with a grounded 60-foot vertical between the antennas. Resonance frequency of antenna-2 system - 237 kc 28
Antenna and antenna-system currents as function of frequency for coupled antenna system consisting of 60-foot vertical antennas spaced 5 feet. Resonance frequency of antenna-2 system - 237 kc 29

DECLASSIFIED

Antenna and antenna-system currents as function of frequency for coupled antenna system consisting of 60-foot vertical antennas spaced 5 feet and with a grounded 60-foot vertical between the antennas. Resonance frequency of antenna-2 system - 237 kc. . . . . Plate 30
Ratio of field strengths for antenna-2 system grounded and for resonance frequency of antenna-2 system at 207 kc as function of frequency for 160-foot vertical antennas spaced 30 feet (see Plate 3) 31
Ratio of field strengths for antenna-2 system grounded and for resonance frequency of antenna-2 system at 207 kc as function of frequency for 160-foot vertical antennas spaced 10 feet (see Plate 3) 32
Ratio of field strengths for antenna-2 system grounded and for resonance frequency of antenna-2 system at 237 kc as function of frequency for 60-foot vertical antennas spaced 10 feet 33
Ratio of field strengths for antenna-2 system grounded and for resonance frequency of antenna-2 system at 237 kc as function of frequency for 60-foot vertical grounded wire between two 60-foot vertical antennas spaced 10 feet 34
Ratio of field strengths for antenna-2 system grounded and for resonance frequency of antenna-2 system at 237 kc as function of frequency for 60-foot vertical antennas spaced 5 feet. 35
Ratio of field strengths for antenna-2 system grounded and for resonance frequency of antenna-2 system at 237 kc as function of frequency for 60-foot vertical grounded wire between two 60-foot vertical antennas spaced 5 feet 36
Coupling reactance, X_m, between two 160-foot vertical antennas as a function of antenna spacing at 200, 400, and 600 kc. 37
Coupling between two vertical antennas of the same height as a function of their height for various spacings between antennas at 200 kc 38
Ratio of coupling reactance, X_m, between two vertical antennas of the same height to reactance, X, of antenna-1 only as a function of their heights for various spacings between antennas at 200 kc. 39

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AUTHORIZATION

1. The general problem of investigating antenna and antenna systems is authorized by Bureau of Ships Problem B1-R and B8-2R.

Reference: (a) NRL Report No. R-1658 of 8 October 1940, "Report on Investigation of Antenna Systems on USS SEADRAGON, USS SEARAVEN, USS TAMBOR, USS TRIPPE and USS MAYRANT."

(b) NRL Report No. R-1448 of 13 June 1938, "A Study of the Radiation Characteristics of Shipboard Antenna Systems."

(c) NRL Report No. R-1796 of 4 November 1941, "Investigation and Measurement of Radio Transmitting Antenna Systems on USS NORTH CAROLINA.

INTRODUCTORY

2. Naval personnel have observed that coupling exists between various intermediate-frequency antennas and that this coupling produces serious effects if the coupled antenna system (including antenna loading coil) is near its resonance frequency. The general procedure used to avoid these coupling difficulties was to be sure that no two transmitter-antenna systems were tuned to nearly the same frequency. This can be accomplished by grounding or opening all antenna systems that are not in actual use. By following the above simple precautionary measures, the detrimental effects of coupling between transmitting antennas at the intermediate frequencies have been avoided.

3. The following investigation was undertaken in order to obtain a clearer understanding of the coupling between antennas, the magnitude and phase of the coupling impedance, the methods of computing the coupling impedance, the methods of measuring coupling impedance, the necessary frequency separation between tuned transmitter-antenna systems in order to avoid detrimental coupling effects, and ways of reducing the coupling coefficient. This information should prove helpful in designing antennas when a number of intermediate-frequency antennas are to be located in a relatively small area and in operating a number of closely spaced transmitter-antenna systems at maximum efficiency.

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THEORY

4. The general problem to be solved is the coupling between two partially shielded vertical antennas with slanting top sections. The general solution for this antenna system would be very complex and probably would be of little practical value. The simpler problem on the coupling between two vertical antennas of different heights can be readily solved and the results expressed in a form which lends itself to easy computation. The solution for the more general case of the coupling between two partially shielded antennas can be expressed in the same form as for the vertical antennas, but in terms of a number of constants. Methods are indicated for determining these constants by experimental measurements. Hence, a solution is obtained for the general problem.

Coupling Between Two Vertical Antennas

5. The two vertical antennas are of heights L_1 and L_2 above a conducting flat earth (see Plates 1 and 2). The current I_{1a} at the base of antenna 1 and the antenna-1 system current I_{1s} (see Plate 2) are produced by a transmitter connected to this system. Antenna 2 is assumed to be grounded at its base. The current I_{2a} is produced by the coupling between the two antennas. Later in the theory, the antenna-2 system will be assumed to be grounded through a base loading coil, as shown in Plate 2.

6. The current at any height z in antenna 1 is given by

$$i_{1z} = \frac{I_{1a}}{\sin kL_1} \sin k(L_1 - z) \sin \omega t \qquad (1)$$

Where i_{1z} is the current at a height z in antenna 1,
ω is $2\pi f$,
f is the frequency in cycles per second,
k is $2\pi/\lambda$,
λ is the wave length, in feet,
t is the time,
c is the velocity of light,
L_1 is the height of antenna 1.

7. Similarly, the current at any height u in antenna 2 is given by

$$i_{2u} = \frac{I_{2a}}{\sin kL_2} \sin k(L_2 - u) \sin \omega t \qquad (2)$$

where L_2 is the height of antenna 2.

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8. From Maxwell's Equations it can be shown that the z component of the electric field produced by antenna 1 at the point P is given by

$$E_{1z} = \frac{30\, I_{1a}}{\sin kL_1} \left\{ \frac{2\cos(\omega t - kr_o)}{r_o} \cos kL_1 - \frac{\cos(\omega t - kr_1)}{r_1} - \frac{\cos(\omega t - kr_2)}{r_2} \right\} \tag{3}$$

Where E_{1z} is the electric field at the point P in volts per meter,
I_{1a} is the current in amperes at the base of the antenna,
r_o, r_1, and r_2 are distances in meters (see Plate 1).

9. A similar expression is obtained for the field E_{2u} produced by antenna 2 at any point P.

10. If the point P coincides with the surface of antenna 1, then the power radiated by this antenna is

$$P_{11} = -\int_0^{L_1} E_{1z}\, i_{1z}\, dz \tag{4}$$

The minus sign appears in Eq. (4) since E_{1z} is the electric field produced by the current in antenna 1 and is equal and opposite to the electric field that produces the current in antenna 1.

11. The power supplied to antenna 1, due to the presence of antenna 2 or the transfer of power from antenna 1 to antenna 2, must also be fed to antenna 1, or

$$P_{12} = -\int_0^{L_1} E_{2u}\, i_{1z}\, dz \tag{5}$$

Where E_{2u} is the field produced at antenna 1 by the current flowing in antenna 2.

12. Similarly, the power supplied to antenna 2 due to the presence of antenna 1 is

$$P_{21} = -\int_0^{I_2} E_{1z}\, i_{2u}\, d_u \tag{6}$$

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13. It can be shown that

$$P_{12} = P_{21} \tag{7}$$

14. Finally, the power radiated by antenna 2 is

$$P_{22} = -\int_0^{L_2} E_{2u}\, i_{2u}\, d_u \tag{8}$$

15. The power that must be supplied to antennas 1 and 2 is given by the following equations:

$$P_1 = P_{11} + P_{12} \tag{9}$$

$$P_2 = P_{21} + P_{22} = P_{12} + P_{22} \tag{10}$$

Where P_1 is the power input to antenna 1,
P_2 is the power input to antenna 2.

16. In this application, P_2 is zero; hence, Eq. (9) and (10) become

$$P_1 = P_{11} + P_{12} \tag{11}$$

$$0 = P_{12} + P_{22} \tag{12}$$

17. If one solves Eq. (4), (5), (6) and (8) and, in addition, makes the following assumptions:

(a) $D \leq \lambda/15$
(b) $L_1 \leq \lambda/10$
(c) $L_2 \leq \lambda/10$,

then one obtains, after considerable manipulation,

$$P_{11} = \left[10k^2L_1^2 - j\frac{60}{kL_1}\left\{\left(\log_e \frac{24L_1}{d}\right) - 1\right\}\right] I_{1a}^2 \tag{13}$$

$$P_{12} = P_{21} = \left[10k^2L_1L_2 - jXm \right] I_{1a}I_{2a} \tag{14}$$

$$P_{22} = \left[10k^2L_2^2 - \frac{60}{kL_2}\left\{\left(\log_e \frac{24L_2}{d}\right) - 1\right\}\right] I_{2a}^2 \tag{15}$$

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where

$$X_m = \frac{30}{kL_1L_2}\left\{2D - 2\sqrt{D^2 + L_1^2} - 2\sqrt{D^2 + L_2^2}\right.$$

$$+ \sqrt{D^2 + (L_1 - L_2)^2} + \sqrt{D^2 + (L_1 + L_2)^2}$$

$$- \frac{(L_1 + L_2)}{2} \log_e \left[\frac{\sqrt{D^2 + (L_1 + L_2)^2} + (L_1 + L_2)}{\sqrt{D^2 + (L_1 + L_2)^2} - (L_1 + L_2)}\right] \quad (16)$$

$$+ \frac{(L_1 - L_2)}{2} \log_e \left[\frac{\sqrt{D^2 + (L_1 - L_2)^2} - (L_1 - L_2)}{\sqrt{D^2 + (L_1 - L_2)^2} + (L_1 - L_2)}\right]$$

$$\left. + L_1 \log_e \left[\frac{\sqrt{D^2 + L_1^2} + L_1}{\sqrt{D^2 + L_1^2} - L_1}\right] + L_2 \log_e \left[\frac{\sqrt{D^2 + L_2^2} + L_2}{\sqrt{D^2 + L_2^2} - L_2}\right]\right\}$$

18. If the antennas are the same height L, then Eq. (16) reduces to

$$X_m = \frac{30}{kL}\left\{\frac{3D}{L} - \frac{4\sqrt{D^2 + L^2}}{L} + \frac{\sqrt{D^2 + 4L^2}}{L}\right.$$

$$\left. + 2 \log_e \left[\frac{\sqrt{D^2 + L^2} + L}{\sqrt{D^2 + L^2} - L}\right] \left[\frac{\sqrt{D^2 + 4L^2} - 2L}{\sqrt{D^2 + 4L^2} + 2L}\right]^{1/2}\right\} \quad (17)$$

19. If, in addition to the antennas being the same height, the spacing is such that $6D < L$, then X_m is given quite accurately by

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$$X_m = \frac{30}{kL}\left\{\frac{3D}{L} - 2 - \frac{7D^2}{4L^2} + 2\log_e\left(\frac{L}{D}\right)\right\} \qquad (18)$$

20. In Eq. (13) to (15), the loss resistance of both antennas has been neglected and, in addition, antenna 2 has been assumed grounded at its base. Now, if one considers the more practical case in which antenna 2 is connected to a trunk and the trunk is connected to the loading coil of a transmitter (see Plate 2) and, in addition, if the loss resistances of antenna 1 and the antenna-2 system including the loading coil are included, one obtains

$$P_{11} = (R_{1a} + j X_{1a}) I_{1a}^2 \qquad (19)$$

$$P_{12} = (10k^2 L_1 L_2 - j X_m) I_{1a} I_{2a} \qquad (20)$$

$$P_{22} = (R_{2t} + j X_{2t}) I_{2a}^2 \qquad (21)$$

$$X_{1a} \cong -\frac{60}{kL_1}\left\{\left(\log_e \frac{24L_1}{d}\right) - 1\right\} \qquad (22)$$

$$X_{1a} = -\frac{10^{12}}{2\pi f C_{1a}} \qquad (23)$$

$$X_{2t} \cong \frac{10^{12}}{\pi f_r C_{2a}}\left(\frac{f - f_r}{f_r}\right) \qquad (24)$$

for a base loaded antenna near resonance.

$$R_{2t} = \left(\frac{I_{2s}}{I_{2a}}\right)^2 (R_{2s} + R_{2L}) \qquad (25)$$

$$R_{2t} = \left(\frac{C_{2s}}{C_{2s} - C_{2t}}\right)^2 (R_{2s} + R_{2L}) \qquad (26)$$

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R_{1a} is the resistance of antenna 1 only. It is the sum of the loss resistance and radiation resistance.

X_{1a} is the reactance of antenna 1 only and can be computed from Eq. (23). If the antenna capacity is not known, then Eq. (22) can be used to give the approximate value.

X_m is the reactive component of the coupling impedance.

$10k^2L_1L_2$ is the resistive component of the coupling impedance.

R_{2t} is the resistance of the antenna-2 system including the base loading coil referred to the base of the antenna. R_{2t} can be computed from Eq. (25) or (26).

R_{2s} is the resistance of the antenna-2 system. It is the sum of the radiation and loss resistance.

R_{2L} is the resistance of the base loading coil in the antenna-2 system. If a transmitter is connected to the antenna-2 system, then R_{2L} is the resistance of the antenna loading coil in the transmitter.

X_{2t} is the reactance of the antenna-2 system referred to the base of the antenna. If the antenna 2 is base loaded and at resonance, then X_{2t} is zero. For frequencies near the resonance frequency of the antenna 2, the reactance X_{2t} can be computed from Eq. (24). For antenna 2 grounded at its base, $X_{2t} = 1/2\pi fC_{2a}$.

d is the diameter of the antenna wire in inches.

L_1 is the height of antenna 1 in feet.

L_2 is the height of antenna 2 in feet.

f is the operating frequency in c.p.s.

C_{1a} is the capacity of antenna 1 in $\mu\mu f$.

C_{2a} is the capacity of antenna 2 in $\mu\mu f$.

f_r is the resonance frequency in c.p.s. of antenna 2 when base loaded.

I_{2s} is the antenna-2 system current in amperes.

C_{2s} is the capacity in $\mu\mu f$ of the antenna-2 system.

C_{2t} is the capacity in $\mu\mu f$ of the trunk in the antenna-2 system.

21. Substituting Eq. (20) and (21) in Eq. (12), one obtains

$$I_{2a} = - I_{1a} \frac{\left[10k^2L_1L_2 - j X_m\right]}{R_{2t} + j X_{2t}} \qquad (27)$$

22. Then, substituting Eq. (27), (19) and (20) in Eq. (11), one has

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$$P_1 = I_{1a}^2 \left\{ R_{1a} + j X_{1a} + \frac{(X_m^2 - 100k^4L_1^2L_2^2) R_{2t} + 2k^2L_1L_2 X_m X_{2t}}{R_{2t}^2 + X_{2t}^2} - j \frac{\left[X_{2t} (X_m^2 - 100k^4L_1^2L_2^2) - 20k^2L_1L_2 X_m R_{2t}\right]}{R_{2t}^2 + X_{2t}^2} \right\} \quad (28)$$

and

$$P_1 = I_{1a}^2 (R_a + j X_a) \quad (29)$$

Where R_a is the resistance referred to at the base of antenna 1 when antenna 1 is coupled to antenna 2,
X_a is the reactance referred to the base of antenna 1 when antenna 1 is coupled to antenna 2.

23. From Eq. (28) and (29), one obtains

$$R_a = R_{1a} + \frac{\left[(X_m^2 - 100k^4L_1^2L_2^2) R_{2t} + 2k^2L_1L_2 X_m^2 X_{2t}\right]}{R_{2t}^2 + X_{2t}^2} \quad (30$$

$$X_a = X_{1a} - \frac{X_{2t} (X_m^2 - 100k^4L_1^2L_2^2) - 20k^2L_1L_2 X_m R_{2t}}{R_{2t}^2 + X_{2t}^2} \quad (31$$

24. It should be noted that R_a as given by Eq. (30) is the sum of the radiation and loss resistance. The radiation resistance component of the resistance R_a is

$$R_{ra} = 10k^2L_1^2 \left\{ \frac{(R_{2t} - 10k^2L_2^2)^2 + (X_{2t} + X_m L_2/L_1)^2}{R_{2t}^2 + X_{2t}^2} \right\} \quad (32)$$

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25. In the majority of applications, it is desirable to know the resistance and the radiation resistance of the antenna system. If one refers the antenna resistance and radiation resistance as given by Eq. (30) and (32) to the transmitter end of the trunk 1 and includes the loss resistance of trunk 1, then one obtains

$$R_s = R_{1s} + \frac{\left[(X_m^2 - 100k^4L_1^2L_2^2)\, R_{2t} + 20k^2L_1L_2\, X_m\, X_{2t}\right]}{(R_{2t}^2 + X_{2t}^2)\, I_{1s}^2} I_{1a}^2 \quad (33)$$

$$R_{rs} = 10k^2L_1^2 \left\{ \frac{(R_{2t} - 10k^2L_2^2)^2 + (X_{2t} + X_m\, L_2/L_1)^2}{R_{2t}^2 + X_{2t}^2} \right\} \frac{I_{1a}^2}{I_{1s}^2} \quad (34)$$

$$\frac{I_{1a}}{I_{1s}} \simeq \frac{C_{1s} - C_{1t}}{C_{1s}} \quad (35)$$

Where R_s is the resistance of antenna-1 system when it is coupled to the antenna-2 system. R_s is referred to the transmitter end of the trunk. Note both antennas must be simple verticals.

R_{1s} is the resistance of the antenna-1 system when the effect of coupling between the two antennas is negligible.

R_{rs} is the radiation resistance of the antenna-1 system when it is coupled to the antenna-2 system.

26. It must be emphasized that Eq. (33) and (34) are valid for vertical antennas that are in the clear (no shielding).

Coupling Between Two Partially Shielded Vertical Antennas With Slanting Top Sections

27. The following assumptions are made in regard to the physical dimensions of the antennas:

(a) The total length of each antenna system is less than $\lambda/4$.
(b) The antennas are less than $\lambda/10$ in height.
(c) The spacing between the antennas is less than $\lambda/15$.

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Then, a careful study of development of the equations for vertical antennas leads to the conclusion that the antenna system resistance and antenna system radiation resistance of a coupled antenna system consisting of partially shielded vertical antennas with slanting top sections are given by

$$R_s = R_{1s} + \frac{\left[(X_m^2 - R_m^2)\, R_{2t} + 2\, R_m\, X_m\, X_{2t}\right] I_{1a}^2}{(R_{2t}^2 + X_{2t}^2)\, I_{1s}^2} \tag{36}$$

$$R_{rs} = R_{1r} \left\{ \frac{(R_{2t} - R_{2r})^2 + \left(X_{2t} + X_m \sqrt{\frac{R_{2r}}{R_{1r}}}\right)^2}{(R_{2t}^2 + X_{2t}^2)} \right\} \frac{I_{1a}^2}{I_{1s}^2} \tag{37}$$

$$\frac{I_{1a}}{I_{1s}} = \frac{C_{1s} - C_{1t}}{C_{1s}} \tag{38}$$

Where R_s is the resistance of the antenna-1 system when it is coupled to the antenna-2 system;

R_{1s} is the resistance of the antenna-1 system when the effect of the coupling between the two antennas is negligible;

X_m is the reactive component of the coupling impedance, (X_m can be computed from Eq. (41) or (43));

R_m is the real component of the coupling coefficient. At the intermediate frequencies for short antennas with relatively close spacing, R_m is small compared to X_m and the terms involving R_m in Eq. (36) and (37) can be neglected in most instances. R_m is given approximately by

$$R_m = \sqrt{R_{1r}\, R_{2r}}$$

R_{1r} is the radiation resistance of antenna 1 when the effect of the coupling between the antennas is negligible.

R_{2r} is the radiation resistance of antenna 2 when the effect of the coupling between the antennas is negligible. Note R_{1r} and R_{2r} can be obtained from field strength measurements or from the calculated radiation resistance and the shielding factor.

R_{2t} is the resistance of the antenna-2 system including the loading coil referred to the base of the antenna. R_{2t} can be computed from Eq. (25) or (26).
X_{2t} is the reactance of the antenna-2 system including the base loading coil referred to the base of the antenna. X_{2t} can be computed from Eq. (24).
I_{1a} is the antenna-1 current.
I_{1s} is the antenna-1 system current.

Conditions for Maximum and Minimum Radiation Resistance

28. If one varies X_{2t} in Eq. (32), (34) and (37) and at the same time keeps the antenna current I_{1a} constant, then the radiation resistance will be a maximum and a minimum when

$$X_{2t}^2 X_m \frac{L_2}{L_1} + X_{2t}\left[X_m^2\left(\frac{L_2}{L_1}\right)^2 + (R_{2t} - 10k^2L_2^2)^2 - R_{2t}^2\right] - R_{2t}^2 X_m \frac{L_2}{L_1} = 0 \quad (39a)$$

for simple vertical antennas and

$$X_{2t}^2 X_m\sqrt{\frac{R_{2r}}{R_{1r}}} + X_{2t}\left[X_m^2 \frac{R_{2r}}{R_{1r}} + (R_{2t} - R_{2r})^2 - R_{2t}^2\right] - R_{2t}^2 X_m\sqrt{\frac{R_{2r}}{R_{1r}}} = 0 \quad (39b)$$

for partially shielded antennas.

29. It is apparent from Eq. (39) that the radiation resistance is a maximum at approximately the resonance frequency of the antenna-2 system or $X_{2t} \cong 0$. Attention is invited to the fact that the radiated power for a transmitter-antenna system is not necessarily a maximum when the radiation resistance is a maximum. For example, the radiated power for two identical antenna systems with vertical antennas is a maximum when $X_{2t} = X_m$ providing X_m is large compared to R_{2t}.

30. A careful study of Eq. (39) reveals that the radiation resistance is a minimum in the vast majority of

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coupled antenna systems when

$$X_{2t} \cong - X_m \frac{L_2}{L_1} \qquad (40a)$$

or

$$X_{2t} \cong - X_m \sqrt{\frac{R_{2r}}{R_{1r}}} \qquad (40b)$$

Measurement of the Coupling Impedance or $R_m - j X_m$

31. There are formulas in the theory for computing the coupling impedance between simple vertical antennas. The coupling impedance between the partially shielded antennas with slanting top sections must be measured. Thus, in order to apply the theory to intermediate-frequency shipboard antennas, methods must be developed for measuring the coupling impedance. An investigation of the theory reveals that the coupling impedance cannot be measured directly, but that it can be computed from other measurements.

32. It is evident from paragraph 28 that Eq. (39) is valid when the radiation resistance is a minimum. If the frequency at which the radiation resistance is a minimum, and the resonance frequency of the antenna-2 system and the electrical constants of the antenna-2 system are known, then the coupling reactance X_m can be computed from Eq. (39). The frequency at which the radiation resistance of the antenna-1 system is a minimum can be determined by either of the following methods. In the first method, the coupled antenna system is tuned to a definite frequency and field strength measurements are made in the frequency band below the resonance frequency of the antenna-2 system. Either the p-a input power to the transmitter or the antenna-1 system current is kept constant during these measurements. The measured field strength is a minimum at the frequency for which the radiation resistance is a minimum. In the second method, the transmitter feeding the antenna-1 system is set on a definite frequency and either the p-a input power or the antenna-1 system current is kept constant during the measurements. Field strength measurements are made for various settings of the base loading coil for the antenna-2 system. The field strength is a minimum at the frequency for which the radiation resistance is a minimum. The coupling reactance can be computed from Eq. (41).

33. The resonance frequency of the antenna-2 system can be determined by a number of methods. One method is to

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measure the antenna-1 system current at constant p-a input power to the transmitter in the frequency band near the resonance frequency of the antenna-2 system. The antenna-1 system current is a minimum at the resonance frequency of the antenna-2 system. The resonance frequency of the antenna-2 system can also be determined by measuring the resistance of the antenna-1 system. The resistance of the antenna-1 system is a maximum at the resonance frequency of the antenna-2 system.

34. If one solves Eq. (39) for the condition of minimum field strength, one obtains for X_m

$$X_m = -\frac{B}{2X_{2t}}\left\{(X_{2t}^2 - R_{2t}^2) + \sqrt{(X_{2t}^2 - R_{2t}^2)^2 + 4X_{2t}^2(2AR_{2t} - A^2)}\right. \quad (41)$$

Where $A = 10k^2L_2^2$ for simple vertical antenna,

$A = R_{2r}$ for a partially shielded antenna,

$B = \frac{L_1}{L_2}$ for simple vertical antenna,

$B = \sqrt{\frac{R_{1r}}{R_{2r}}}$ for partially shielded antenna,

$$X_{2t} = \frac{10^2}{\pi f_r C_{2a}}\left(\frac{f_s - f_r}{f_r}\right),$$

f_s = frequency in c.p.s. at which the field strength is a minimum.

35. The magnitude of the coupling impedance can be computed from measurements of the antenna currents in the two antenna systems. From Eq. (27), one has

$$I_{2a} = -I_{1a}\frac{\left[10k^2L_1L_2 - j\,X_m\right]}{R_{2t} + j\,X_{2t}} \quad (42a)$$

36. If one takes the general case for the coupling between two partially shielded antennas, one obtains

$$I_{2a} = -I_{1a}\frac{\left[R_m - j\,X_m\right]}{R_{2t} + j\,X_{2t}} \quad (42b)$$

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37. If either the reactance X_{2t} or the operating frequency of the transmitter is varied until the two antenna currents are equal, then it follows directly from Eq. (42) that

$$\sqrt{100k^4L_1^2L_2^2 + X_m^2} = \sqrt{R_{2t}^2 + X_{2t}''^2} \qquad (43a)$$

for simple vertical antennas and

$$\sqrt{R_m^2 + X_m^2} = \sqrt{R_{2t}^2 + X_{2t}''^2} \qquad (43b)$$

for partially shielded antennas.

38. The left side of Eq. (43) is the coupling impedance and thus can be readily computed if R_{2t} and X_{2t}'' are known. The resistance R_{2t} can be computed from Eq. (25). The simplest method for determining X_{2t}'' in Eq. (43) is to measure the frequencies f_1 and f_2 below and above the resonance frequency of the antenna-2 system at which the antenna currents in the two antenna systems are equal. This procedure eliminates the measurement of the resonance frequency of the antenna-2 system. The reactance X_{2t}'' is given by

$$X_{2t}'' = \frac{2 \times 10^{12} (f_2 - f_1)}{\pi C_{2a} (f_1 + f_2)^2} \qquad (44)$$

39. In some cases, the coupling between the antennas will be so low that the maximum value of I_{2a} will be less than I_{1a}. For this condition, the above method for measuring the coupling impedance fails, but the following simple method can be used. The maximum value of I_{2a} occurs at the resonance frequency of the antenna-2 system or for $X_{2t} = 0$ and thus is a point that can be readily determined experimentally. At this resonance frequency, $X_{2t} = 0$ in Eq. (42) and one has

$$\left[100k^4L_1^2L_2^2 + X_m^2\right]^{1/2} = \frac{I_{2a}}{I_{1a}} R_{2t} \qquad (45a)$$

for a simple vertical antenna and

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$$\left[R_m^2 + X_m^2\right]^{1/2} = \frac{I_{2a}}{I_{1a}} R_{2t} \qquad (45b)$$

for a partially shielded antenna.

40. The reactive component of the coupling impedance can be computed from field strength measurements and Eq. (41). The magnitude of the coupling impedance can be computed from the antenna current measurements and Eq. (43) or (45). The resistive component of the coupling impedance R_m can be computed from the measured values of X_m and

$$\sqrt{R_m^2 + X_m^2}.$$

R_m is the order of magnitude of the radiation resistance of the antennas and thus is relatively small quantity for shipboard antennas. In general, R_m either will be small compared to X_m or X_m will be so small that the effect of the coupling between the antennas can be neglected. Hence, it will not be necessary to determine R_m, and X_m can be assumed to be equal to the magnitude of the coupling impedance. Thus, the antenna-current method for measuring the coupling impedance can be used to determine X_m and the cumbersome field-strength method for measuring X_m can be omitted.

41. The reactive component of the coupling impedance is capacitive. It can be seen from Eq. (17), (18) or (19) that

$$X_m = \frac{1}{\omega C_m} \qquad (46)$$

where C_m is the coupling capacity. The coupling capacity C_m is independent of the frequency, providing the assumptions given in paragraph 27 are fulfilled. The height and spacing of the intermediate-frequency antennas on board ship are within the instructions of the theory; thus, the coupling capacity C_m is a constant and for this reason it is necessary only to measure C_m or X_m at one frequency.

Examples.

42. The general theory of the coupling between antennas gives formulas for computing radiation resistance, antenna system resistance and phase and magnitude of the currents in two coupled antennas. The variation of the above factors with the frequency is illustrated by the following examples:

DECLASSIFIED

43. The antenna arrangement is shown in Plate 3. Both antennas are 160-foot verticals with a spacing of 30 feet. Both antennas are connected to 30-foot trunks. The antenna-1 system is connected to a TBL-2 transmitter while the antenna-2 system is grounded through a loading coil from a TBL-2 transmitter. The resonance frequency of the antenna-2 system including the loading coil was 207 kc. The measured values of I_{2s}/I_{2a} and I_{1s}/I_{1a} were 1.5 and 1.43, respectively. The measured value of R_{2t} was 8.3 ohms as computed from Eq. (25). X_m was computed from Eq. (17) and found to be 281.

44. The magnitude of the ratio of I_{2a}/I_{1a} as calculated from Eq. (27) is plotted as a function of the frequency in Plate 5. At the resonance frequency of the antenna-2 system, 207 kc, this current ratio attains a maximum value of about 33. When the current ratio is a maximum, both the antenna-1 and antenna-1 system currents are much smaller than the normal values; thus, the transmitter is operating into a high resistance load. The antenna currents are equal (unity current ratio) at 194 and 219 kc.

45. In Plate 6 the phase of I_{2a} relative to I_{1a} is plotted as a function of the frequency. When the antenna-2 system is at resonance (207 kc), the current I_{2a} leads the current I_{1a} by 90 degrees. Near the resonance frequency of the antenna-2 system, the phase of I_{2a} shifts rapidly; e.g., the phase angle shifts 150 degrees when the frequency is changed from 206 to 208 kc. For frequencies above the resonance frequency of the antenna-2 system, the currents in the two antennas are nearly in phase. Since the spacing between the antennas is a small fraction of a wavelength and the currents are in phase, the fields produced by the two antennas are in phase and thus tend to give a maximum radiated power. The radiated power for the coupled condition when the antenna currents are in phase is always greater than the radiated power for the antenna-2 system grounded (see paragraph 50).

46. For operating frequencies less than the resonance frequency of the antenna-2 system, the currents in the two antennas are nearly 180 degrees out of phase. The fields produced by the two antennas will also be nearly 180 degrees out of phase; hence, the field strength at any distance and the radiated power will be a minimum when the two antenna currents are equal. These facts are illustrated very clearly in Plates 5 to 8, inclusive. The antenna currents are approximately equal and opposite at 194 kc (see Plates 5 and 6); the radiation resistance and the radiation efficiency are also a minimum at 194 kc (see Curve R_{rs} of Plate 7 and Curve 2 of Plate 8).

DECLASSIFIED

47. In Curves R_s and R_{rs} of Plate 7, the resistance and radiation resistance R_s and R_{rs} of the antenna-1 system when it is coupled to the antenna-2 system are plotted as a function of the frequency. It should be noted that the radiation resistance is a minimum at 194 kc. Both the antenna system resistance and the radiation resistance are a maximum at the resonance frequency of the antenna-2 system, and the extremely high value of antenna system resistance should be noted.

48. The antenna-1 system resistance and radiation resistance when antenna 2 is grounded are plotted in Plate 7 (Curves R_{1s} and R_{1rs}) for comparison purposes. At 219 kc (antenna currents are equal), the radiation resistance for the coupled antenna-1 system is 4.0 times the value for the antenna-1 system when antenna 2 is grounded (compare Curves R_{rs} and R_{1rs} in Plate 6).

49. The calculated radiation efficiencies of the TBL-2 transmitter operating into the antenna-1 system with the antenna-2 system grounded and with the antenna-2 system tuned to resonance at 207 kc are plotted as a function of the frequency in Plate 8. In the dotted section of Curve 2, the resistance of the antenna-1 system when coupled to the antenna-2 system (see Plate 7) exceeds the operating range of the coupling circuits of the transmitter, and the dotted section of curve is the radiation efficiency that could be obtained with a more flexible coupling unit. The actual radiated power for this section of the curve would be extremely low.

50. It should be noted that the radiated power near 216 kc is greater when the antenna-2 system is resonated at 207 kc than when it is grounded. In this particular case, the radiated power is about 2.5 times the value for antenna 2 grounded. Thus, it is actually possible to increase the radiated power by using the coupling that exists between closely spaced antennas to the best advantage. The extremely low radiation efficiency in a narrow frequency band near 194 kc for the coupled system is due to a corresponding low radiation resistance in this frequency band (compare Plates 7 and 8).

51. One of the important facts to remember when considering the effect of coupling for shipboard antennas at the intermediate frequencies is that the radiation resistance is small compared to the loss resistance of the antenna system. This means that the actual changes in the radiation resistance that occur for a coupled system need not necessarily show themselves in the measured value of the antenna system resistance; that is, the loss resistance of the antenna system may obscure changes in the radiation resistance which occur, since the radiation resistance is much smaller than the loss resistance in the vast majority of cases. This fact is illustrated in

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Plate 7. The radiation resistance has a minimum value of less than 1 per cent of the normal value at 187 kc (see Curve R_{rs} of Plate 7), but there is no evidence of this extremely low value of radiation resistance in the curve for the antenna-system resistance (see Curve R_s of Plate 7). In fact, the antenna-system loss resistance is greater than the values when the coupling effect between the two antennas is negligible (compare Curves R_{1s} and R_s of Plate 7).

52. The above example indicates a number of important facts in regard to the coupling between antennas for the special case of vertical antennas of the same height; however, one cannot draw conclusions from it when the antennas are not the same height. The following example illustrates the effects of coupling between two vertical antennas of different heights.

53. The antenna arrangement is shown in Plate 4. The antenna-1 system, which consists of a 50-foot vertical antenna and a 50-foot trunk, is connected to a TBL-2 transmitter. The antenna-2 system is a 150-foot vertical and is either grounded at its base or is grounded through a loading coil. The resonance frequency of the antenna-2 system when grounded through the loading coil is 200 kc. The constants of this coupled transmitter-antenna system are tabulated below. All of these quantities remain essentially constant in the narrow frequency band considered in this example.

Resistance of antenna-1 system - R_{1s} = 2.0 ohms.
Resistance of loading coil of TBL-2 transmitter. . . . . - R_{1L} = 6.0 ohms.
Capacity of antenna-1 system . - C_{1s} = 375 μμf.
Capacity of antenna 1. . . . . - C_{1a} = 125 μμf.
Capacity of trunk 1. . . . . - C_{1t} = 250 μμf.
Height of antenna 1. . . . . - L_1 = 50 feet.
Resistance of antenna-2 system or antenna 2 . . . . . - R_{2s} = 2.0 ohms.
Resistance of base loading coil for antenna 2 . . . . . - R_{2L} = 6.0 ohms.
Capacity of antenna 2. . . . . - C_{2a} = 320 μμf.
Resonance frequency when antenna 2 is connected to loading coil . . . . . - f_r = 200 kc.
Height of antenna 2. . . . . - L_2 = 150 feet.
Spacing between antennas . . . - D = 30 feet.
Coupling reactance as computed from Eq. (16). . . . . - X_m = 175 at 200 kc.
R_{2t} = 8.0 ohms as computed from Eq. (26).
(Note: C_{2t} = 0 - no trunk).

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54. The resistance and radiation resistance of the antenna-1 system when the antenna 2 is grounded is plotted as a function of the frequency in Plate 9 (Curves R_{1s} and R_{1rs}). The effect of coupling between the antennas upon the resistance and radiation resistance of the antenna-1 system is negligible. The resistance and radiation resistance of the antenna-1 system when the resonance frequency of the antenna-2 system is 200 kc is plotted as a function of the frequency in Plate 9 (Curves R_s and R_{rs}). The antenna-1 system resistance attains a maximum value of 410 ohms at 200 kc (see Curve R_s of Plate 9), while at 198 or 202 kc this resistance has dropped to 10 ohms. It should be noted that the antenna-1 system resistance (Curve R_s of Plate 9) is symmetrical about 200 kc.

55. The radiation resistance of the antenna-1 system for antenna 2 base loaded attains a maximum value of 19 ohms at 200 kc and decreases rapidly on both sides of the resonance frequency of the base loaded antenna-2 system. The value of X_{2t} for the maximum value of the radiation resistance is given by Eq. (39a). The calculated value of X_{2t} is 0.12. The frequency at which $X_{2t} = 0.12$ is 200.005 kc, as computed from Eq. (24). Thus, it is seen that the maximum radiation resistance occurs for all practical purposes at the resonance frequency of the antenna 2 system.

56. The frequency at which the minimum value of radiation resistance occurs in Curve R_{rs} of Plate 9 can be computed from Eq. (39a) or (41) and (24). The value of X_{2t} as computed from Eq. (39a) or (41) is $X_{2t} = -.525$; i.e., for all practical purposes

$$X_{2t} = - X_m \frac{L_2}{L_1}$$

and the minimum radiation resistance occurs at 179 kc.

57. It is of interest to note that the minimum radiation resistance does not occur when the two antenna currents are equal, as was the case for identical vertical antennas, but is a minimum when

$$I_{2a} \cong I_{1a} \frac{X_m}{\sqrt{\left(\frac{L_2}{L_1}\right)^2 (X_m^2 - R_{2t}^2)}} \qquad (47)$$

or

$$I_{2a} \cong I_{1a} \frac{L_1}{L_2} \left[1 + \frac{1}{2} \left(\frac{L_1 R_{2t}}{L_2 X_m} \right)^2 \right] \qquad (48)$$

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or, for all practical purposes,

$$I_{2a} = \frac{L_1}{L_2} I_{1a} \qquad (49)$$

58. The radiation efficiency of the transmitter-antenna system is given by

$$\text{Rad. Eff.} = \frac{100\ R_{rs}}{R_s + R_{1L}}\ \% \qquad (50)$$

and the radiated power is equal to the product of the radiation efficiency and the p-a tank power. The p-a tank power is greater than the nominal power rating of a transmitter and is about 500 watts for a TBL-2 transmitter.

59. The radiation efficiency of the TBL-2 transmitter-antenna 1 system is plotted as a function of the frequency in Plate 10 for antenna 2 grounded (Curve 1) and for antenna 2 tuned to resonance at 200 kc (Curve 2). The low radiation efficiency when antenna 2 is grounded is to be expected because antenna 1 is short. When the antenna-2 system is tuned to resonance at 200 kc, the radiation efficiency of the transmitter-antenna system varies from a minimum value of 0.00011 per cent at 179 kc to a maximum value of 4.5 per cent at 200 kc. The minimum and maximum values of the radiation efficiency in Curve 2 are about 0.0025 and 80 times the values as given at the same frequency for the antenna 2 grounded. The low minimum value of radiation efficiency at 179 kc is to be expected, because of the low radiation resistance at this frequency. The radiation resistance (Curve R_{rs} of Plate 9) and the radiation efficiency (Curve 2 of Plate 10) are similar for the coupled condition. At 200 kc the maximum value of the radiation efficiency of 4.5 per cent is equal to the radiation efficiency of the antenna 2 in the clear with the base loading coil.

60. The above example brings out a very important fact in regard to the radiation efficiency of coupled antenna systems. If one assumes the following conditions:

(a) Antenna 1 is a short vertical and is connected to a transmitter through a long trunk.
(b) Antenna 2 has a sufficient height and flat top to be a good radiator and is grounded through a base loading coil (no trunk).
(c) Sufficient coupling impedance exists between the two antennas.
(d) Both antennas fulfill the three assumptions in paragraph 17 or 27.

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Then for a narrow band of frequencies near the resonance frequency of antenna 2, the radiation efficiency of the transmitter-antenna-1 system will be equal to that of the antenna-2 system; that is, the radiation efficiency for this narrow band of frequencies will be the same value as would be obtained if the transmitter were connected directly to antenna 2.

61. The third example will show the radiated power as a function of the height of the coupled antenna. The resonance frequency of the coupled antenna is assumed to be adjusted for maximum radiated power. The following conditions are assumed:

Transmitter - TBL-2.
Operating Frequency - 200 Kc.
Capacity of Trunk 1 - 170 μμf.
Height of Antenna 1 - 75-foot vertical.
Resistance of Antenna-1 System - 2.0 ohms.
Resistance of Antenna-2 System - 2.0 ohms.
Capacity of Trunk 2 - 170 μμf.
Capacity of Antenna-2 computed from physical dimensions.
Base Loading Coil for Antenna-2 System was a TBL-2 loading coil.

62. The calculated radiated power is plotted as a function of the height of the antenna 2 in Plate 11, Curve 1. The base loading coil for the antenna-2 system was assumed to be adjusted for maximum radiated power for each height of antenna 2. In Curve 2 of Plate 11, the radiated power is plotted as a function of the height of antenna 2 for the transmitter connected directly to the antenna-2 system and with antenna 1 removed. The radiated power for antenna 2 of zero height is the same as for the antenna-1 system in the clear; i.e., the coupling effect is negligible. The radiated power increases as the height of the antenna 2 increases and, for the two antennas of the same height, the radiated power is doubled. As the height of antenna 2 increases, the radiated power for the transmitter connected directly to the antenna-2 system approaches the value for the coupled condition.

EXPERIMENTAL WORK

63. The trunks used in conjunction with the antennas in the experimental work had originally been installed in a fixed position. Therefore, the antenna ends of the trunk were not moved for the various antenna spacings. The counterpoise system was at a higher elevation above ground than the antenna ends of the trunks. For each antenna spacing, the antennas were separated the correct distance at the top and near the bottom directly above the counterpoise wires and from there brought at whatever angle was necessary to connect it to the antenna end of the trunk. This procedure rendered

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part of the lower end of the antennas ineffective in regard to coupling. Because of this condition, the work was done in two parts. In the first part, the values of coupling impedance for the various antenna spacings, with and without a shield consisting of a ground wire centered between the two antennas, was determined with the antennas arranged as described above. This gave the relative values of coupling impedance for the different antenna spacings.

64. To obtain a comparison between the experimental and theoretical values of the coupling impedance, it was necessary to arrange the antennas in the clear. To do this, the coupled antenna was connected to ground through a load coil directly above the counterpoise and power was fed directly into the other antenna, the spacing between the antennas being the same at top and bottom. For this part, antenna current measurements only were made.

65. The work was carried on in an Antenna House, which is completely shielded. A TBL-2 transmitter was used for field strength and current measurements. The trunk used with antenna 1 was 29 feet long, 12 inches outside diameter, with a 3/8-inch diameter inner conductor (see Plate 2). The antenna end of the trunk was 3 feet above ground and 10 feet below the counterpoise. The trunk used with the coupled antenna, which will be called antenna 2, was 30 feet long, 10 inches deep and 8-inch wide outside dimensions with a 5/16-inch diameter inner conductor. The antenna end of the trunk was 7 feet above ground and 4 feet below the counterpoise. The other end of trunk 2 was connected either directly to ground or through a loading coil to ground. This loading coil was used to tune antenna 2 to frequencies from 200 to 235 kc. The antenna cable was 3/8-inch in diameter and was supported from a messenger cable between the 200-foot high towers. The wire used as a shield between the two antennas was seven-strand no. 18 phosphor bronze wire, 1/8-inch in diameter.

66. Field strength, antenna current and antenna constants measurements were made for the following antenna conditions at frequencies ranging from 175 to 450 kc to obtain the relative coupling. Both antennas were of the same height.

Antenna Height Feet	Antenna Spacing Feet	Antenna-2 System Coil End	Vertical Ground Wire Between Antennas
160	30	Gd. and Tuned to 200 Kc	Out
160	10	Gd. and Tuned to 200 Kc	In and Out
60	30	Gd. and Tuned to 235 Kc	Out
60	10	Gd. and Tuned to 235 Kc	In and Out
60	5	Gd. and Tuned to 235 Kc	In and Out

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67. Antenna current measurements were made to obtain a comparison between the experimental and theoretical coupling impedance for the following antenna conditions:

Antenna 1 Height Feet	Antenna 2 Height Feet	Antenna Spacing Feet	Antenna 2 Tuned to
160	160	9	228.7 kc
60	160	9	228.7 kc
148	160	230	231.0 kc

68. Antenna Constants. Antenna resistance and capacity measurements were made on the antenna-1 system for the antenna 1 - antenna 2 conditions as listed in paragraph 66. The radio-frequency bridge was used with the 160-foot antenna and the "Q"-Meter with the 60-foot antenna. In each case, the substitution method was employed. A General Radio Type 222 Condenser (60 to 1500 μμf) with fused quartz insulators was used as the standard condenser and a General Radio Constant Inductance Decade Resistor as the standard resistor. Because of the difficulty of setting the measuring equipment at the exact resonance frequency of the coupled antenna and the very high resistance at and near the resonance frequency, the resistance and capacity curves do not necessarily show the precise value of the resistance and capacity at the exact resonance frequency, but do give a comparison of the coupling between the two antennas when both are 160 or 60 feet high, with or without the one-wire shield between them for the 30, 10 and 5-foot spacing between antennas.

69. Field Strength Measurements. The field strength measurements were made at the No. 1 or No. 2 Compass House. A Model OF, Ferris Instrument Corp., Interference Locator was used to measure the field strength. A Boonton Type 140A Beat-Frequency Generator was used to produce the same reading on the Interference Locator Instrument as was obtained when the actual field strength was being measured. The Beat-Frequency Generator output voltage required to produce the same reading is proportional to the field strength. These measurements were made over the frequency range with the antenna-2 system tuned and then grounded at the coil end of the trunk. The ratio of the field strength with antenna 2 tuned to that for the antenna-2 system grounded gives the relative field strength. The Model OF Interference Locator was not accurate enough to be used for measuring absolute field strength, but gives reproduceable results when relative values are measured by this method. The TBL-2 transmitter was operated at a constant p-a input of 26 per cent of the rated value for all measurements.

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70. Antenna Current Measurements. Current measurements were obtained over the frequency range on the antenna-1 system at the antenna terminal of the transmitter, which is the antenna system current I_{1s}, and at the base of the antenna, I_{1a}. On the antenna-2 system, current readings were taken at the ground side of the load coil, when the coil was in the circuit between the trunk inner conductor and ground and directly to ground when the load coil was out of the circuit. This is antenna-2 system current I_{2s}. The antenna current reading I_{2a} was taken at the base of antenna 2. These measurements were taken for the relative coupling antenna conditions outlined in paragraph 66 with the TBL-2 transmitter operating at a p-a input of 26 per cent of the rated value. At frequencies near the resonance frequency of the tuned antenna-2 system, the transmitter voltage feed was too low to operate the transmitter. Consequently, antenna current and field strength could not be measured at the exact resonance frequency of the coupled antenna.

71. For the part of the experimental work where a comparison of the measured and the theoretical values of coupling impedance was obtained, three different antenna conditions were used as tabulated in paragraph 67. In all cases the coupled antenna 2 was the same, a 160-foot vertical connected to a load coil at its base with the other terminal of the load coil connected to an r-f ammeter and then to ground. The load coil was located on top of the Antenna House, which also supports the center of the radial counterpoise system, the counterpoise being grounded at its center and at the end of each radial conductor. Antenna 1 was arranged so that its top was the same height as antenna 2 and with the antenna-1 current meter the same height above the ground as the antenna-2 current meter. From the antenna-1 current meter, a lead was run to the TBL-2 transmitter inside the Antenna House. The transmitter frequency was varied until $I_{1a} = I_{2a}$ at a frequency both above and below the resonance frequency of the antenna-2 system.

72. The same measurements were repeated with a 60-foot vertical antenna 1, all meter arrangements being the same as before. The TBL-2 transmitter would not resonate the antenna-1 system for frequencies below 255 kc when the antenna height was less than 60 feet, so a capacitor was connected in parallel with the antenna-1 system in order to extend the operating frequency range of the transmitter-antenna system to the lower frequencies.

73. Another measurement was made with the antenna-2 system the same as above and the antenna-1 system consisting of a vertical antenna and a TAJ-5 transmitter. The spacing between the antennas was 230 feet. This transmitter was located in the Transmitter Building with the antenna run

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vertically from the entering insulator. It was close to the building for the first 17 feet, or to the top of the parapet wall, and the remaining 148 feet were in the clear. An r-f ammeter was placed at the entering insulator. Since the first 17 feet of the antenna were close to the building, the effective antenna height was 148 feet. This shielding of the antenna was taken into account in the computation of the coupling impedance. The TAJ-5 transmitter frequency was varied until the ratio of the antenna-2 current to the antenna-1 current was a maximum. This occurred at the resonance frequency of the antenna-2 system. The transmitter could be tuned to the exact frequency of the antenna-2 system because the distance between the antennas was so great that the coupling impedance was much smaller than had previously been the case for the closer spacings.

RESULTS

74. Antenna Constants. The antenna-1 system is normally connected to the transmitter, and the antenna-2 system is the coupled antenna system (see Plate 2). Both of the antenna systems are verticals. The resistance and capacity of the antenna-1 system were measured with the antenna-2 system grounded and open. The resistance and the capacity of the antenna-1 system for these conditions are plotted as a function of the frequency in Plate 12. It should be noted that the measured points for the two conditions--antenna-2 system grounded and open--are the same. This indicates that the effect of the coupling between the two antennas is negligible for the above conditions.

75. A study of Eq. (31) and (33) reveals that X_m must be of the same order of magnitude as X_{2t} if the coupling is to affect the constants of the antenna-1 system. For the antenna-2 system open or grounded, the reactance X_{2t} is large compared to the coupling impedance X_m; hence, the coupling effect should be negligible. If the length of the antenna system were approximately a quarter wave, then the impedance X_{2t} for a grounded antenna-2 system may be of the same order of magnitude or even small compared to X_m. This condition will be the exception on board ship, even at 600 kc, since a quarter wavelength at this frequency is about 410 feet. The resonance frequency of the open antenna is about twice the value for the grounded condition, and thus the effect of the coupling would be less when the antenna-2 system is open than when it is grounded.

76. Next, the antenna-2 system was connected to the base loading coil and the inductance of this loading coil was adjusted to give a resonance frequency of 207 kc. The number 2 antenna was a 160-foot vertical and was spaced 30 feet from a

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160-foot number 1 antenna (see Plate 2). The resistance and the capacity of the antenna-1 system for this condition are plotted as a function of the frequency in Plate 13. The resistance of the antenna-1 system for the antenna-2 system grounded is included in Plate 13 for comparison purposes. The antenna-1 system resistance is a maximum at the resonance frequency of the antenna-2 system or 207 kc. In fact, the resistance was too large to be measured with a Q-Meter for frequencies within 2 kc of 207 kc; however, at 175 and 250 kc, the resistance of the antenna-1 system is practically down to the normal value or the resistance for the antenna-2 system grounded. A comparison of Curves R_s and R_{1s} of Plate 13 reveals that the effect of the coupling between the two antennas upon the resistance of the antenna-1 system is appreciable only in a band of frequencies near the resonance frequency of the antenna-2 system. The width of this frequency band depends upon the capacity and the resistance of the antennas and the coupling impedance.

77. The measured value of R_s (see Curve R_s of Plate 13) is similar to the calculated curve R_s in Plate 7. The maximum value of R_s in Plate 7 is about 4500 ohms, which indicates the high value of the antenna-1 system resistance that is attained at the resonance frequency of the antenna-2 system. Thus, if measurements had been made at 207 kc, the antenna-1 system resistance would have been many times the maximum value plotted in Plate 13. This high value of antenna-1 system resistance was borne out by the fact that the TBL-2 transmitter would not load up near 207 kc because of insufficient coupling. The sharpness of the R_s curves in Plates 7 and 13 makes it impractical to compare the theoretical and experimental values except at the resonance frequency of the antenna-2 system or 207 kc. A comparison of the antenna-1 system resistance for the antenna-2 system tuned to 207 kc in Plates 7 and 13 reveals that the curves are of the same form and, so far as can be observed, are approximately the same.

78. It should be noted in Plate 13 that the capacity of the antenna-1 system is influenced by the antenna-2 system only near the resonance frequency of the antenna-2 system. The calculated curve for the same antenna conditions shows a greater variation in the capacity near 207 kc. This is to be expected. As will be shown later, the actual coupling between these two antennas was less than the theoretical value for simple vertical antennas.

79. The theoretical equation for the coupling impedance is valid only for antennas in the clear and the above antenna arrangement does not fulfill this condition (see Par. 63). As will be shown later, the measured and theoretical values of the coupling impedance are in agreement for vertical antennas

DECLASSIFIED

in the clear (see Par. 87). Attention is invited to the fact that, if the measured value of the coupling impedance X_m were used instead of the theoretical value, then the calculated values--computed from Eq. (31) and (33)--of the antenna-1 system resistance and capacity would be in good agreement with the measured values plotted in Plate 13.

80. The resistance and the capacity of the antenna-1 system when coupled to the antenna-2 system are given as a function of the frequency for a number of antenna systems in Plates 14, 15, 16, 17, 18, 19 and 20. All of these resistance and capacity curves are of the same form as the one for the 160-foot vertical antennas spaced 30 feet; i.e., the antenna 1 resistance and capacity are changed from their normal values only in the region of the resonance frequency of the antenna-2 system. A careful study of these curves reveals the following facts:

(a) The resistance of the antenna-1 system is different from its normal value only in the region of the resonance frequency of the antenna-2 system.

(b) The capacity of the antenna-1 system is different from its normal value only in the region of the resonance frequency of the antenna-2 system.

(c) The coupling effect increases as the spacing between the antennas decreases; i.e., the frequency range in which a given change in resistance or capacity occurs increases as the spacing between the antennas decreases.

(d) The use of a ground wire between the antennas reduces the coupling impedance. This can be done in practice by placing a high-frequency antenna between two intermediate-frequency antennas.

(e) If the antenna-2 system is grounded and is somewhat less than $\lambda/4$ in length, or open and somewhat less than $\lambda/2$ in length, then the effect of the coupling between the two antennas upon the resistance and capacity of the antenna-1 system is negligible.

81. Antenna Currents. The antenna current and field strength measurements were made at the same time. The TBL-2 transmitter was operated at 26 per cent of full power for all of these measurements. The transmitter was connected to the

DECLASSIFIED

antenna-1 system consisting of a 30-foot trunk and either a 60-foot or a 160-foot vertical antenna. The antenna-2 system, or coupled antenna system, consisted of a 60 or 160-foot vertical, a 30-foot trunk and was either grounded directly or through a base loading coil (see Plate 2). The first measurements were made with a spacing of 30 feet between the 160-foot vertical antennas. In Plate 21 the antenna-1 current I_{1a}, the antenna-1 system current I_{1s}, the antenna-2 current I_{2a} and the antenna-2 system current I_{2s} are plotted as a function of the frequency. The resonance frequency of the antenna-2 system was 207 kc. It should be noted that the antenna-1 and the antenna-1 system currents decrease rapidly as the resonance frequency of the antenna-2 system is approached. In a narrow band of frequencies near 207 kc, the antenna-1 system resistance was several hundred ohms (see Plate 13) and was too high for the coupling system of the TBL-2 transmitter. Thus, no current measurements were made in this frequency band. The intermediate-frequency transmitters are designed for antenna resistances less than 20 ohms. The rapid rise of the antenna-1 system resistance near 207 kc accounts for the decrease in the antenna-1 and antenna-1 system currents near this resonance frequency.

82. The antenna-2 and the antenna-2 system currents increase rapidly as the resonance frequency of the antenna-2 system is approached (see Plate 21). The maximum measured values of the antenna-2 and the antenna-2 system currents were approximately the same as the normal values of the antenna-1 and antenna-1 system currents. The antenna-1 current at 207 kc would be about 2.75 amperes when the antenna-2 system is grounded as can be seen by connecting the 175 and 250 kc values in Plate 21 with a straight line. The measured antenna-1 current for antenna-2 grounded was 2.8 amperes (see Plate 23). This value is in good agreement with the maximum measured value of the antenna-2 current in Plate 21.

83. For frequencies near 207 kc, the currents in the antenna-1 system are low and the currents in the antenna-2 system are high. Since the resistances of the two antenna systems, including the loading coils, are practically the same and the current in the antenna-2 system for frequencies near 207 kc is many times the value for the antenna-1 system, practically all of the power supplied to the antenna-1 system is transferred to the antenna-2 system. In other words, nearly all of the power is either dissipated in or radiated by the antenna-2 system. Since the resistances of the two antenna systems are about the same, the maximum value of the antenna currents in the antenna-2 system should be approximately the same as the current in the antenna-1 system when the coupling effect is negligible. A study of Plate 21 reveals that, if current measurements were made closer to 207 kc, the values

DECLASSIFIED

of I_{2a} and I_{2s} would be approximately the same as the maximum measured values. Thus, if sufficient coupling exists between two antenna systems and the operating frequency is near the resonance frequency of a coupled antenna, then practically all of the antenna system power is transferred to the coupled antenna system and the antenna current for the coupled antenna would be about the same value as if the transmitter were connected directly to the coupled or antenna-2 system.

84. In Plate 22, the ratio of the antenna-2 current to the antenna-1 current is plotted as a function of the frequency from the data of Plate 21. It should be noted that the current ratio is equal to unity at $f_1 = 199$ and $f_2 = 213$ kc. The coupling impedance between the two antennas can be computed from Eq. (43) and (44), the antenna and the antenna system constants and the frequencies f_1 and f_2. R_{2t} can be computed from Eq. (26). The value of X_m computed from the above data is 159 ohms. This value is about 60 per cent of the theoretical value of X_m as computed from Eq. (17). This does not mean that such a large discrepancy exists between the theory and the experiment, but in this particular experiment the antenna arrangement was far from the ideal condition, as would be necessary in order to compare the theory and the experiment. The theoretical curve for I_{2a}/I_{1a} would be the same as the measured curve in Plate 22 if the measured value of X_m were used in Eq. (42) when computing the theoretical curve between antennas. Thus, the general theory of coupling can be applied to antennas that are not simple verticals and are not in the clear if the experimentally measured X_m is used in the theoretical equations.

85. In Plates 24 to 36, the antenna and antenna-system currents for the other coupled antenna systems are plotted as a function of the frequency. It should be noted that all of these curves are similar to the curve in Plate 21 for the 160-foot vertical antennas spaced 30 feet. The same conclusions can also be drawn from these curves. The coupling impedance can be computed in the same way as for the 160-foot antennas spaced 30 feet. If this is done, one observes that

(a) The coupling impedance increases as the spacing between the antennas decreases.

(b) The coupling impedance is reduced if a grounded wire is placed between the two coupled antennas. In a shipboard installation, this would correspond to placing a high-frequency antenna between the two intermediate-frequency antennas.

(c) The coupling impedance between two antennas even with a grounded wire between them is extremely large for close spacings.

DECLASSIFIED

(d) The coupling impedance increases slowly with the antenna height.

86. The measured value of the coupling reactance is given in Table 2 for the 160 and 60-foot vertical antennas with and without a grounded vertical wire between them for various antenna spacings. The coupling reactance was computed from Eq. (43) and (44) and the frequencies at which the antenna currents were equal in Plates 21 to 30. These data show that the addition of a vertical grounded wire between the antennas reduces the coupling reactance to about 70 per cent of the original value. Thus, the coupling reactance is reduced but not eliminated by placing a grounded wire between the antennas. The general effects of coupled antennas are not changed when a vertical ground wire is added, but the frequency range over which the coupling effects are observed is reduced. The high-frequency antennas are effectively grounded wires at the intermediate frequencies, and, thus, placing a high-frequency antenna between two intermediate-frequency antennas will reduce the coupling. In general, the arrangement of antennas on board ship is such that high-frequency antennas are positioned between intermediate-frequency antennas, thus reducing the coupling between the i-f antennas.

87. In order to compare the theoretical and measured values of the coupling impedance, it was necessary to approach as nearly as possible to the condition of two simple vertical antennas in the clear above a flat earth of high conductivity. These conditions were fulfilled for the 160-foot vertical antennas and 60-foot and 160-foot vertical antennas as described in paragraph 71. The measured value of the coupling impedance can be computed from Eq. (43) and (44) and the data are tabulated in Table 1. The measured values of X_m are given in Table 1, together with the theoretical values of X_m as computed from Eq. (16) and (17). It should be noted that the experimental values differ only 4 per cent and 0.0 per cent from the theoretical values for the coupled antenna systems consisting of two 160-foot vertical antennas, a 160-foot and a 60-foot vertical antenna. These small differences are of the same magnitude as the experimental errors which are inherent in these measurements and the experimental arrangement. The coupling impedance was also measured between a 160-foot antenna and a 148-foot antenna which were spaced 230 feet. In this case, one of the 200-foot antenna towers was on the line between the two antennas, and thus would reduce the coupling impedance. The measured and theoretical values of the coupling impedance were computed from the data in Table 1 and were found to be 5.2 and 11.8 ohms, respectively. In this case, the coupling between the two antennas was not sufficient to make the antenna-2 current equal to the antenna-1

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current, even at the resonance frequency of the antenna-2 system. Hence, Eq. (25) and (45) were used to compute the coupling impedance. The lower value of the measured coupling impedance is undoubtedly due to the antenna's not being entirely in the clear.

88. The above data show that when two vertical antennas are essentially in the clear, then the theory is in agreement with the experiment. On the other hand, if the antennas are not in the clear, the coupling impedance between the two antennas will always be less than the theoretical value for the antennas in the clear. In fact, a relatively small deviation from the ideal condition of two vertical antennas in the clear will decrease the coupling impedance considerably. The experimental results also show that a considerable reduction in the coupling impedance was obtained when a grounded wire was placed between the two vertical antennas. The data do indicate that the coupling impedance between two intermediate-frequency antennas on board ship will be sufficient to affect the antenna resistance and the radiation characteristics of the transmitter-antenna systems if the resonance frequency of any other antenna system on board ship is near the operating frequency.

89. The coupling reactance X_m for two 160-foot vertical antennas is plotted as a function of the spacing between them in Plate 37. These curves were computed from Eq. (17) in the theory. For partially shielded antennas, the coupling reactance would be less. These curves indicate that the coupling reactance between intermediate-frequency antennas is large even for antenna spacings of 50 feet. The coupling reactance is inversely proportional to the frequency.

90. The coupling reactance between two identical vertical antennas is plotted as a function of the antenna height for a number of antenna spacings in Plate 38. These theoretical computations were made for an operating frequency of 200 kc. The coupling reactance for antenna spacings of 5 and 10 feet decreases slowly as the antenna height increases. For an antenna spacing of 30 feet, the coupling reactance is practically independent of the antenna height. The reactance of antenna 2 is plotted as a function of the antenna height in Plate 38. The antenna capacity increases with the increase in antenna height, and thus the antenna reactance should decrease as the antenna height increases.

91. In Plate 39, the ratio of the coupling reactance to the antenna reactance is plotted as a function of the antenna height for the same antenna arrangement as for Plate 38. When the coupling between the antennas is high, the effect of the coupling upon the characteristics of the antenna-1 system

DECLASSIFIED

is primarily a function of the ratio X_m/X_{2a}. Since this ratio increases with the antenna height in Plate 39, one can conclude that the frequency range over which the effect of coupling will be observed will increase with the increase in antenna height.

92. Field Strength. The field strength measurements were made at approximately 1850 feet from the transmitting antennas. The input power to the power amplifier to the TBL-2 transmitter was kept constant at 26 per cent of full power. The antenna and antenna system currents in the antenna-1 and antenna-2 systems were also recorded. The measured field strengths were only relative values and thus comparisons could not be made between the values for various frequencies. Measurements have shown that the field strength is the same for the coupled antenna either grounded or open at its base or completely removed; that is, the effect of the coupled antenna upon the field strength is negligible if the operating frequency is not near the resonance frequency of a coupled antenna.

93. Field strength measurements were made for the 160-foot vertical antenna-2 system grounded and tuned to 207 kc at a number of frequencies in the region of the resonance frequency of the antenna-2 system. The 160-foot antenna-1 system was spaced 30 feet from the antenna-2 system. The ratio of the field strengths for the antenna-2 system base loaded to resonate at 207 kc for the antenna-2 system grounded is proportional to the square root of the relative radiated powers for these two conditions. If this ratio is less than unity, then the radiated power for the coupled condition with the antenna-2 system tuned to 207 kc is less than for the condition in which the coupling effect between the two antennas is negligible. This latter condition is attained by grounding or opening the antenna-2 system or completely removing it. On the other hand, if this field strength ratio is greater than unity, then the effect of the coupling between the two antennas is to increase the radiation efficiency of the transmitter antenna system. For a field strength ratio of unity, the coupling does not affect the transmitter antenna radiation efficiency.

94. This field strength ratio is plotted as a function of the frequency for the two 160-foot vertical antennas spaced 30 feet in Plate 31. The base loading coil was adjusted to a resonance frequency of 207 kc for the coupled antenna system for the tuned condition. It should be noted that there is a sharp minimum in the field strength ratio at a frequency somewhat less than the resonance frequency of a coupled antenna system. This minimum is very sharp and it is difficult to obtain the exact minimum experimentally. The radiated power at the minimum value of the field strength ratio (at 199 kc)

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corresponds to 0.2 per cent of the normal power for the antenna-2 system grounded. It can be seen from Plate 22 that the antenna currents are equal at 199 kc; i.e., the antenna currents are equal at the frequency at which the radiated power is a minimum. The antenna-1 current is approximately the same value at 199 kc for the following conditions of the antenna-2 system (see Plate 23):

(a) Grounded.

(b) Resonance frequency of antenna-2 system - 207 kc.

The great reduction in radiated power must be due to a reduction in the radiation resistance. It was shown in paragraph 46 of the theory that the radiation resistance is a minimum for two vertical antennas of the same height when antenna currents are equal. It was also shown in the theory that, for operating frequency below the resonance frequency of the antenna-2 system, the antenna currents in the two systems were nearly 180 degrees out of phase. A comparison of Plates 22 and 31 reveals that the antenna currents were equal when the field strength ratio and the radiated power were a minimum. This is in agreement with the theory, since the theory predicts the radiated power to be a minimum at a frequency below the resonance frequency of the antenna-2 system at which the antenna currents are equal in magnitude. It is of interest to note that the antenna-1 system resistance does not show any minimum at the frequency for which the radiation resistance is a minimum (see Plate 13). This is due to the fact that the radiation resistance is only a few per cent of the loss resistance and thus changes in radiation resistance would result in practically a negligible change in the antenna system resistance.

95. The field strength ratio was a maximum at about 215 kc or above the resonance frequency of the antenna-2 system (see Plate 31). A comparison of Plates 22 and 31 reveals that the antenna-1 and antenna-2 currents were approximately equal when the field strength ratio was a maximum. This is also in agreement with the theory. The maximum value of the field strength ratio was 1.65. Since the radiated power is proportional to the square of the field strength, the ratio of the radiated powers would be $(1.65)^2$ or 2.7. This means that the radiated power at 215 kc for the coupled antenna system tuned to 207 kc is 2.7 times the value for the antenna-1 system in the clear, or the antenna-2 system grounded.

96. The coupling between the antennas at the intermediate frequencies is important only in a narrow band of frequencies near the resonance frequency of the antenna-2 system. For operating frequencies in this band below the resonance frequency of the antenna-2 system, the radiated

DECLASSIFIED

power is less than when the coupled antenna is grounded; hence, in this band of frequencies, the effect of coupling is to reduce the radiation efficiency, i.e, it is detrimental. On the other hand, for operating frequencies above the resonance frequency of the antenna-2 system, the radiated power is greater than for the coupled antenna grounded or removed in a limited frequency range. These data indicate that under certain conditions it is possible to increase the radiated power from a given transmitter-antenna system if the coupling between the antennas is used to the best advantage.

97. Field strength measurements were made for two 160-foot antennas at 30, 10 and 5-foot spacings, and for 60-foot vertical antennas at 30, 10 and 5-foot spacings. In a number of cases, grounded wires were inserted between the two antennas. All of these antenna systems were fed by the TBL-2 transmitter operating at 26 per cent of full power. The ratio of the field strength for the coupled antenna system at resonance and for the coupled antenna system grounded is plotted as a function of the frequency for these various antenna systems in Plates 32 to 36. The resonance frequency of the coupled antenna system was 237 kc for the 60-foot antenna and 207 kc for the 160-foot vertical antenna. All of these field strength ratio curves are of the same general form and, in addition, the maximum value of this ratio is approximately equal to the value predicted by the theory.

98. The following general conclusions can be drawn from the field strength measurements or Plates 31 to 36:

(a) The detrimental effect of coupling exists only for frequencies below the resonance frequency of the coupled antenna system and, generally, this band of frequencies is relatively narrow.

(b) For a band of frequencies above the resonance frequencies of the antenna-2 system, the coupling between the antennas increases the field strength and the radiated power.

(c) The widths of these two frequency bands are approximately the same.

(d) In the case of identical antennas, the sum of these two frequency band widths is approximately equal to the difference in the frequencies for which the antenna currents are equal.

(e) The total band width for which the effect of the coupling is appreciable is approximately twice the band width for which the antenna currents are equal.

DECLASSIFIED

(f) Outside of a narrow band of frequencies near the resonance frequency of the antenna-2 system, the effect of coupling between the two antennas is negligible.

APPLICATIONS

99. The intermediate-frequency transmitters are normally used for communication ranges up to about 300 miles. In some instances the radiated power may not be sufficient to establish the desired communication circuit. However, an increase in the radiated power by a factor of two or more may be sufficient to raise the other ship. A number of examples are given below for which the use of coupling between antennas may increase the radiated power sufficiently to establish the communication circuit. It is assumed in all of the following examples that sufficient coupling exists between the antennas so that the coupling reactance is large compared to the sum of the resistance of the antenna system and the base loading coil. The experimental measurements at the Laboratory indicate that this assumption should be valid for the vast majority of shipboard antennas. However, no measurements have been made of the coupling impedance between antennas on Naval vessels, and therefore the predictions that are given in the following examples may be in error in some instances due to the lack of sufficient coupling between the antennas.

100. Example 1. The TAJ transmitter in the forward radioroom in a new destroyer is out of order and it is necessary to use the TBL transmitter in the auxiliary radioroom. The operating frequency is assumed to be 355 kc. The maximum radiated power for the TBL-2 transmitter at 355 kc on the USS MAYRANT was 0.9 watt (see Plate 18 of reference (a)). If one assumes that a field strength of 50 microvolts per meter is the minimum signal strength on which communication can be carried on through the existing static, then the maximum communication range for 0.9 watt of radiated power is 110 miles (see Plate 9 of reference (b)).

101. It is assumed that the antenna loading coil and the antenna for the TAJ-6 transmitter are in operating condition on the USS MAYRANT. A study of Plate 18 of reference (a) reveals that the radiation efficiency of the TBL-2 antenna system was very low compared to that of the TAJ-6 antenna system. It was shown in paragraph 60 above that if a transmitter is operating into an inefficient antenna and sufficient coupling exists between this antenna and an efficient antenna system, then it is possible by properly tuning the base loading coil for the coupled antenna to transfer practically all of the radio-frequency power to the coupled antenna system and obtain the radiation efficiency of this efficient system. In this appli-

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cation, the TAJ-6 transmitter-antenna system is more efficient than the TBL-2 transmitter-antenna system. The radiated power for the TAJ-6 transmitter at 355 kc is 19 watts and the p-a tank power is 720 watts. This corresponds to a transmitter-antenna system radiation efficiency of 100 x 19/720 = 2.6 per cent. The p-a tank power for the TBL-2 transmitter is 500 watts. Since all of this r-f power is transferred to the TAJ-6 transmitter-antenna system when the proper tuning of the antenna loading coil in the TAJ-6 transmitter is obtained, the radiated power for the coupled condition is 2.6 per cent of 500 or 13 watts. From Plate 18 of reference (b), one sees that a field strength of 50 microvolts per meter for a radiated power of 13 watts corresponds to a transmission distance of 260 miles. The radiated power has been increased from 0.9 to 13 watts and communication range has been increased from 110 to 260 miles by taking advantage of the coupling between the TAJ-6 and TBL-2 antennas on the USS MAYRANT.

102. Example 2. The TAQ-5 transmitter on the USS NORTH CAROLINA has failed and the radiated power from the TAJ-8-T4L-T4-transmitter-antenna system is not sufficient to carry on communication at 355 kc. In this case it is assumed that the base loading coil for the TAQ-5 transmitter is not damaged. The radiated power for the TAJ-8-T4L-T4-transmitter-antenna system is 1.0 watt at 355 kc (see Plate 31 of reference (c)). The radiated power for the TAQ-5-T7L-T7-transmitter-antenna system (battle condition) is 90 watts at 355 kc. The p-a tank power for the TAQ-5 transmitter is about 3100 watts, so the radiation efficiency of the TAQ-5-T7L-TL transmitter-antenna system is 90 x 100/3100 or 2.9 per cent. If sufficient coupling exists between the antennas and the tuning of the TAQ-5 antenna loading coil is properly adjusted, then all of the r-f power from the TAJ-8 transmitter is transferred to the TAQ-5 transmitter-antenna system. The power radiated from the coupled system is 2.9 per cent of 720 or 21 watts. Thus, by taking advantage of the coupling between the antennas, the radiated power has been increased from 1.0 to 21 watts.

103. Example 3. The TAQ-5-T7L-T7 transmitter-antenna system on the USS NORTH CAROLINA is operating on 323 kc, but the radiated power is not sufficient to raise the desired ship. The T7 antenna is in the battle condition and it is not practical to add the after section. The maximum radiated power at 323 kc for the TAQ-5-T7L-T7 transmitter-antenna system is 74 watts (see Plate 31 of reference (c)). This radiated power can be increased to 129 watts if full advantage is taken of the coupling between the T6 and T7 antennas.

104. The base loading coil in the TAJ-8 transmitter is set so that the resonance frequency of the TAJ-8-T6 transmitter-antenna system is about 300 kc. The TAQ antenna and coupling

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circuits and the antenna circuits of the TAJ are adjusted until I_{2s} is 20 amperes and the TAQ-5 transmitter is operating at full power. An antenna system current of I_{2s} = 20 amperes corresponds to the maximum permitted value for the TAJ-8 transmitter.

105. The p-a tank power of the TAQ-5 transmitter is dissipated in the loading coils of the TAQ-5 and TAJ-8 transmitters and the T6 and T7 antenna systems and is given by

$$P_t = I_{1s}^2 (R_{1L} + R_{1s}) + I_{2s}^2 (R_{2L} + R_{2s}) \qquad (51)$$

Where P_t is the p-a tank power of the TAQ-5 transmitter and is 3100 watts,
I_{1s} is the T7 antenna system current,
R_{1L} is the resistance of the TAQ-5 loading coil,
R_{1s} is the resistance of the T7 antenna system,
I_{2s} is the T6 antenna system current,
R_{2L} is the resistance of the TAJ-8 loading coil,
R_{2s} is the resistance of the T6 antenna system.

106. The antenna system and loading coil resistances for an operating frequency of 323 kc are taken from Tables 2 and 4 of reference (c) and are

$R_{1L} = 0.42$
$R_{1s} = 1.32$
$R_{2L} = 0.48$
$R_{2s} = 1.70$
$I_{2s} = 20$ amperes
$P_t = 3100$ watts.

107. Substituting these values in Eq. (51), one obtains for the antenna-1 system current

$$I_{1s} = 35.8.$$

108. The antenna-1 and antenna-2 currents can be computed from Eq. (38) of reference (c) and the data given in Tables 2 and 4 of reference (c).

$$I_{1a} = 35.3 \frac{980 - 375}{980} = 22.1 \text{ amperes.}$$

$$I_{2a} = 11.2 \text{ amperes.}$$

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109. Since the radiation resistances of the T6 and T7 antennas are the same, the spacing between the antennas is a very small fraction of a wave length and the antenna currents are very nearly in phase. The radiated power is given quite accurately by

$$P_r = (I_{1a} + I_{2a})^2 R_{1r}$$

Where P_r is the radiated power,
R_{1r} is the radiation resistance of either antenna T6 or antenna T7. R_{1r} = 0.117 ohm at 323 kc (see Table 4 of reference (c)).

The radiated power is $P_r = (22.1 + 11.2)^2 \times 0.117 = 129$ watts.

110. Thus, the coupling between the antennas has increased the radiated power from 74 watts to 129 watts. If the two transmitters had been TAQ's, then the radiated power would have been doubled.

SUMMARY

111. The general theory of the coupling between antennas gives complex formulas which are difficult to apply to a given coupled antenna system. The intermediate-frequency antennas on Naval vessels generally fulfill the following assumptions:

(a) The height of the antenna is less than $\lambda/10$.

(b) The spacing between the transmitting antennas is less than $\lambda/15$.

(c) The length of the antenna plus trunk is less than $\lambda/4$.

The general theory of the coupling between antennas when applied to simple vertical antennas that fulfill the above assumptions leads to formulas that can be easily applied and readily interpreted. A number of experimental measurements were made in order to check this simplified theory of the coupling between intermediate-frequency antennas. The experimental results were in agreement with the theory.

112. Simple vertical antennas are not normally used on Naval vessels at the intermediate frequencies, so the application of this theory would be limited. The theory was extended to include vertical antennas with slanting top sections that are partially shielded. It is necessary to know the impedance of the antennas and the coupling impedance

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between the antennas in order to apply the theory to a particular antenna installation. In the theory of the coupling between vertical antennas formulas are given for computing the coupling impedance, the antenna radiation resistance and the antenna capacity from the physical dimensions of the antenna. For partially shielded vertical antennas with slanting top sections the coupling impedance, the antenna capacity, the antenna resistance and the radiation resistance of the antenna must be measured. The resistance and capacity of the antennas can be measured by a number of methods. The radiation resistance can be computed from field strength measurements.

113. The resistive component of the coupling impedance is of the same order of magnitude as the radiation resistance of the antennas. Thus, in all applications where the coupling impedance is of sufficient magnitude to affect the radiation characteristics of the transmitter-antenna system, the resistive component of the coupling impedance can be neglected. The coupling impedance is for all practical purposes a pure capacity reactance and is inversely proportional to the frequency; it can be represented as a capacity.

114. The coupling reactance cannot be measured directly, but it can be computed from antenna current or field strength measurements. Hence, a complete solution to the problem of the coupling between partially shielded antennas is obtained. The antenna current method is suitable for coupling reactance measurements on board ship because of its simplicity. The experimental results for the partially shielded antennas are in agreement with the theory.

115. The following facts were observed in regard to the effects of the coupling between intermediate-frequency antennas.

(a) The effect of the coupling between antennas upon the antenna-1 system or the transmitter-antenna-1 system is negligible except for a narrow band of frequencies near the resonance frequency of the coupled or antenna-2 system.

(b) The resonance frequencies of practically all of the intermediate-frequency antenna systems on board ships are above the 600 kc or above the intermediate-frequency band if they are grounded. The resonance frequency of an open intermediate-frequency antenna is about twice the value for the antenna grounded. The effects of coupling for the coupled antenna system either grounded

DECLASSIFIED

or open will be negligible at the intermediate frequencies on Naval vessels. This does not mean that the voltage at the receiver terminal of a receiving antenna will be low, but that the effect of the receiving antenna upon the radiation characteristics of the transmitter-antenna system will be negligible providing the transmitter operating frequency is not near the resonance frequency of the receiver-antenna system.

(c) The resonance frequency of the antenna-2 system will be in the intermediate-frequency band if the antenna-2 system is connected to the antenna terminal of its intermediate-frequency transmitter.

(d) The frequency band over which the coupling effects will be observed is proportional to the coupling reactance. In the majority of cases, the width of this frequency band will be less than ±10 per cent of the resonance frequency of the coupled antenna system.

(e) The antenna-1 system resistance will be a maximum at the resonance frequency of the antenna-2 system. This maximum value of the antenna-1 system resistance may be several hundred times the normal value.

(f) The antenna-1 system capacity is affected by the coupling between the antennas in a very narrow band of frequencies near the resonance frequency of the antenna-2 system.

(g) In some cases the antenna-1 system resistance is so high near the resonance frequency of the antenna-2 system that the output voltage for the transmitter operating at maximum antenna coupling is not sufficient to load up the power amplifier. The coupling circuits of the intermediate-frequency transmitters are designed for resistive loads up to about 25 ohms.

(h) If the coupling between the antennas is to affect the radiation characteristics of the transmitter-antenna-1 system, then the coupling reactance, X_m, must be large compared to the resistance of the antenna-2 system.

(i) If the coupling reactance is large compared to the resistance of the antenna-2 system, then the antenna currents in the two antenna systems will be nearly 180 degrees out of phase for all operating

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frequencies below the resonance frequency of the antenna-2 system.

(j) If the coupling reactance is large compared to the resistance of the antenna-2 system and the operating frequency is less than the resonance frequency of the antenna-2 system, then the radiated power will be a minimum at the operating frequency for which the product of the antenna current and its "effective height" is the same for the two antennas. Under this condition, the antenna currents are nearly 180 degrees out of phase and the field strengths produced by the respective antennas are nearly equal in magnitude and opposite in phase. In some cases the radiated power for this condition may be less than 0.1 per cent of the value for the antenna-2 system either open or grounded.

(k) If the coupling reactance is large compared to the resistance of the antenna-2 system, then the antenna currents in the two antenna systems are nearly in phase for operating frequencies above the resonance frequency of the antenna-2 system.

(l) If the coupling reactance is large compared to the resistance of the antenna-2 system, if the antenna-1 and antenna-2 systems are identical, if the antenna loading coils are the same and if the operating frequency is above the resonance frequency of the antenna-2 system and adjusted to the condition of equal antenna currents, then the radiated power is twice the value that would be obtained when the antenna-2 system is grounded. The antenna current and antenna voltage will be less, although the radiated power has been doubled.

(m) The radiated power when the resonance frequency of the antenna-2 system is less than the operating frequency will be greater than when the antenna-2 system is grounded.

(n) If the radiation efficiency of the transmitter-antenna-1 system is low and if sufficient coupling exists between it and an efficient antenna-2 system, then the maximum radiated power for the coupled condition will be the same as if the transmitter were connected directly to the antenna-2 system. This assumes that the resistances of the two loadings are the same, Thus, in the special case when the antenna 2 is connected directly to a base

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loading coil (no trunk) the losses due to the trunk in the antenna-1 system can be eliminated by operating the transmitter at a frequency near the resonance frequency of the antenna-2 system.

(o) The measured or the effective value of the coupling reactance includes the coupling between the antennas and the coupling that may exist between other parts of the antenna systems; e.g., the coupling between the leads in a common trunk or open leads in the radio room.

(p) In the measurement of the radiation efficiency of a given transmitter-antenna system, it is essential to eliminate the coupling effects if a true picture of the radiation efficiency of the transmitter-antenna system under test is to be obtained; e.g., under special conditions one may actually measure the radiation efficiency of the coupled or the antenna-2 system instead of the transmitter-antenna-1 system. The relatively high radiation efficiency of a number of apparently inefficient transmitter-antenna systems that were tested in the fleet may be due to coupling effects of this type.

[redacted]

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Table 1

Comparison of Theoretical and Experimental Values of the Coupling Reactance between the Following Antenna Systems:

Antenna 2 - A 160-foot vertical.
Antenna 1 - As given below.

Antenna 1 height - feet.	160.	60.	148.
Antenna spacing - feet	9.	9.	230.
Resonance frequency of antenna-2 system - kc.	229.	229.	229.
Coupling reactance, X_m (Theoretical) - ohms	500.	390.	11.8
Frequency f_1 at which the antenna currents are equal - kc.	201.74	206.75	
Frequency f_2 at which the antenna currents are equal - kc.	255.7	250.75	
Antenna-1 current at 231 kc.			3.48
Antenna-2 current at 231 kc.			3.1
Coupling reactance, X_m (Experimental) - ohms.	480.	390.	5.2

[redacted]

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Table 2

The Measured Values of X_m With and Without a Vertical Ground Wire Between the Coupled Antennas

Heights of Antenna 1 and Antenna 2 (Feet)	Spacing Between Antennas (Feet)	Vertical Ground Wire Between Antennas	Measured X_m (Ohms)
160	10	In	214
160	10	Out	285
60	10	In	176
60	10	Out	277
60	5	In	318
60	5	Out	448

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Diagram for coupled vertical antennas.

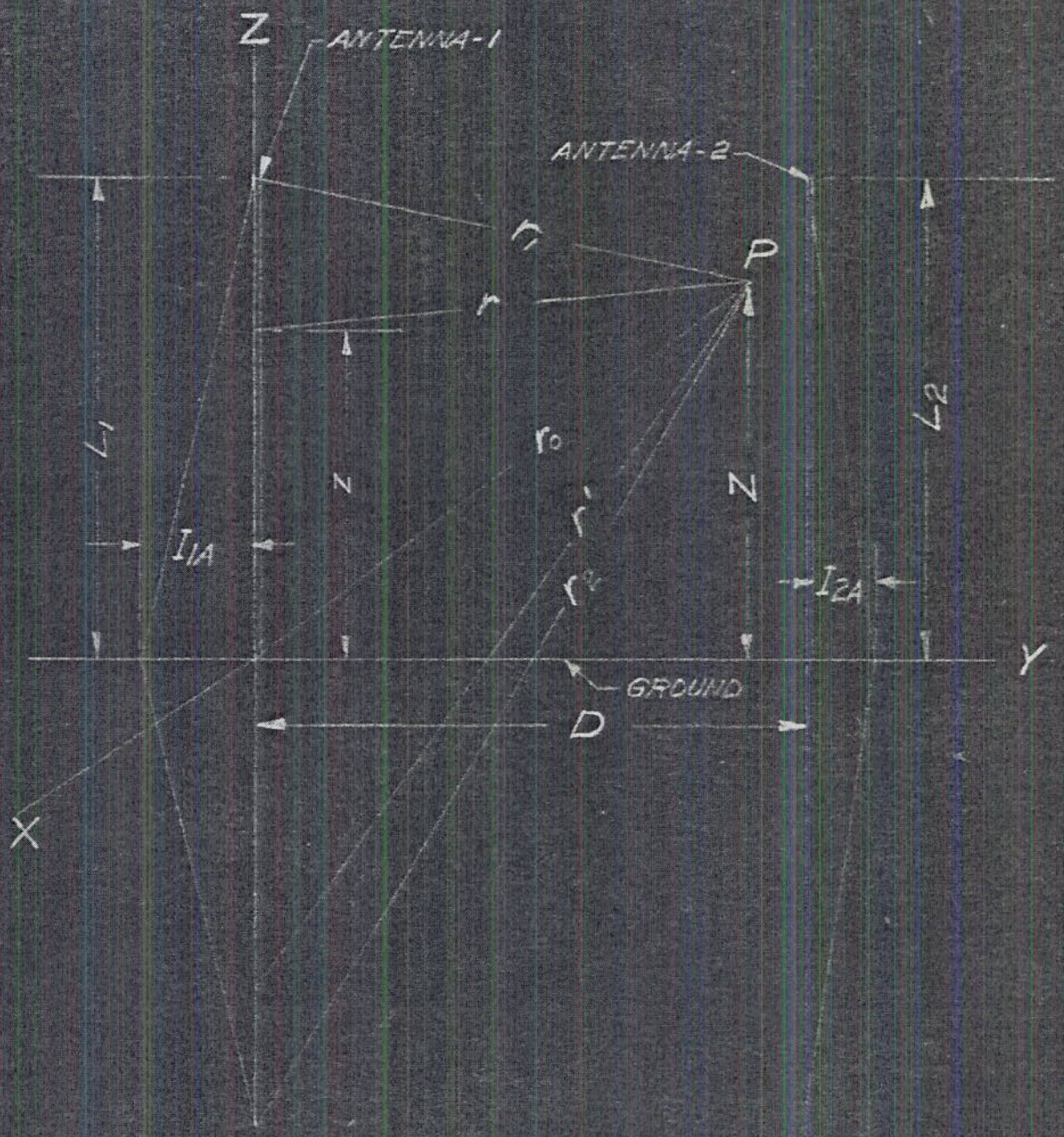

PLATE 1

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Diagram for coupled antenna system.

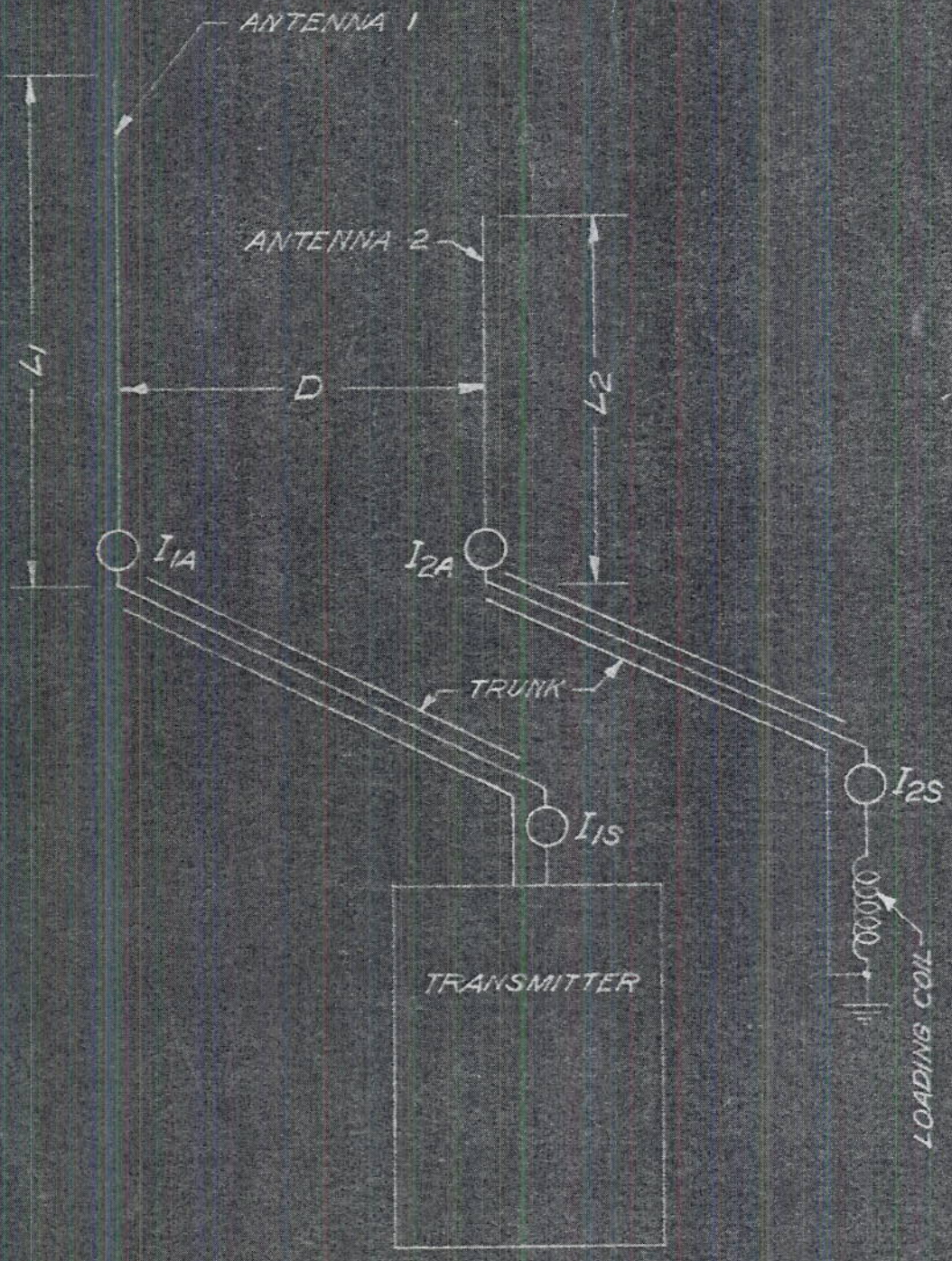

PLATE 2

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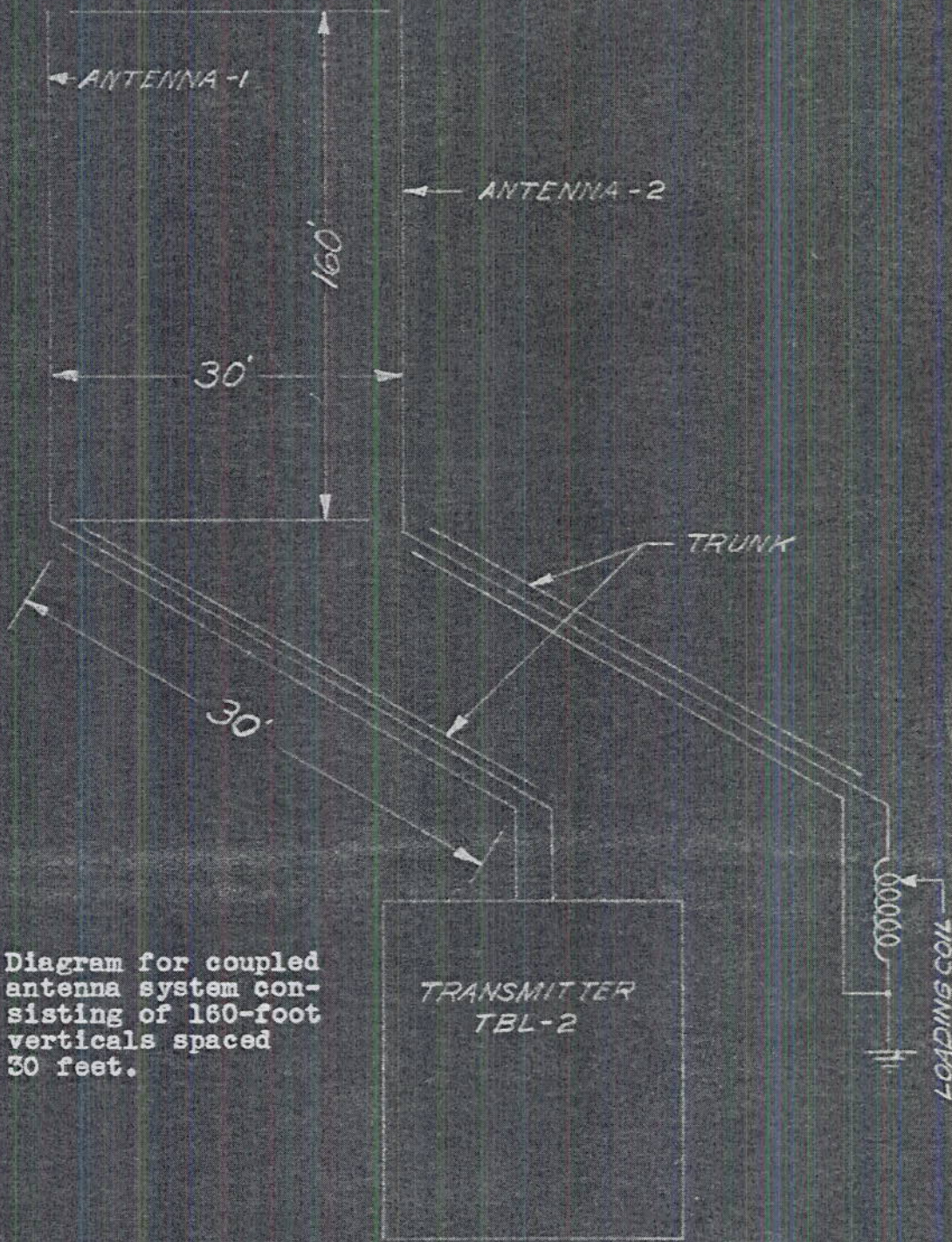

Diagram for coupled antenna system consisting of 160-foot verticals spaced 30 feet.

PLATE 3

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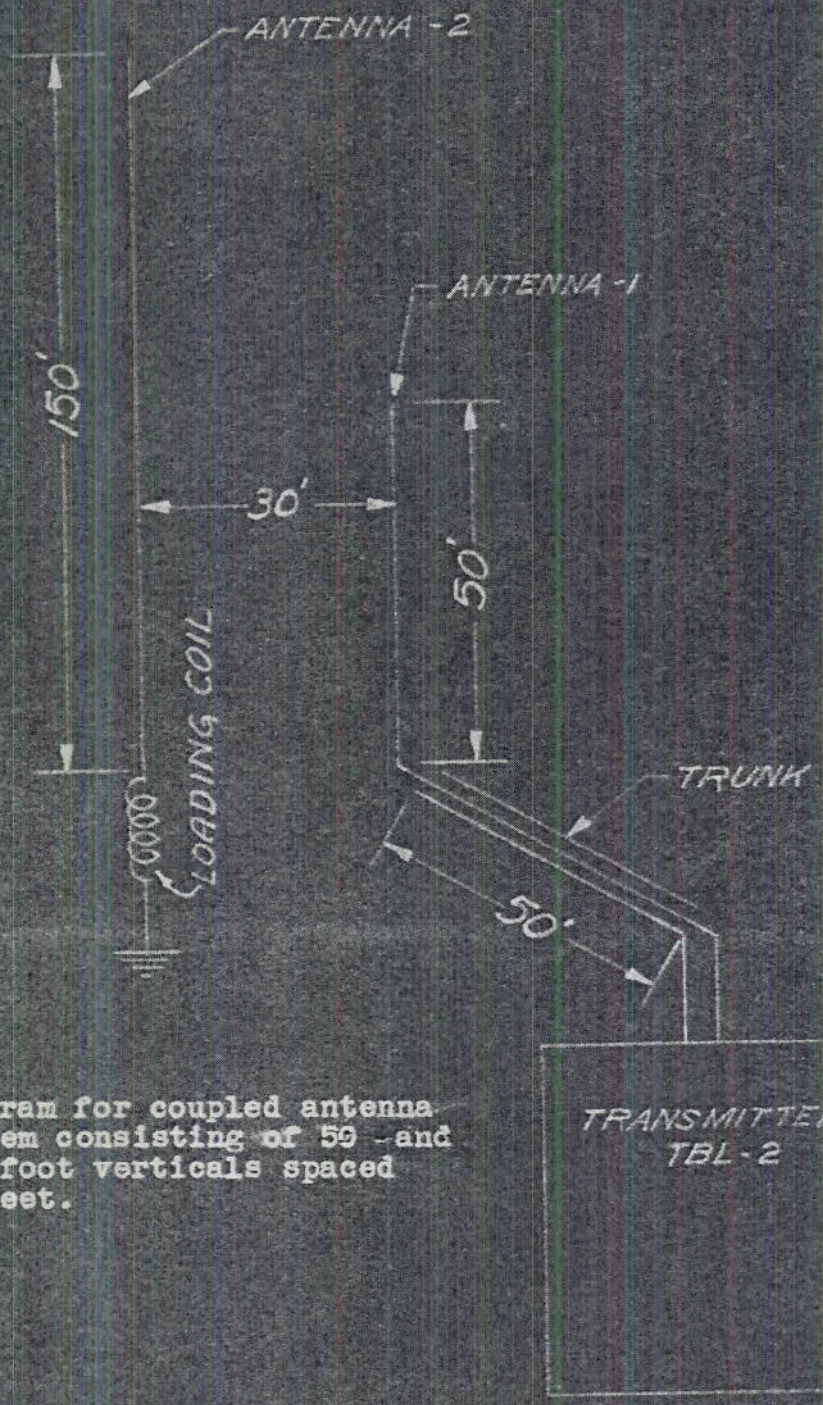

Diagram for coupled antenna system consisting of 50 - and 150-foot verticals spaced 30 feet.

PLATE 4

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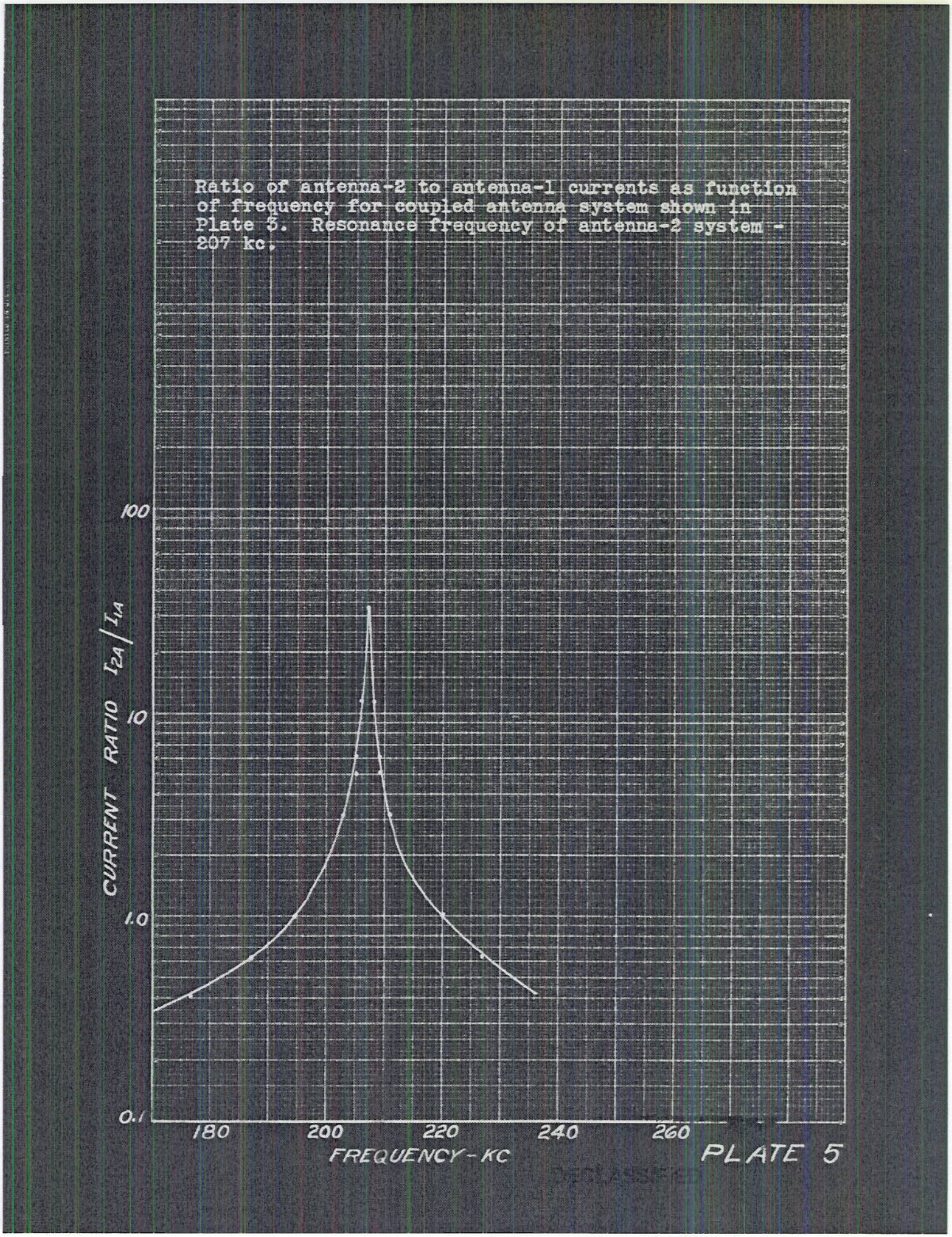
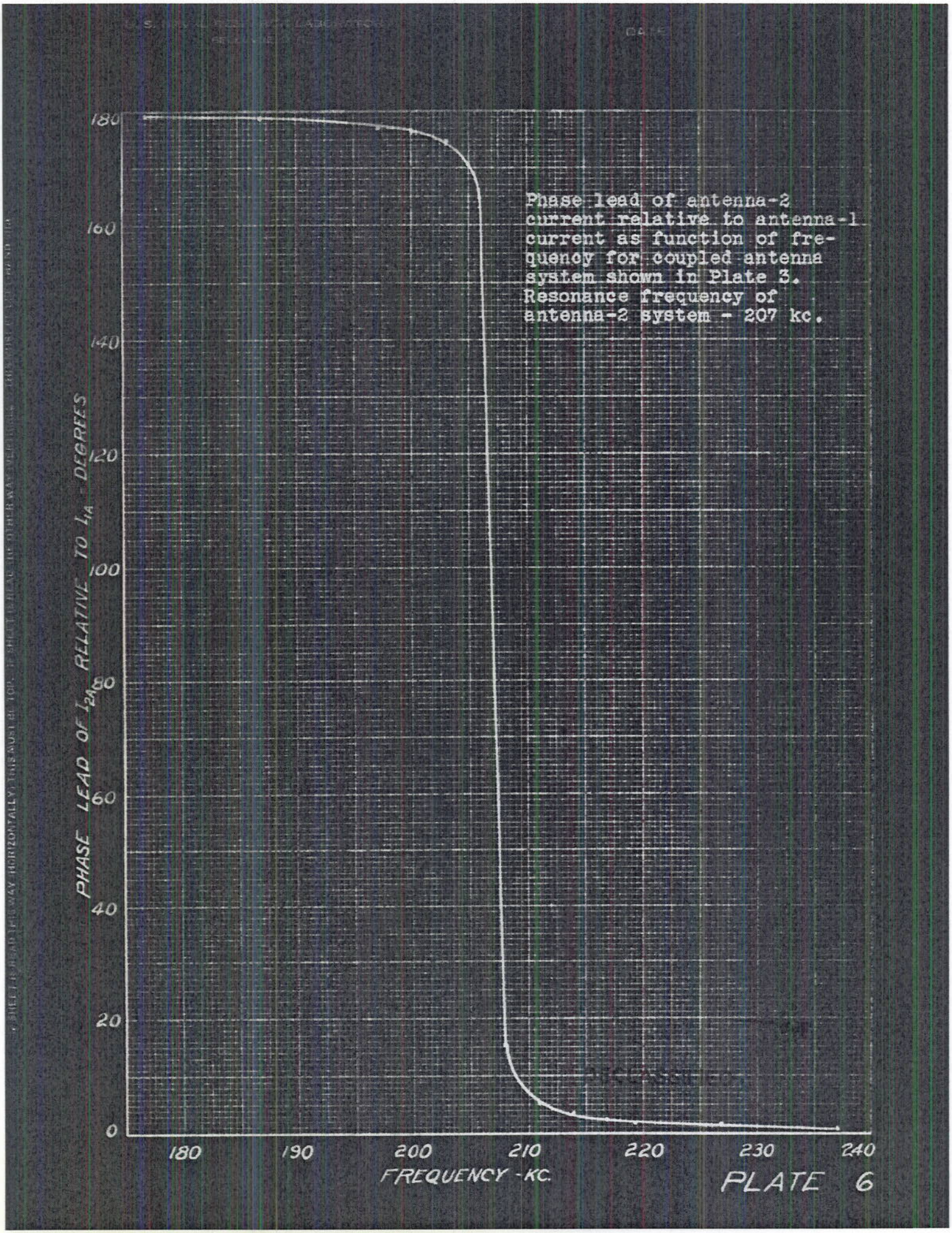

Ratio of antenna-2 to antenna-1 currents as function of frequency for coupled antenna system shown in Plate 3. Resonance frequency of antenna-2 system - 207 kc.
100
10
1.0
0.1
CURRENT RATIO I_{2A}/I_{1A}
180
200
220
240
260
FREQUENCY - KC
PLATE 5


Phase lead of antenna-2 current relative to antenna-1 current as function of frequency for coupled antenna system shown in Plate 3. Resonance frequency of antenna-2 system - 207 kc.
PHASE LEAD OF I_{2A} RELATIVE TO I_{1A} - DEGREES
0
20
40
60
80
100
120
140
160
180
180
190
200
210
220
230
240
FREQUENCY - KC.
PLATE 6

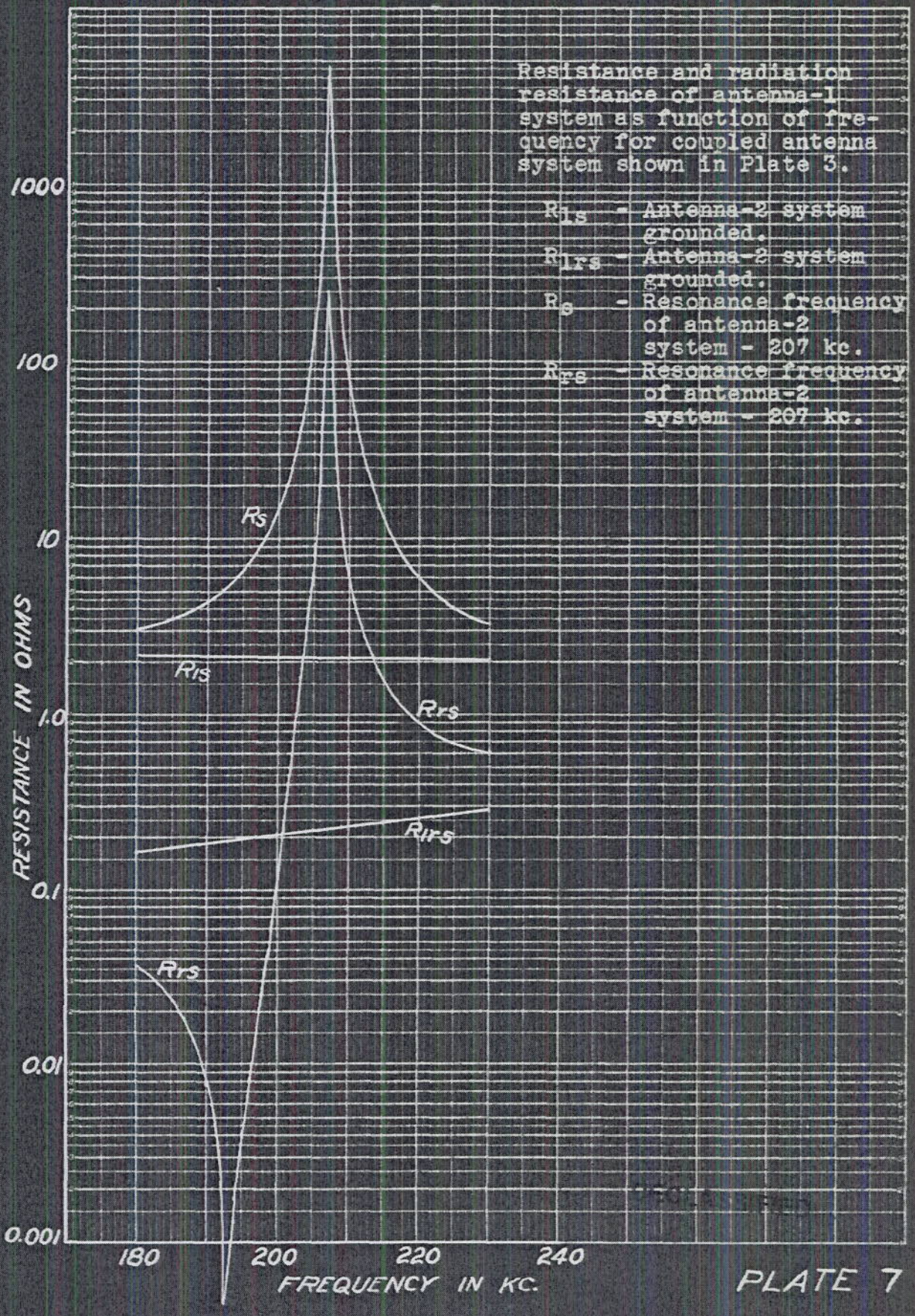

Resistance and radiation resistance of antenna-1 system as function of frequency for coupled antenna system shown in Plate 3.
R_{1s} - Antenna-2 system grounded.
R_{1rs} - Antenna-2 system grounded.
R_s - Resonance frequency of antenna-2 system - 207 kc.
R_{rs} - Resonance frequency of antenna-2 system - 207 kc.
1000
100
10
1.0
0.1
0.01
0.001
RESISTANCE IN OHMS
R_s
R_{1s}
R_{rs}
R_{1rs}
R_{rs}
180
200
220
240
FREQUENCY IN KC.

PLATE 7

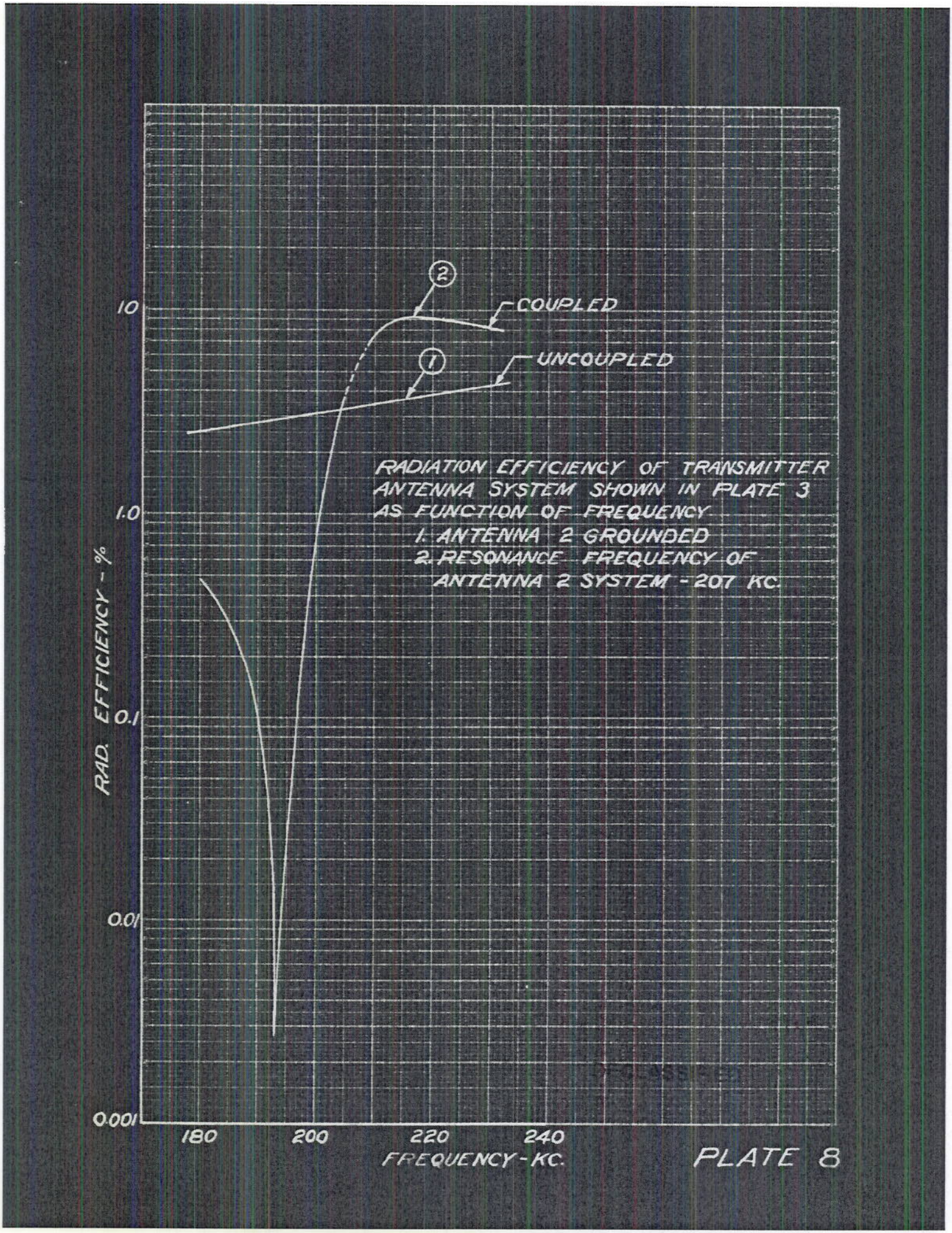

2
COUPLED
1
UNCOUPLED
RADIATION EFFICIENCY OF TRANSMITTER ANTENNA SYSTEM SHOWN IN PLATE 3 AS FUNCTION OF FREQUENCY
1. ANTENNA 2 GROUNDED
2. RESONANCE FREQUENCY OF ANTENNA 2 SYSTEM - 207 KC.
10
1.0
0.1
0.01
0.001
RAD. EFFICIENCY - %
180
200
220
240
FREQUENCY - KC.

PLATE 8

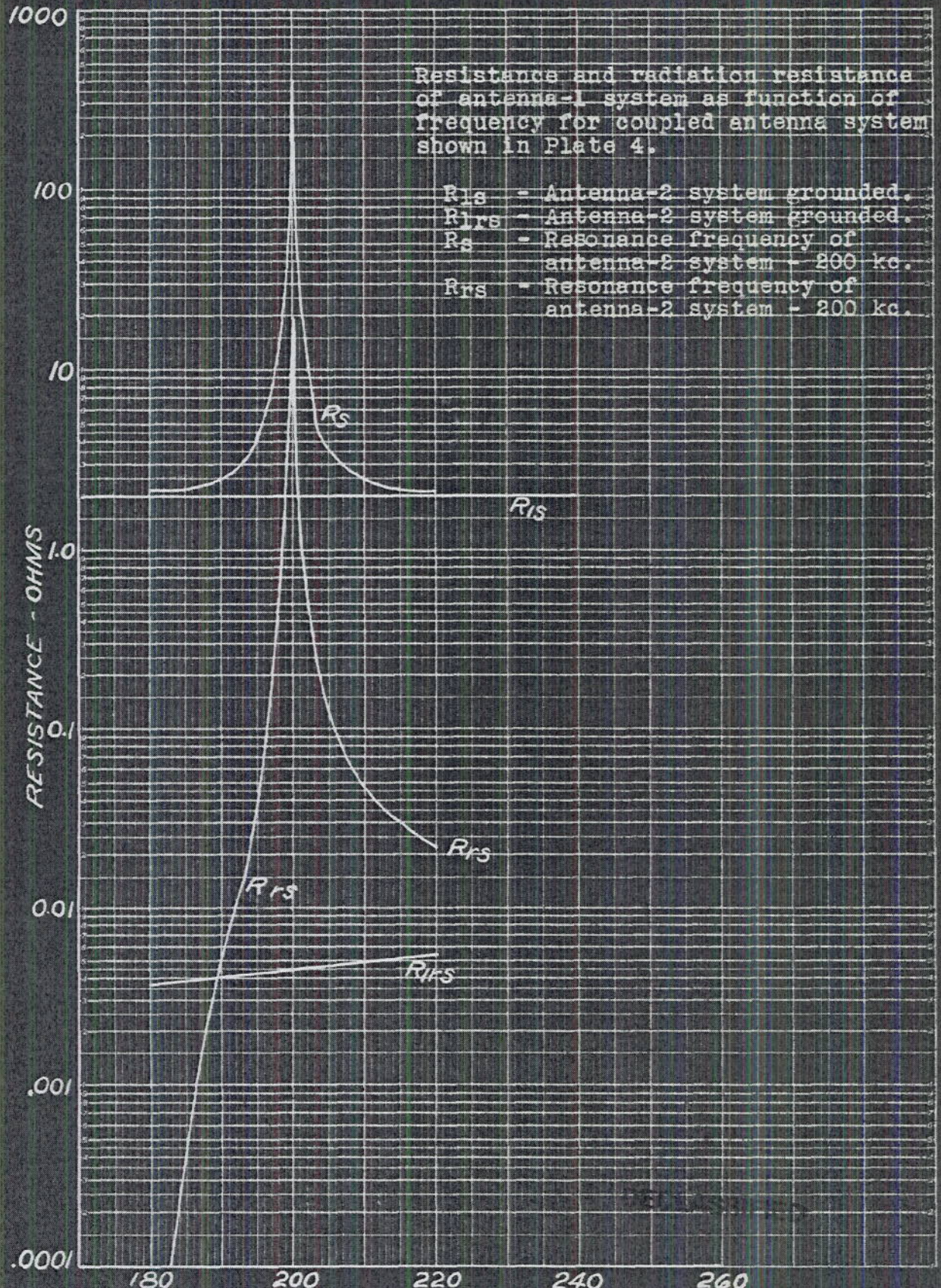

Resistance and radiation resistance of antenna-1 system as function of frequency for coupled antenna system shown in Plate 4.
R_{1s} - Antenna-2 system grounded.
R_{1rs} - Antenna-2 system grounded.
R_s - Resonance frequency of antenna-2 system - 200 kc.
R_{rs} - Resonance frequency of antenna-2 system - 200 kc.
1000
100
10
1.0
0.1
0.01
.001
.0001
RESISTANCE - OHMS
180
200
220
240
260
FREQUENCY - KC.
R_s
R_{1s}
R_{fs}
R_{rs}
R_{1fs}

PLATE 9

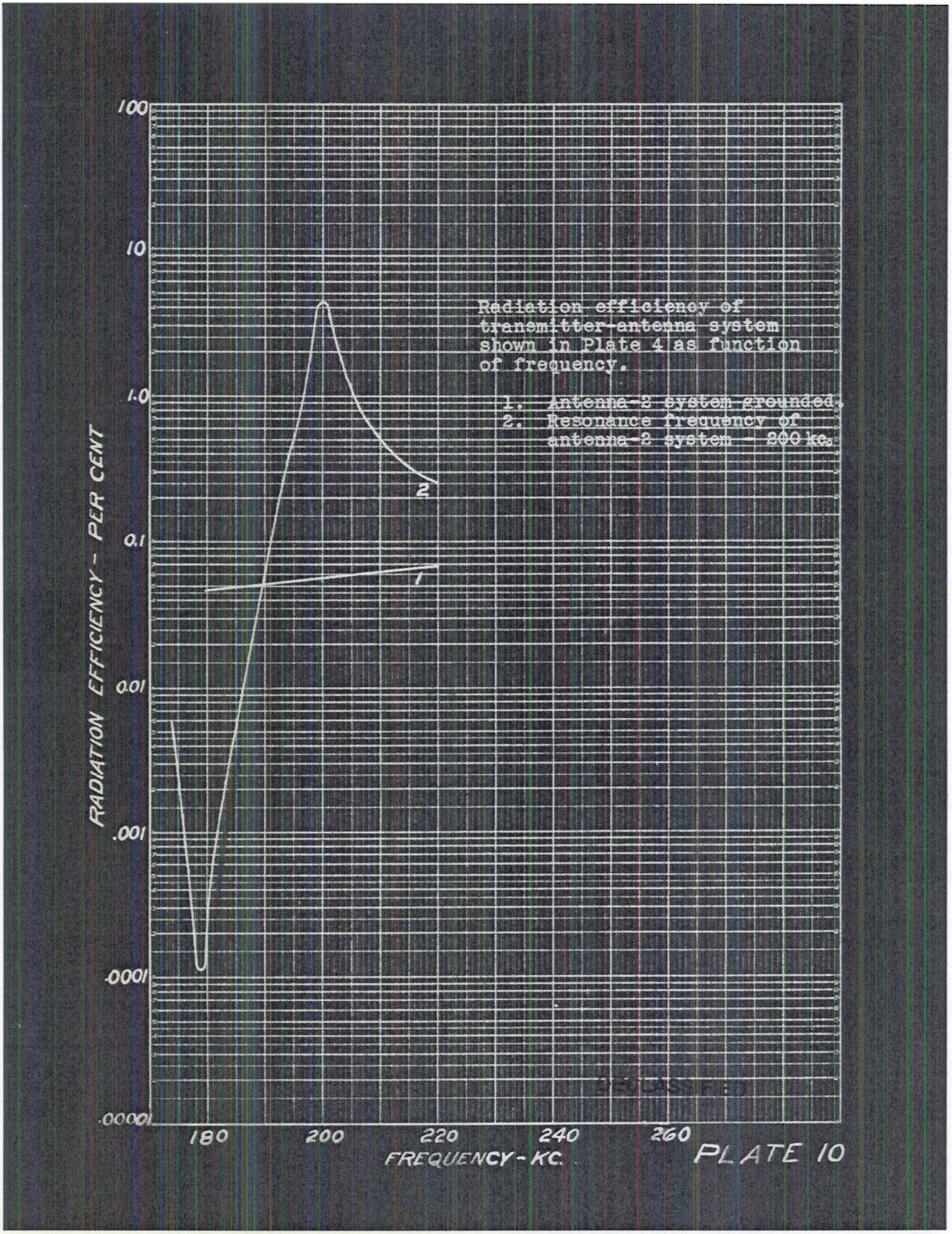

100
10
1.0
0.1
0.01
.001
.0001
.00001
RADIATION EFFICIENCY - PER CENT
180
200
220
240
260
FREQUENCY - KC.
Radiation efficiency of transmitter-antenna system shown in Plate 4 as function of frequency.
1. Antenna-2 system grounded.
2. Resonance frequency of antenna-2 system - 200 kc.
1
2
UNCLASSIFIED

PLATE 10

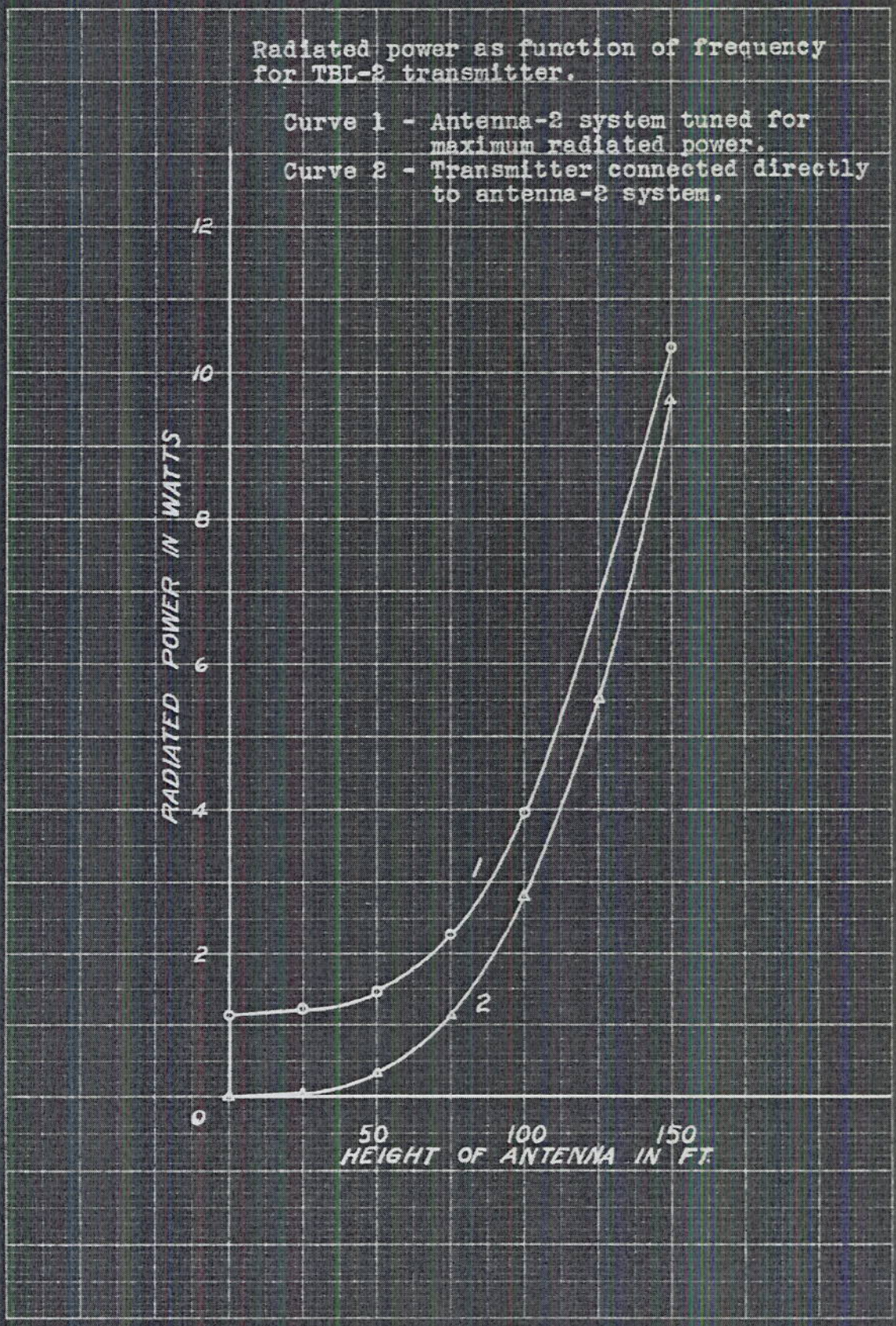

Radiated power as function of frequency for TBL-2 transmitter.
Curve 1 - Antenna-2 system tuned for maximum radiated power.
Curve 2 - Transmitter connected directly to antenna-2 system.
RADIATED POWER IN WATTS
12
10
8
6
4
2
0
1
2
50
100
150
HEIGHT OF ANTENNA IN FT.

PLATE 11

RESISTANCE AND CAPACITY OF ANTENNA-1 SYSTEM AS FUNCTION OF FREQUENCY FOR COUPLED ANTENNA SYSTEM CONSISTING OF TWO -160 FT. VERTICALS SPACED 30 FT.

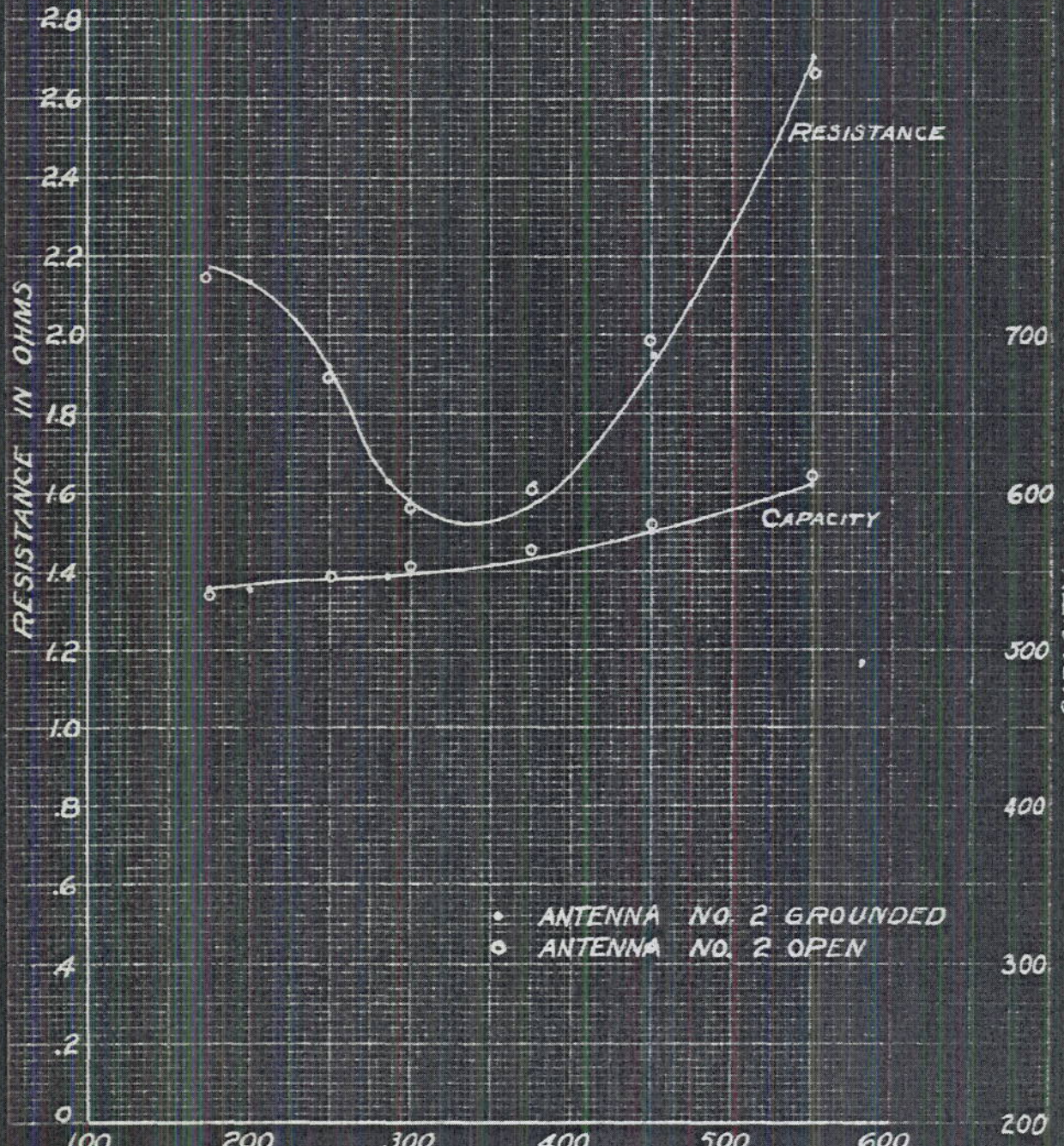


PLATE 12

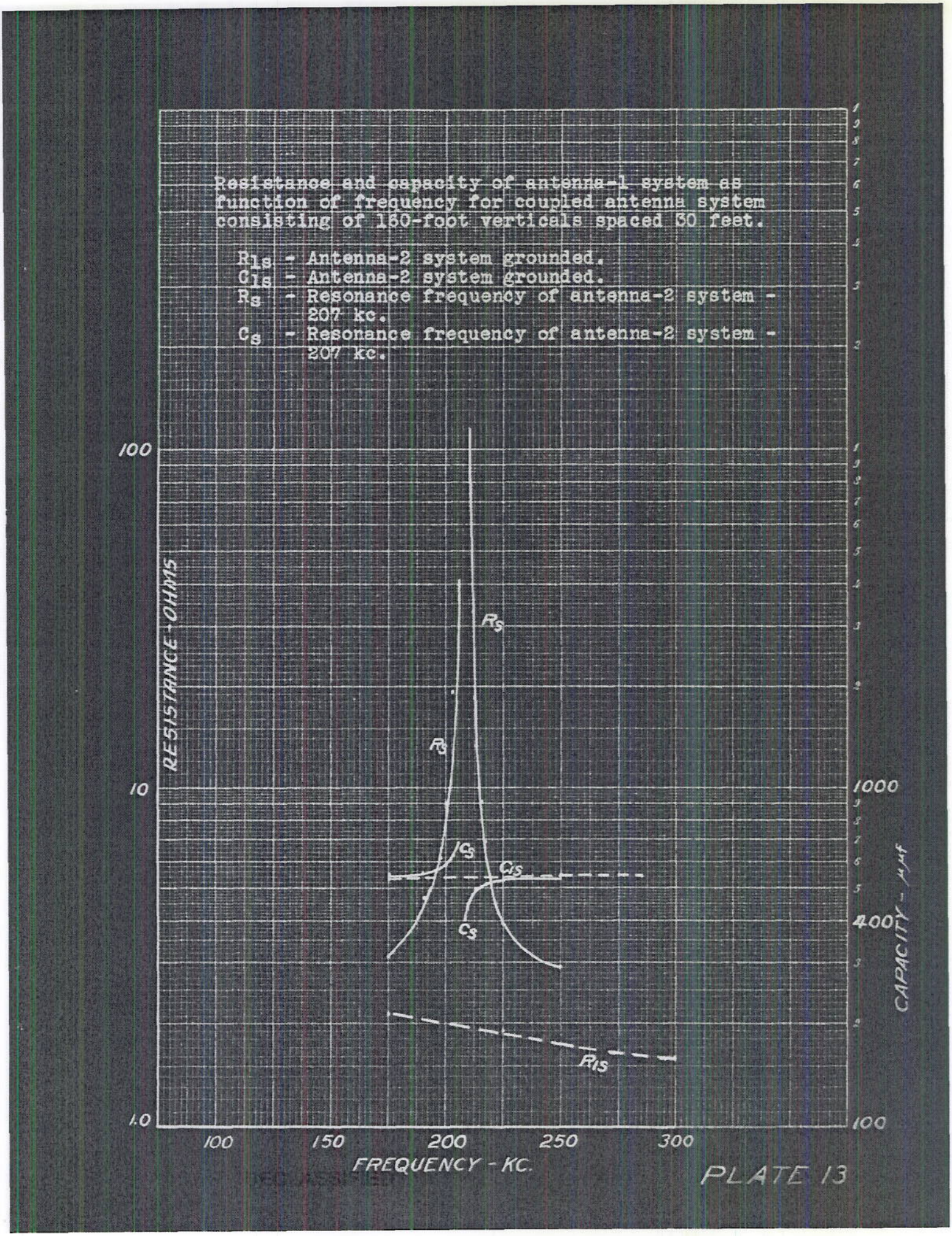

Resistance and capacity of antenna-1 system as function of frequency for coupled antenna system consisting of 160-foot verticals spaced 30 feet.
R_{1s} - Antenna-2 system grounded.
C_{1s} - Antenna-2 system grounded.
R_s - Resonance frequency of antenna-2 system - 207 kc.
C_s - Resonance frequency of antenna-2 system - 207 kc.
100
10
1.0
RESISTANCE - OHMS
R_s
R_s
C_s
C_{1s}
C_s
R_{1s}
1000
400
100
CAPACITY - μμf
100
150
200
250
300
FREQUENCY - KC.

PLATE 13

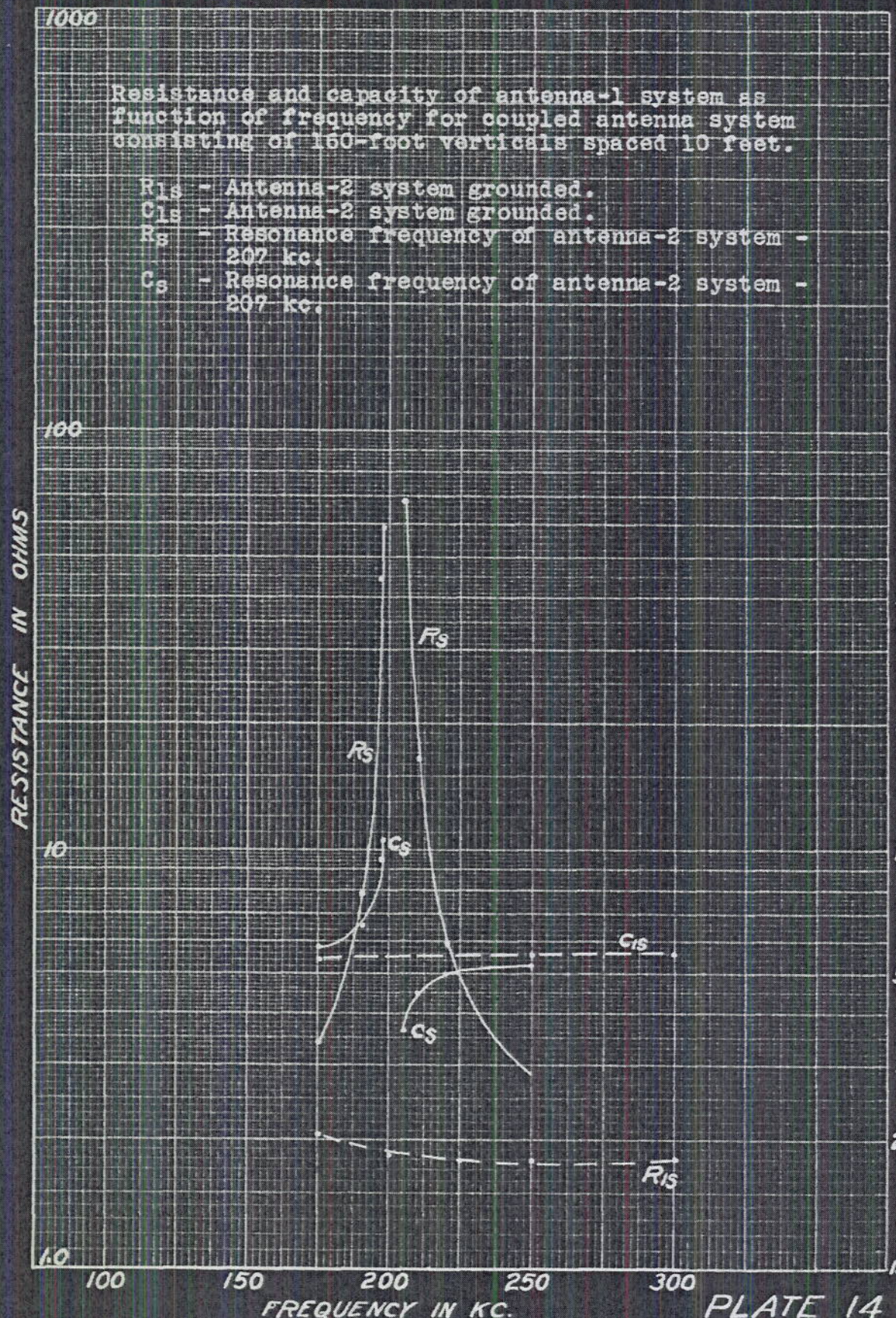

Resistance and capacity of antenna-1 system as function of frequency for coupled antenna system consisting of 150-foot verticals spaced 10 feet.
R_{1s} - Antenna-2 system grounded.
C_{1s} - Antenna-2 system grounded.
R_s - Resonance frequency of antenna-2 system - 207 kc.
C_s - Resonance frequency of antenna-2 system - 207 kc.
1000
100
10
1.0
RESISTANCE IN OHMS
R_s
C_s
C_{1s}
R_{1s}
1000
500
200
100
CAPACITY IN μμf
100
150
200
250
300
FREQUENCY IN KC.

PLATE 14

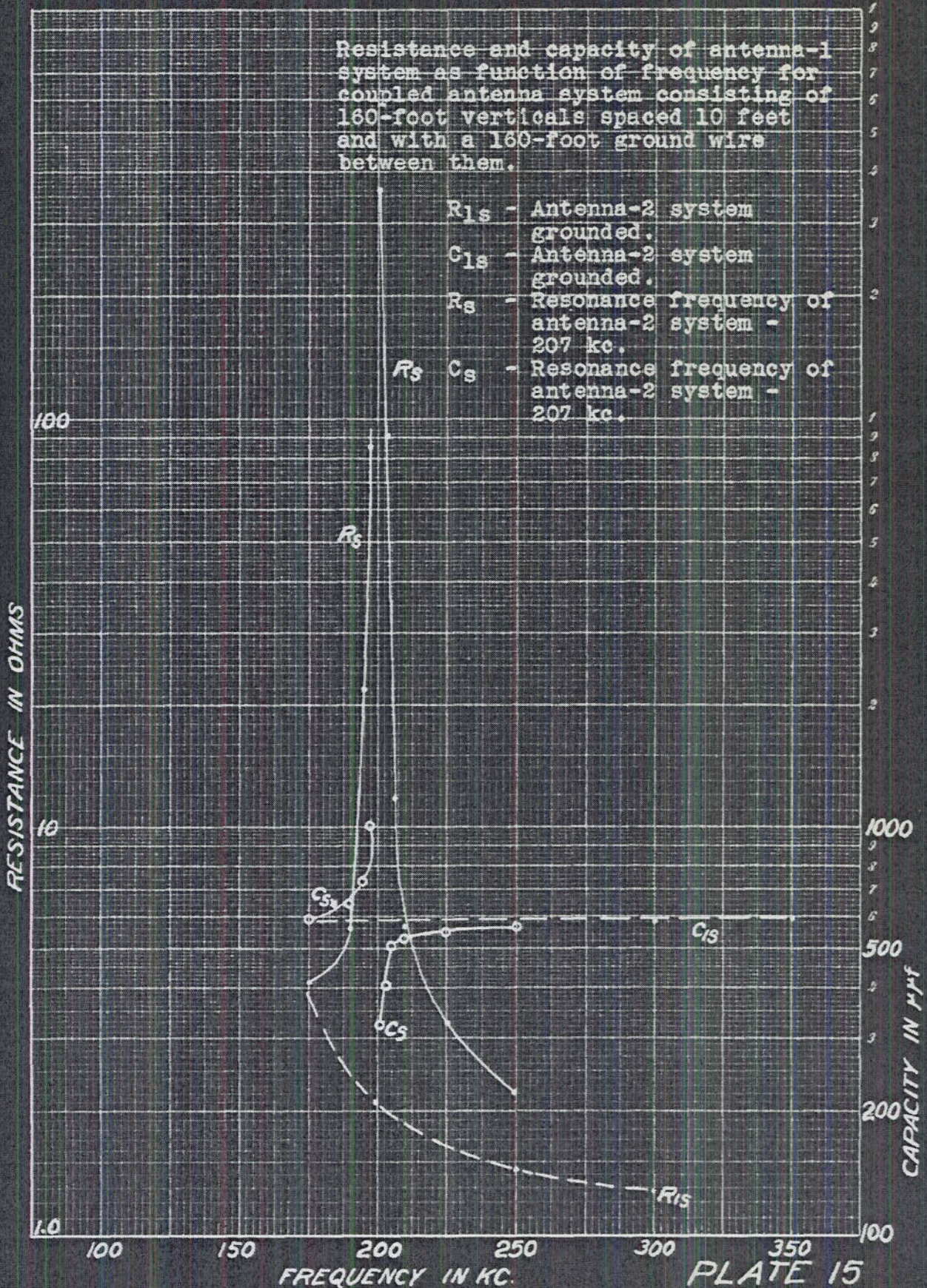

Resistance and capacity of antenna-1 system as function of frequency for coupled antenna system consisting of 160-foot verticals spaced 10 feet and with a 160-foot ground wire between them.
R_{1s} - Antenna-2 system grounded.
C_{1s} - Antenna-2 system grounded.
R_s - Resonance frequency of antenna-2 system - 207 kc.
C_s - Resonance frequency of antenna-2 system - 207 kc.
RESISTANCE IN OHMS
CAPACITY IN μμf
FREQUENCY IN KC.
100
10
1.0
1000
500
200
100
150
200
250
300
350
R_s
C_{s_1}
C_{1s}
C_s
R_{1s}

PLATE 15

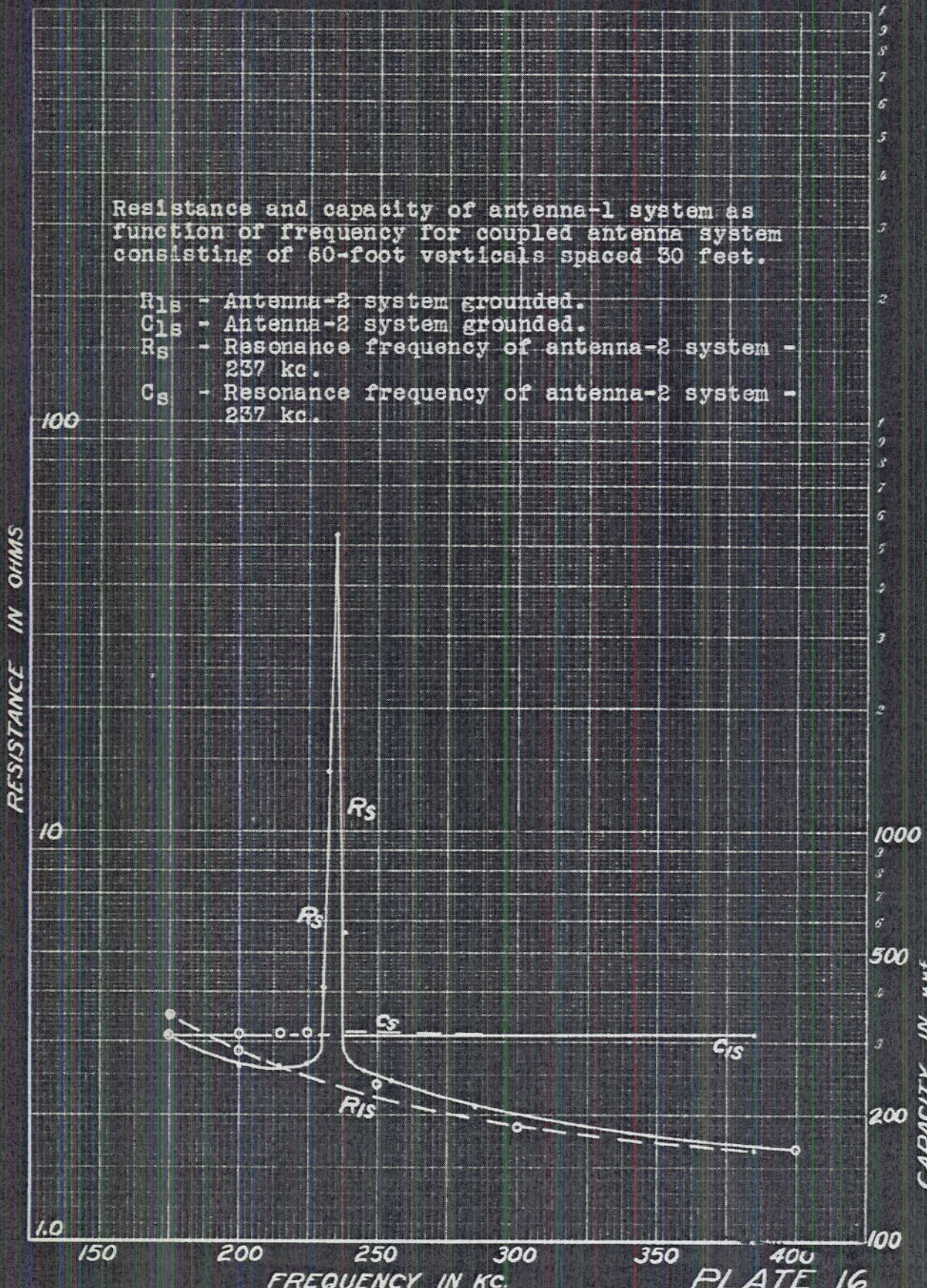

Resistance and capacity of antenna-1 system as function of frequency for coupled antenna system consisting of 60-foot verticals spaced 30 feet.
R_{1s} - Antenna-2 system grounded.
C_{1s} - Antenna-2 system grounded.
R_s - Resonance frequency of antenna-2 system - 237 kc.
C_s - Resonance frequency of antenna-2 system - 237 kc.
RESISTANCE IN OHMS
100
10
1.0
R_s
R_s
C_s
C_{1s}
R_{1s}
1000
500
200
100
CAPACITY IN μμf
150
200
250
300
350
400
FREQUENCY IN KC.

PLATE 16

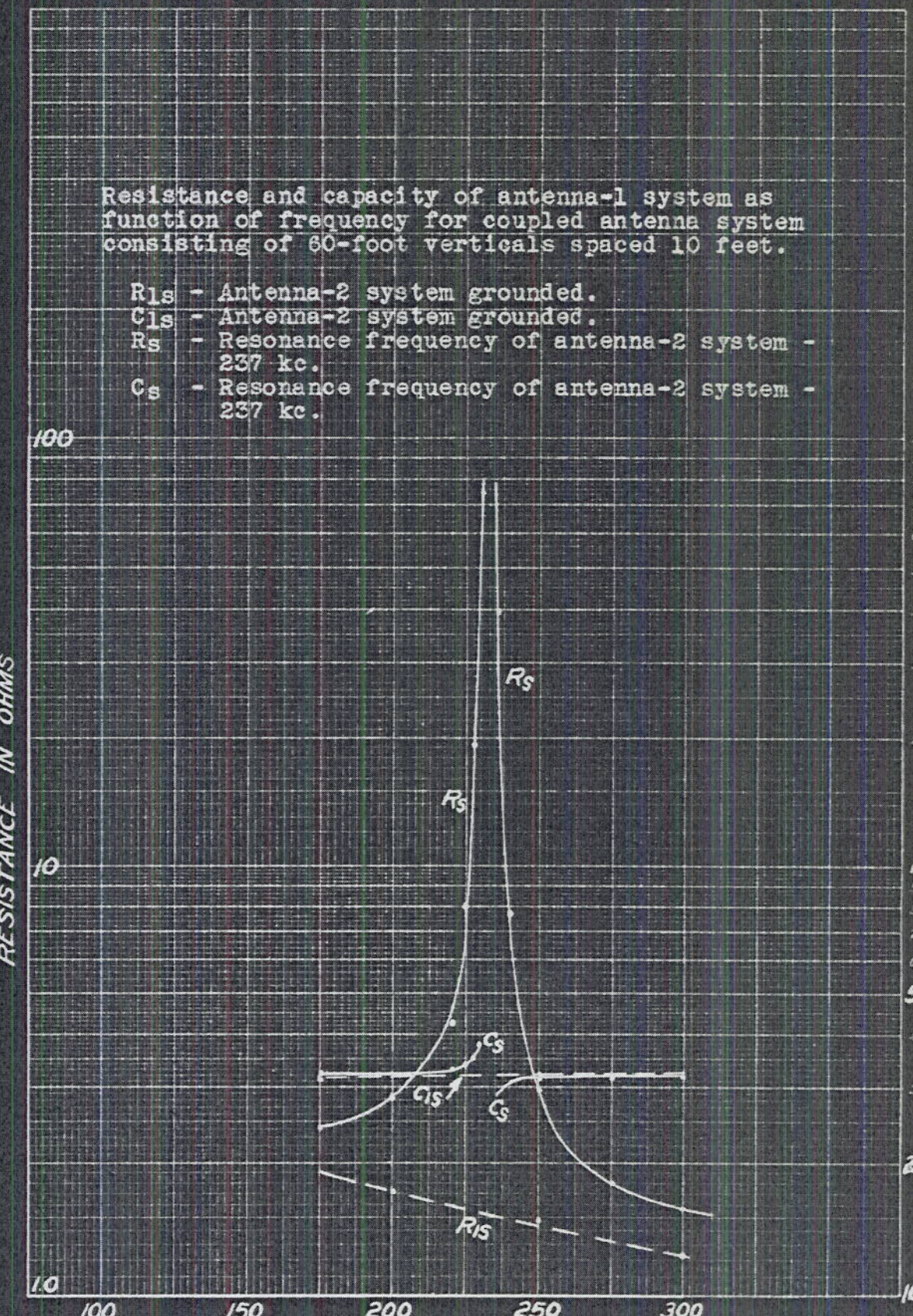

Resistance and capacity of antenna-1 system as function of frequency for coupled antenna system consisting of 60-foot verticals spaced 10 feet.
R1s - Antenna-2 system grounded.
C1s - Antenna-2 system grounded.
Rs - Resonance frequency of antenna-2 system - 237 kc.
Cs - Resonance frequency of antenna-2 system - 237 kc.
100
10
1.0
1000
500
200
100
Rs
Rs
Cs
C1s
Cs
R1s
RESISTANCE IN OHMS
CAPACITY IN μμf
100
150
200
250
300
FREQUENCY IN KC.

PLATE 17

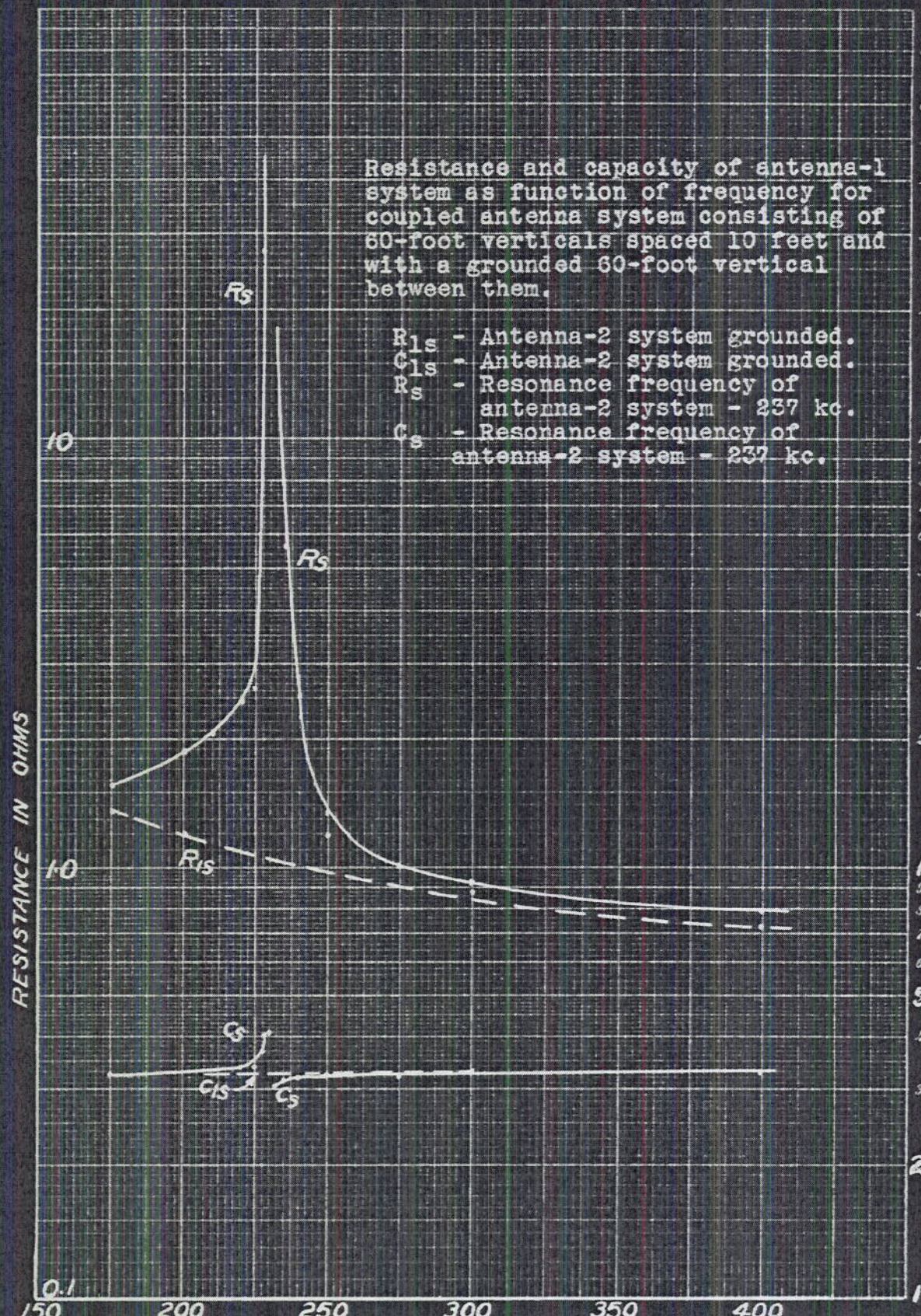

Resistance and capacity of antenna-1 system as function of frequency for coupled antenna system consisting of 60-foot verticals spaced 10 feet and with a grounded 60-foot vertical between them.
R_{1s} - Antenna-2 system grounded.
C_{1s} - Antenna-2 system grounded.
R_s - Resonance frequency of antenna-2 system - 237 kc.
C_s - Resonance frequency of antenna-2 system - 237 kc.
R_s
R_s
R_{1s}
C_s
C_{1s}
C_s
10
1.0
0.1
1000
500
200
100
RESISTANCE IN OHMS
CAPACITY IN μμf
150
200
250
300
350
400
FREQUENCY - KC.

PLATE 18

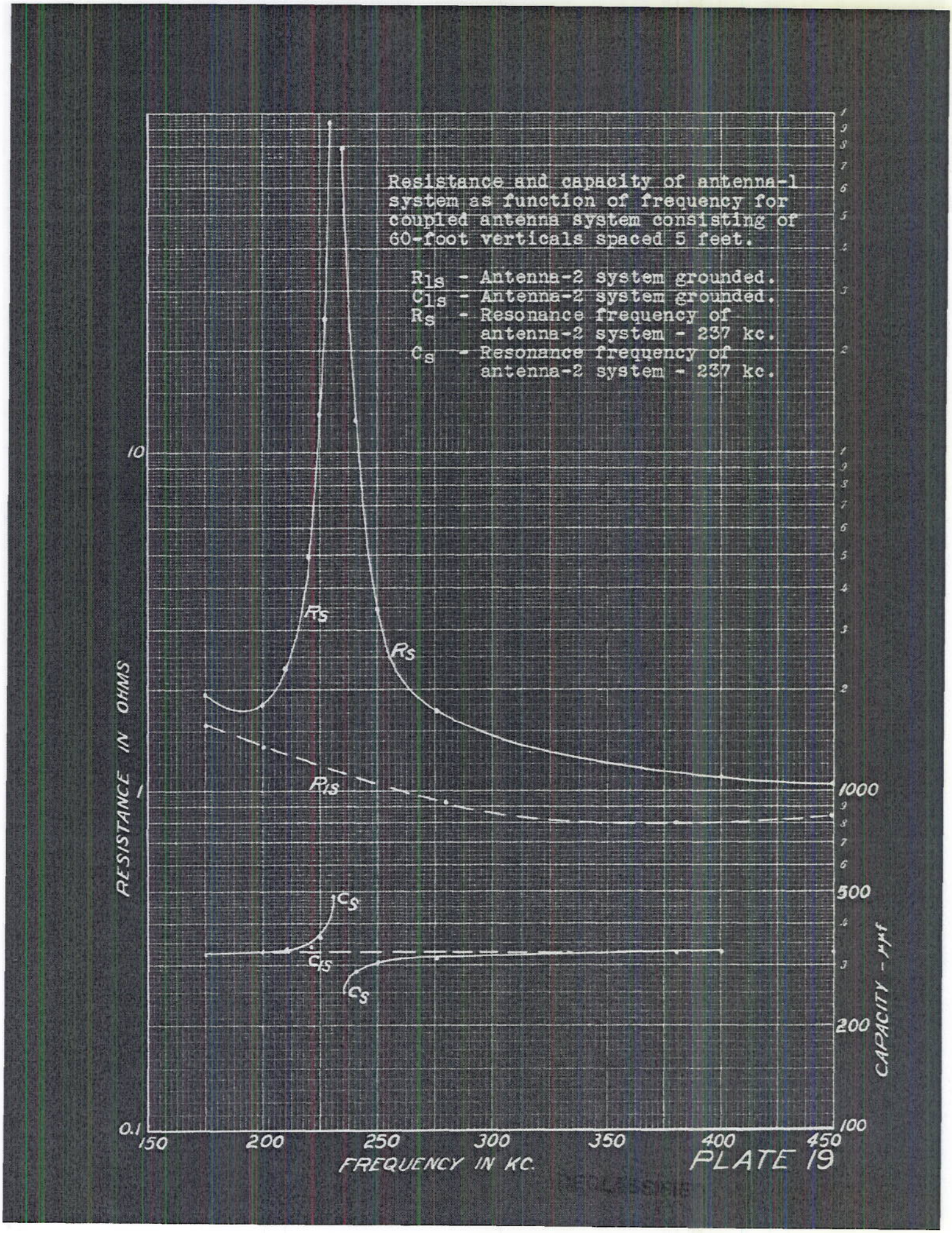

Resistance and capacity of antenna-1 system as function of frequency for coupled antenna system consisting of 60-foot verticals spaced 5 feet.
R_{1s} - Antenna-2 system grounded.
C_{1s} - Antenna-2 system grounded.
R_s - Resonance frequency of antenna-2 system - 237 kc.
C_s - Resonance frequency of antenna-2 system - 237 kc.
RESISTANCE IN OHMS
CAPACITY - μμf
FREQUENCY IN KC.
10
1
0.1
1000
500
200
100
150
200
250
300
350
400
450

PLATE 19

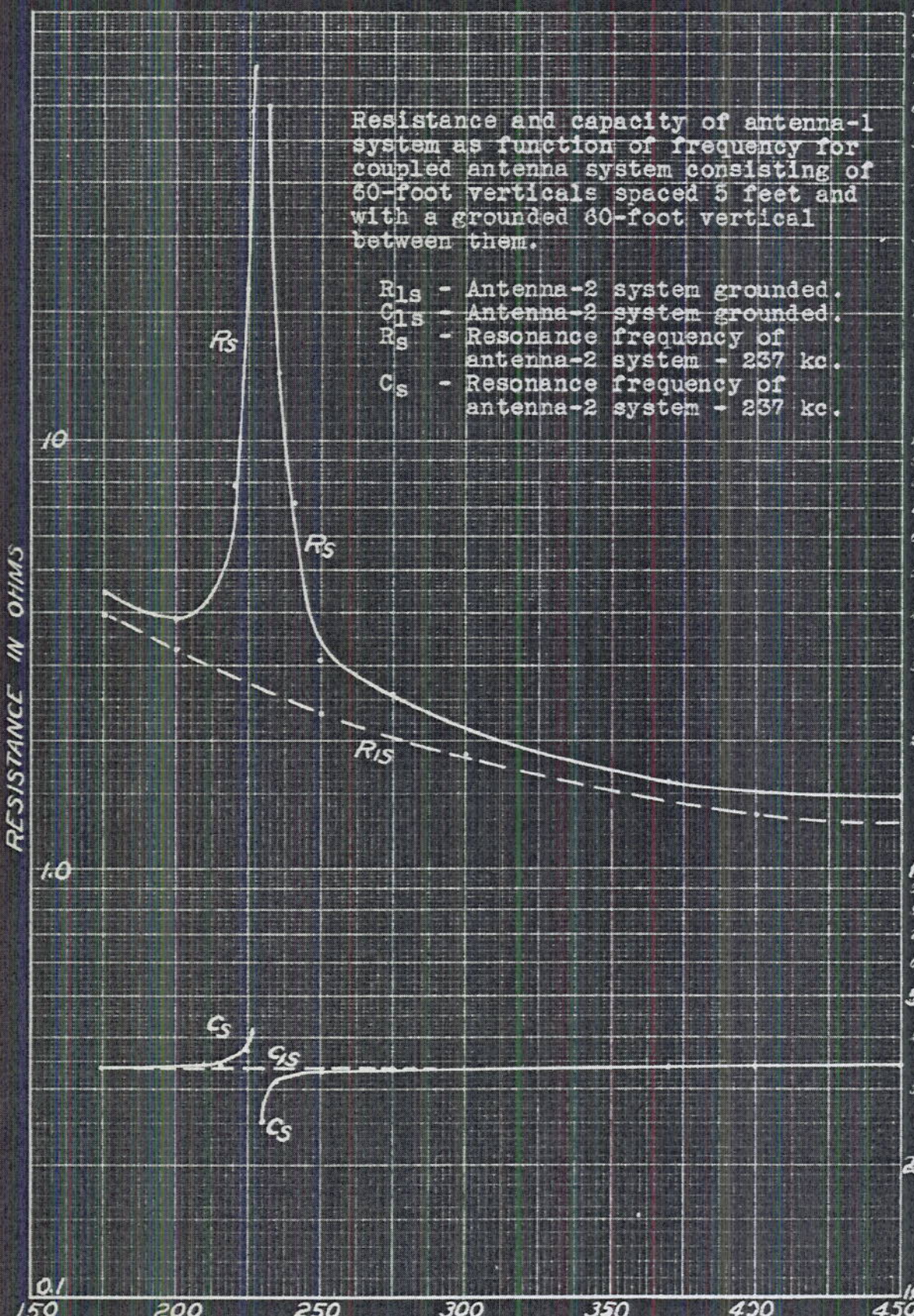

Resistance and capacity of antenna-1 system as function of frequency for coupled antenna system consisting of 60-foot verticals spaced 5 feet and with a grounded 60-foot vertical between them.
R_{1s} - Antenna-2 system grounded.
C_{1s} - Antenna-2 system grounded.
R_s - Resonance frequency of antenna-2 system - 237 kc.
C_s - Resonance frequency of antenna-2 system - 237 kc.
R_s
R_s
R_{1s}
C_s
C_{1s}
C_s
RESISTANCE IN OHMS
10
1.0
0.1
CAPACITY - μμf
1000
500
200
100
150
200
250
300
350
400
450
FREQUENCY IN KC.

PLATE 20

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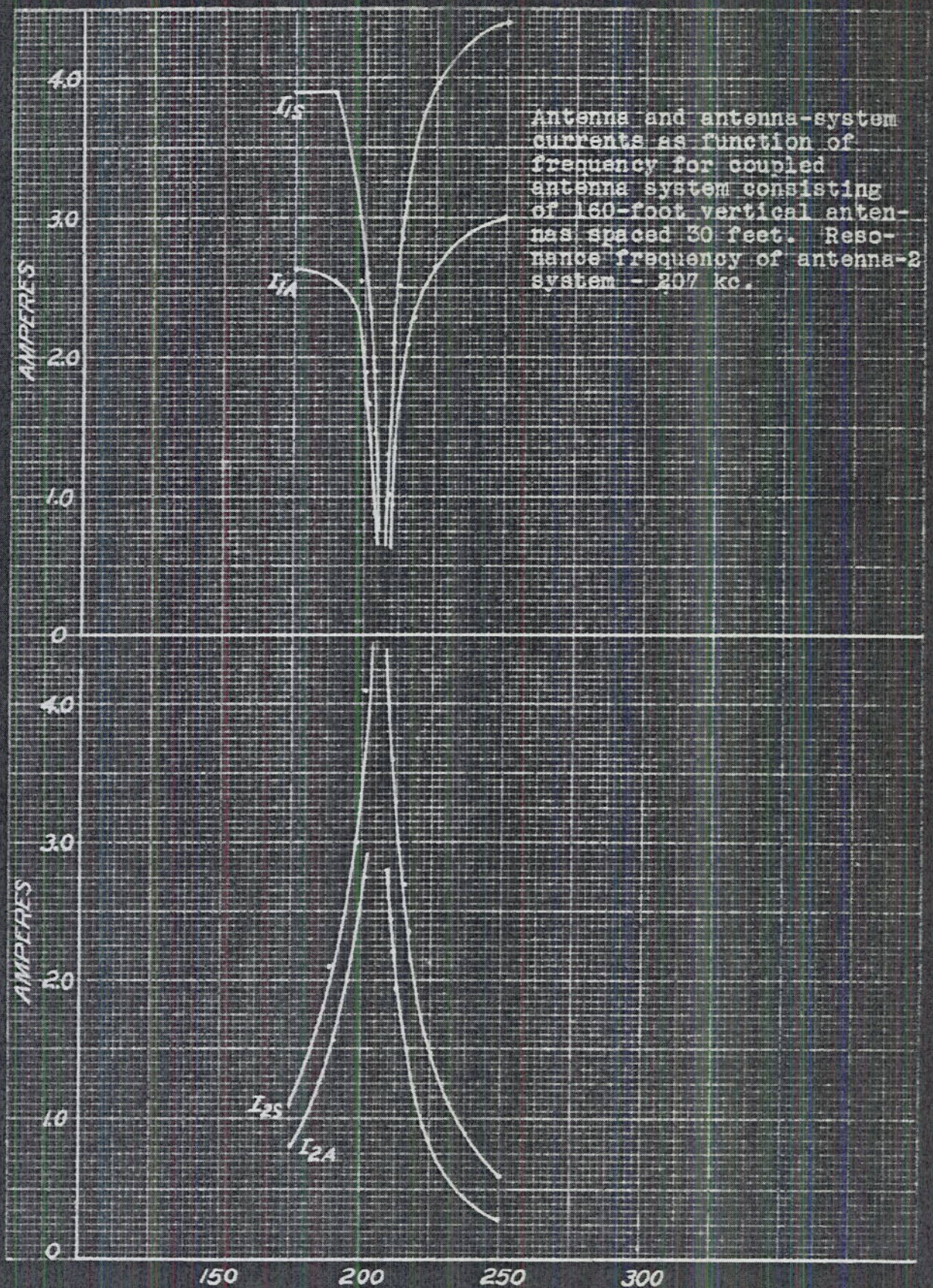
DATE



Antenna and antenna-system currents as function of frequency for coupled antenna system consisting of 160-foot vertical antennas spaced 30 feet. Resonance frequency of antenna-2 system - 207 kc.

PLATE 21

IF SHEET IS READ THIS WAY, HORIZONTALLY, THIS MUST BE TOP. IF SHEET IS READ THE OTHER WAY (VERTICALLY) THIS MUST BE LEFT-HAND SIDE.

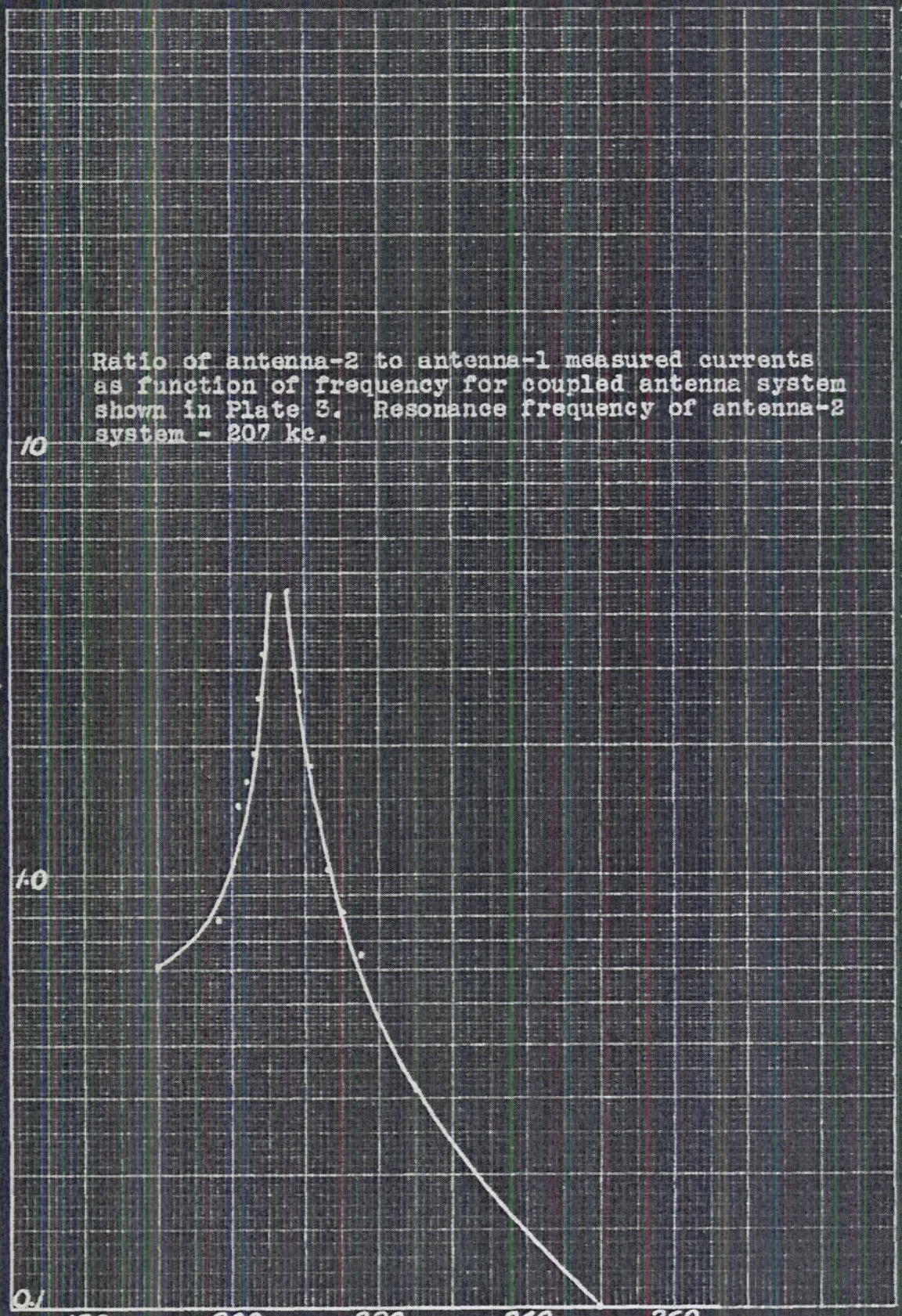

Ratio of antenna-2 to antenna-1 measured currents as function of frequency for coupled antenna system shown in Plate 3. Resonance frequency of antenna-2 system - 207 kc.
10
1.0
0.1
CURRENT RATIO I_{2A}/I_{1A}
180
200
220
240
260
FREQUENCY IN KC.

PLATE 22

Antenna-1 current as function of frequency for antenna system shown in Plate 3.

1. Antenna 2 grounded.
2. Resonance frequency of antenna-2 system - 207 kc.

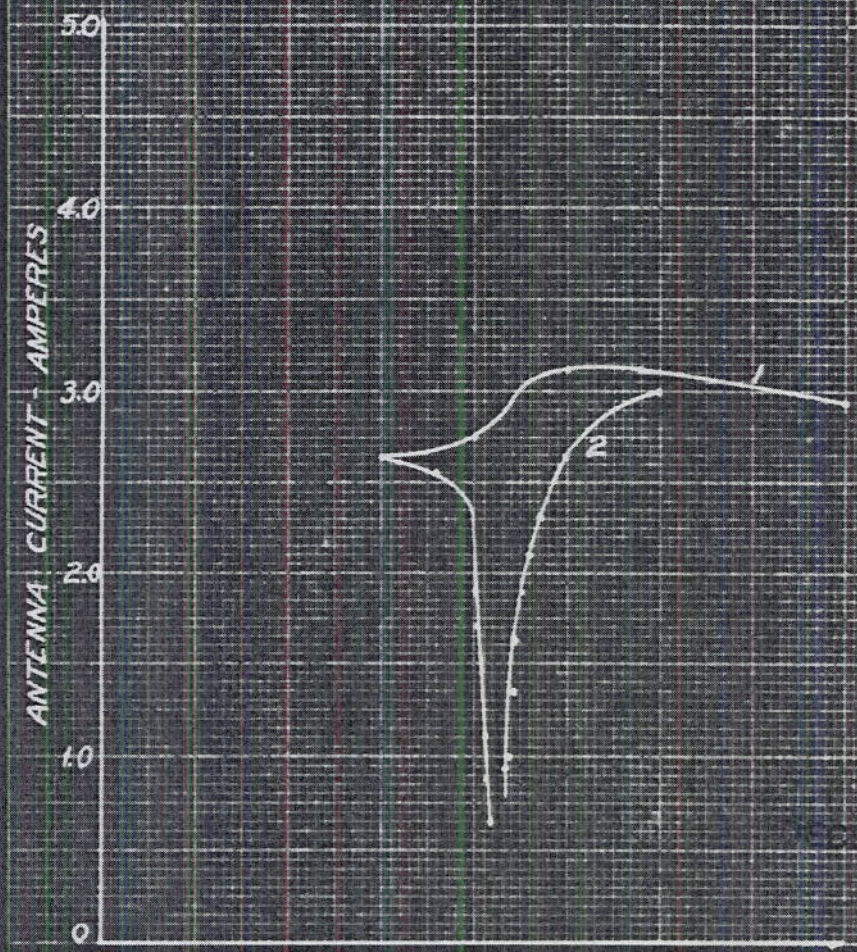


PLATE 23

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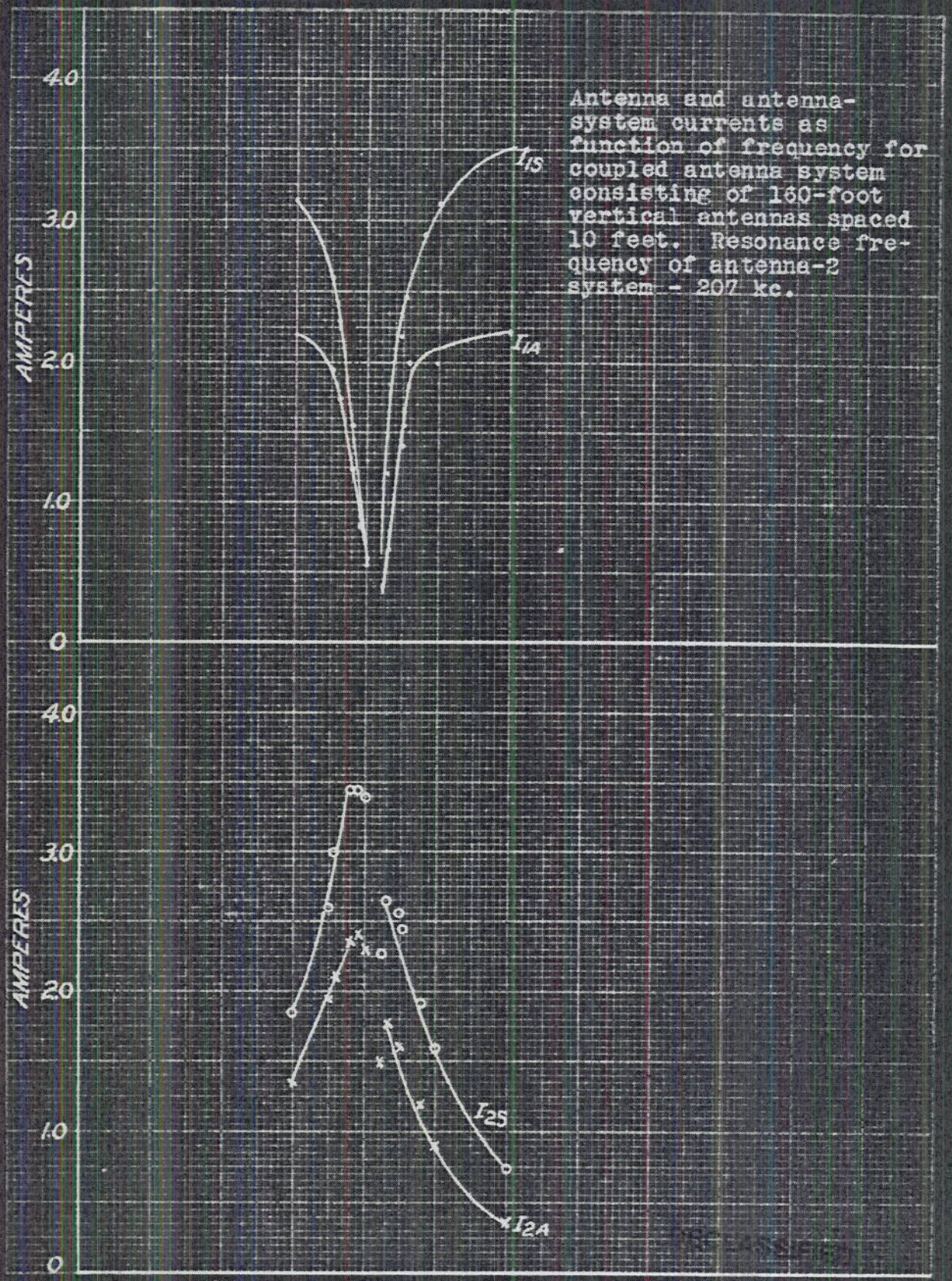
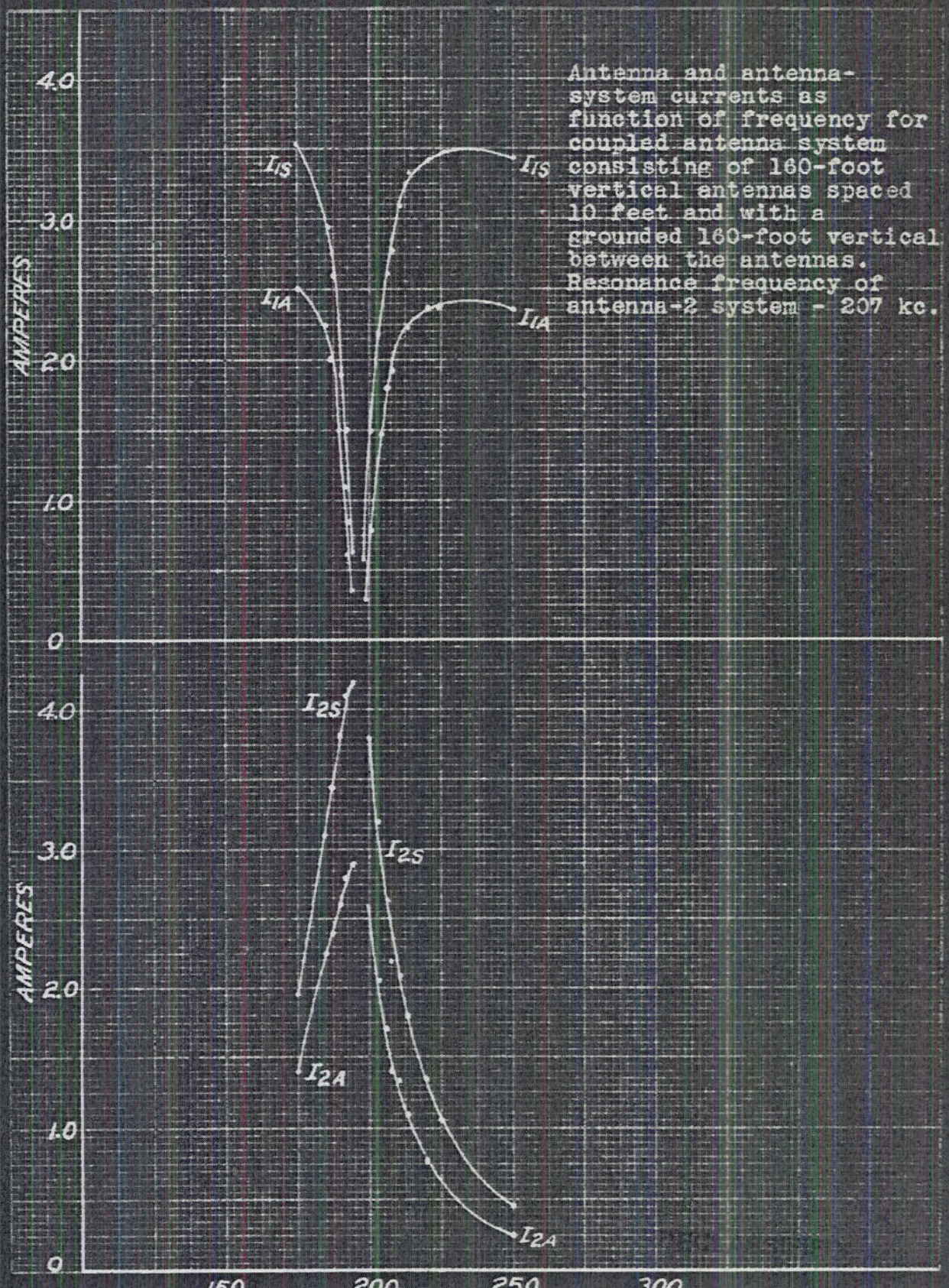


Antenna and antenna-system currents as function of frequency for coupled antenna system consisting of 160-foot vertical antennas spaced 10 feet. Resonance frequency of antenna-2 system - 207 kc.

PLATE 24



Antenna and antenna-system currents as function of frequency for coupled antenna system consisting of 160-foot vertical antennas spaced 10 feet and with a grounded 160-foot vertical between the antennas. Resonance frequency of antenna-2 system - 207 kc.

PLATE 25

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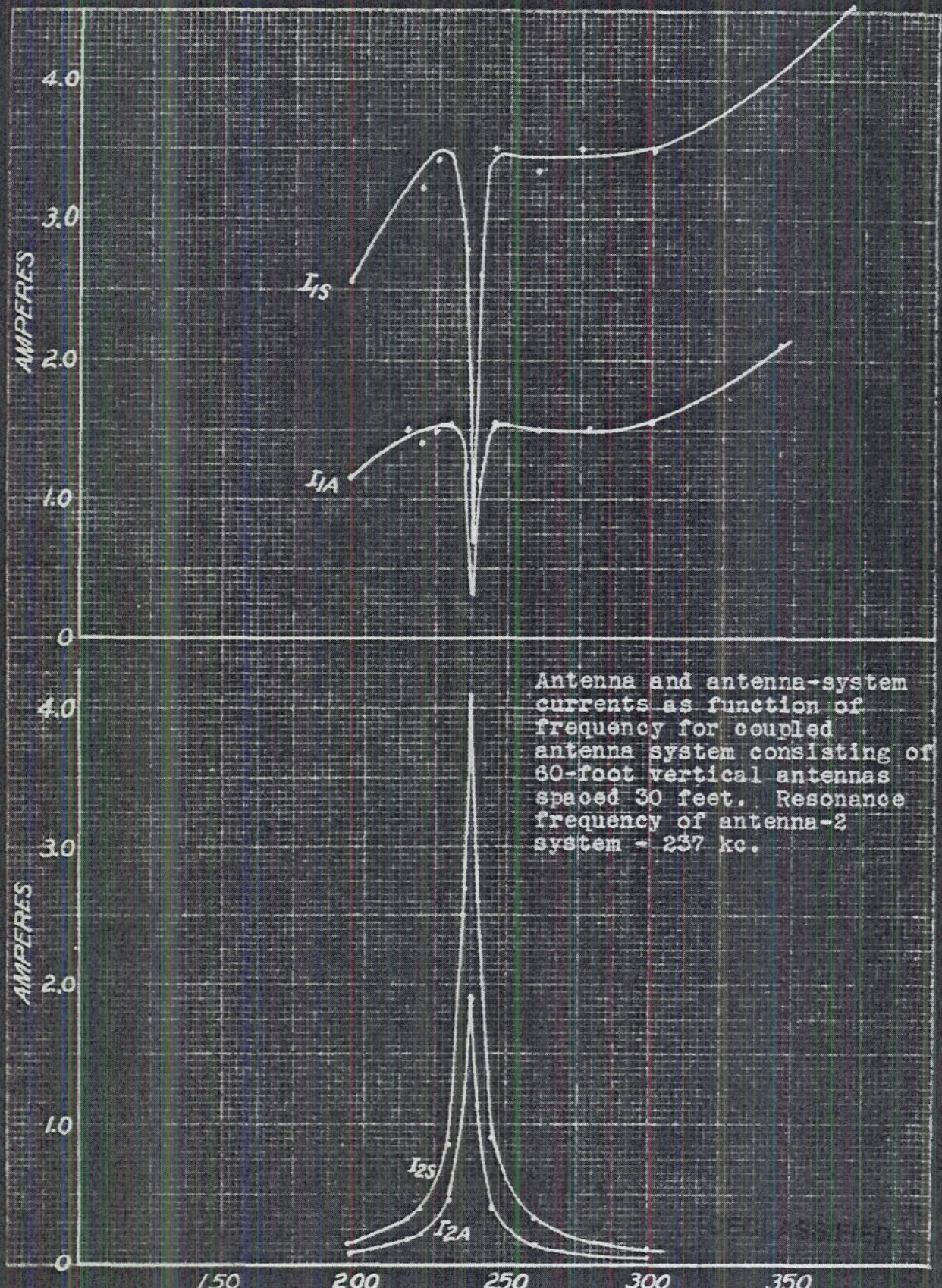


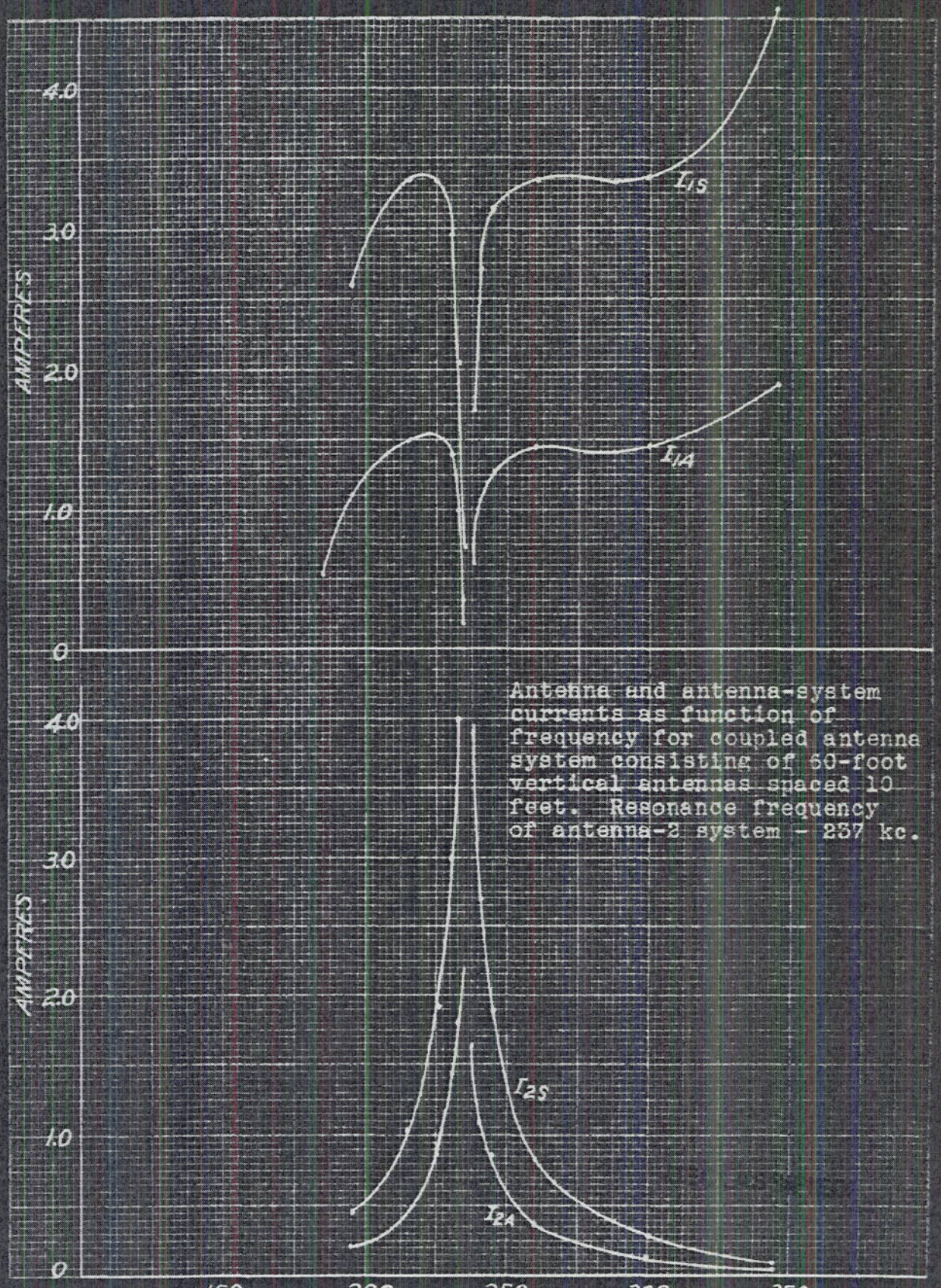
Antenna and antenna-system currents as function of frequency for coupled antenna system consisting of 60-foot vertical antennas spaced 30 feet. Resonance frequency of antenna-2 system = 237 kc.

IF SHEET IS READ THIS WAY (HORIZONTALLY) THIS MUST BE TOP - IF SHEET IS READ THE OTHER WAY (VERTICALLY) THIS MUST BE LEFT-HAND SIDE

DECLASSIFIED

PLATE 26

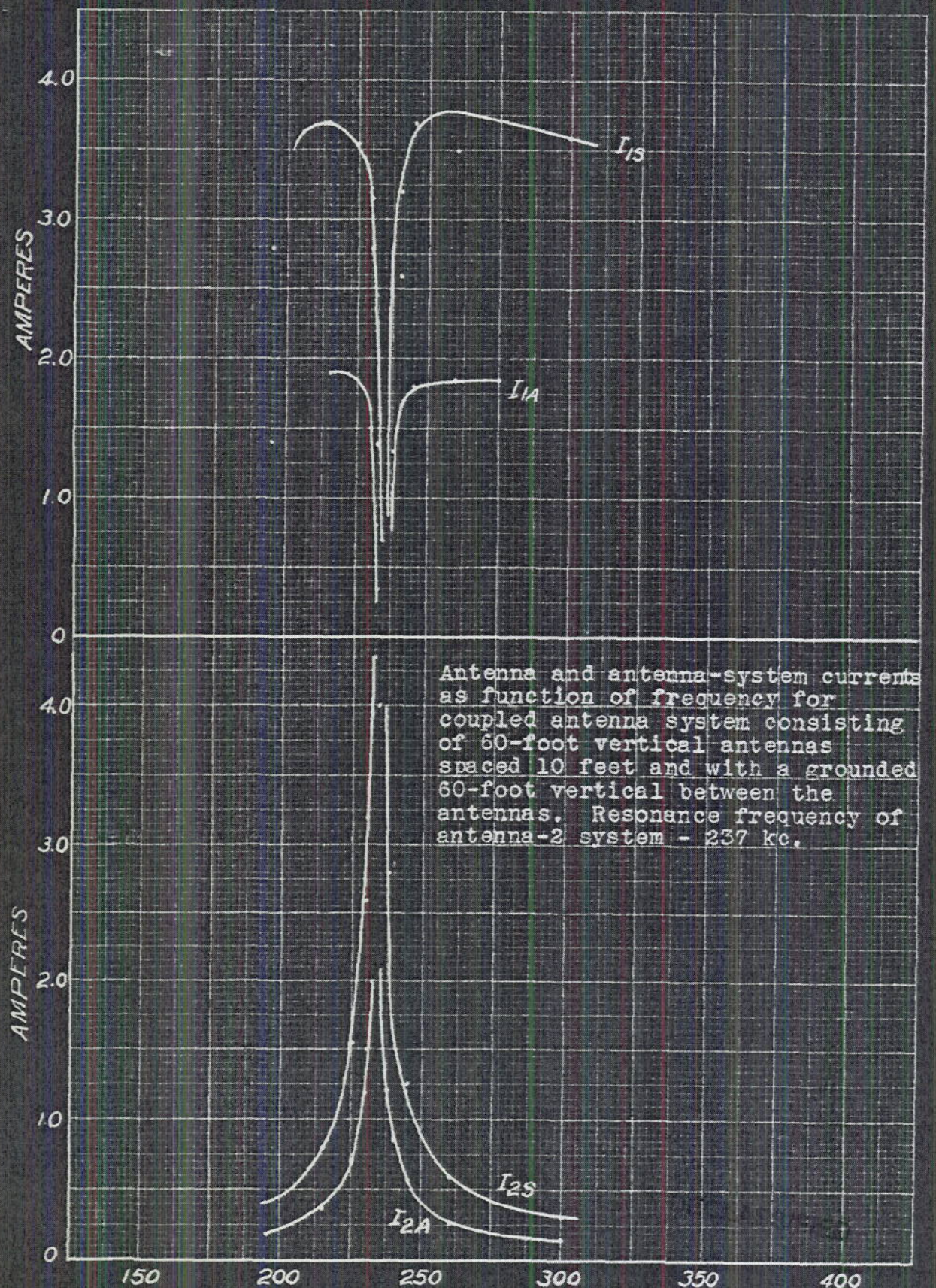
U. S. NAVAL RESEARCH LABORATORY
BELLEVUE, D. C.
DATE



Antenna and antenna-system currents as function of frequency for coupled antenna system consisting of 60-foot vertical antennas spaced 10 feet. Resonance frequency of antenna-2 system - 237 kc.

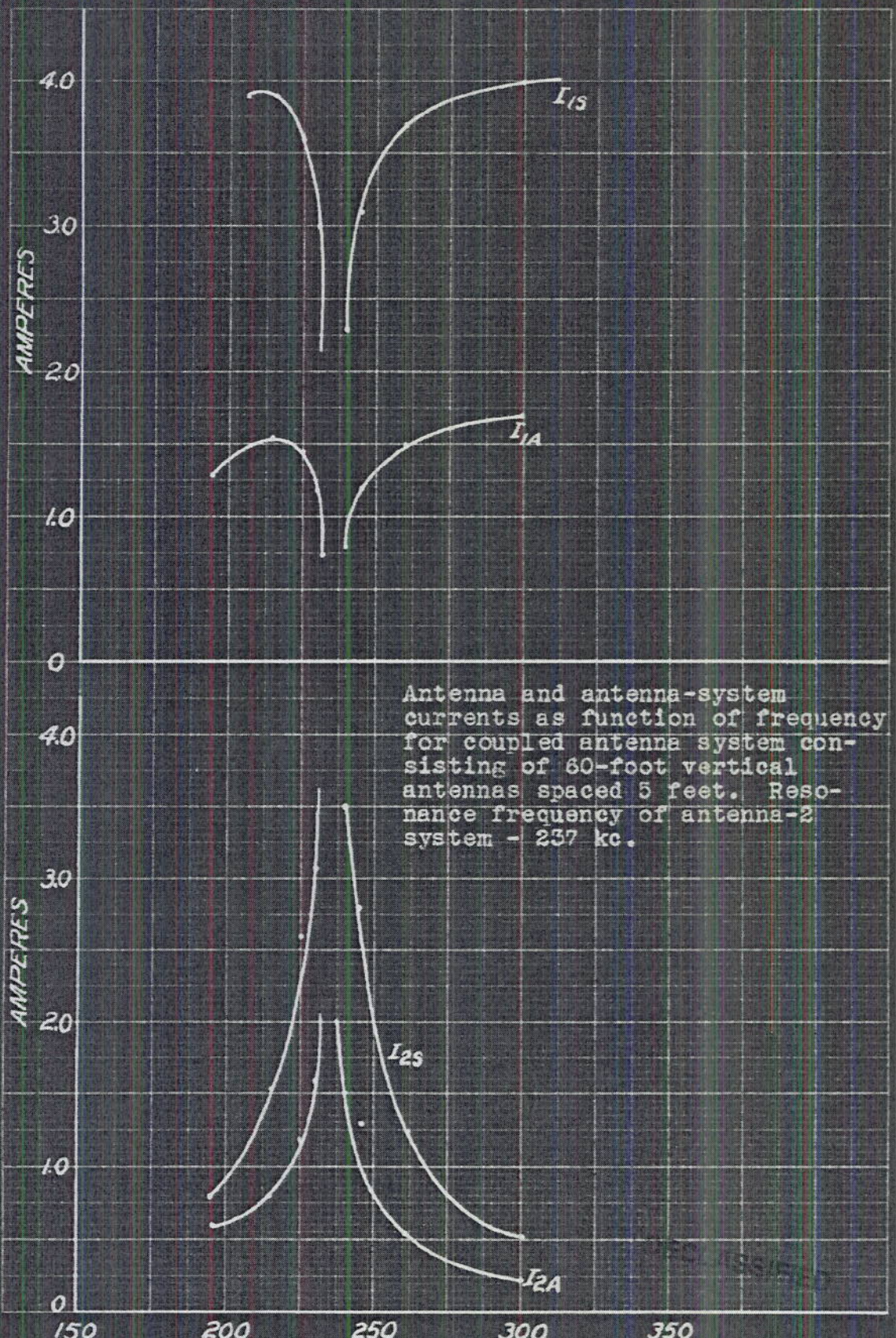
PLATE 27

IF SHEET IS READ THIS WAY HORIZONTALLY THIS MUST BE TOP. IF SHEET IS READ THE OTHER WAY VERTICALLY, THIS MUST BE LEFT-HAND SIDE



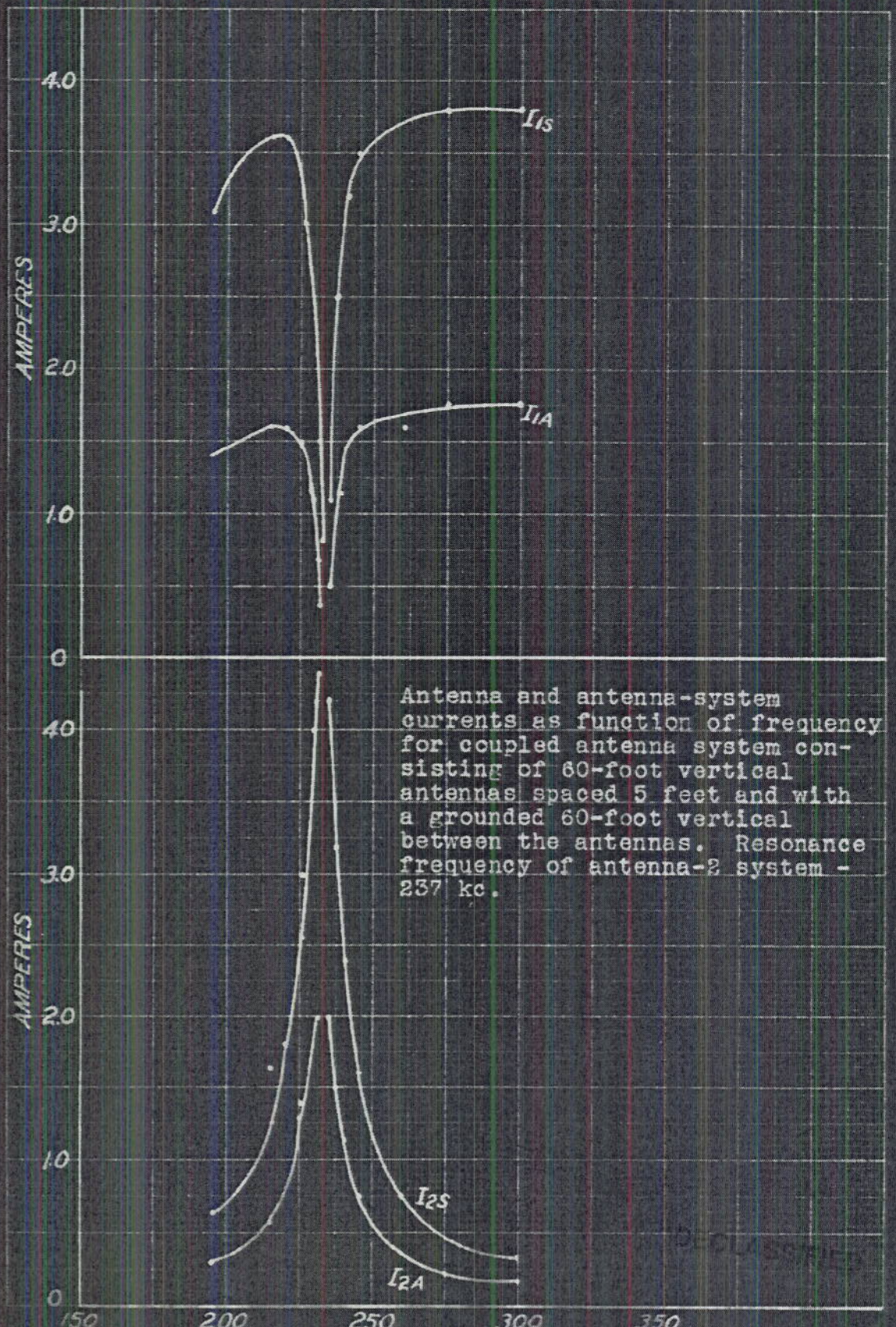
Antenna and antenna-system currents as function of frequency for coupled antenna system consisting of 60-foot vertical antennas spaced 10 feet and with a grounded 60-foot vertical between the antennas. Resonance frequency of antenna-2 system - 237 kc.

PLATE 28



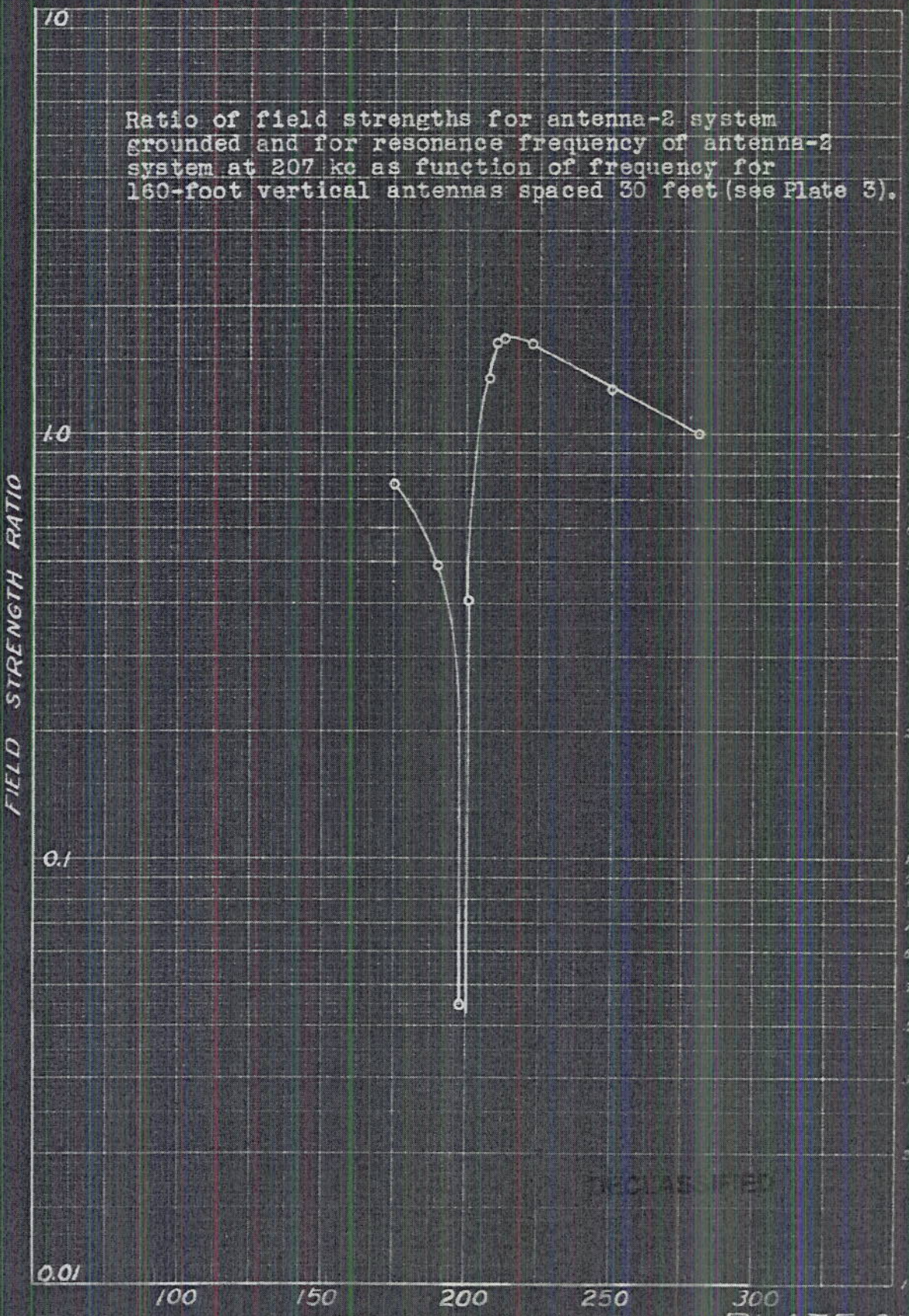
Antenna and antenna-system currents as function of frequency for coupled antenna system consisting of 60-foot vertical antennas spaced 5 feet. Resonance frequency of antenna-2 system - 237 kc.

PLATE 29



Antenna and antenna-system currents as function of frequency for coupled antenna system consisting of 60-foot vertical antennas spaced 5 feet and with a grounded 60-foot vertical between the antennas. Resonance frequency of antenna-2 system - 237 kc.

PLATE 30



DECLASSIFIED

PLATE 31

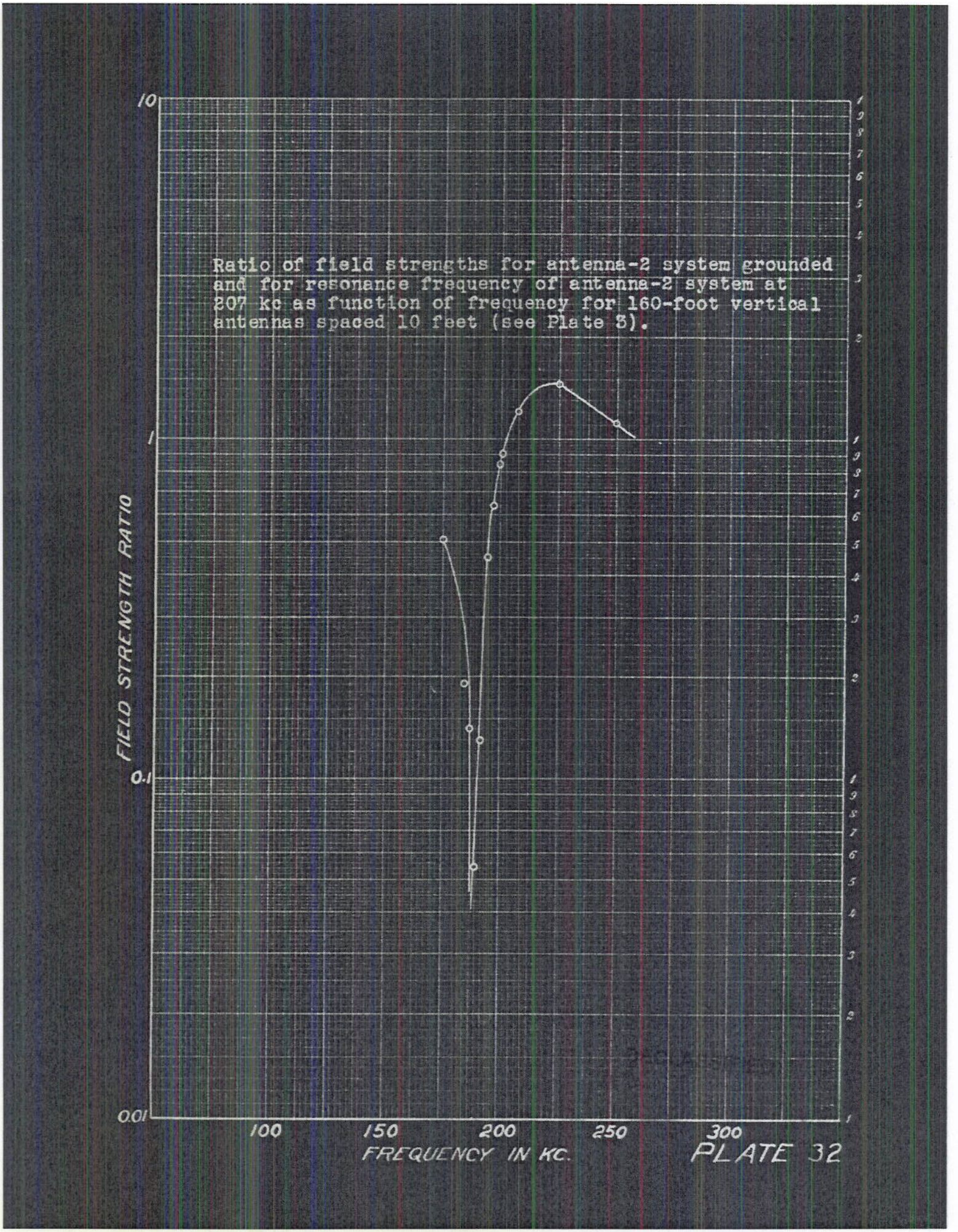
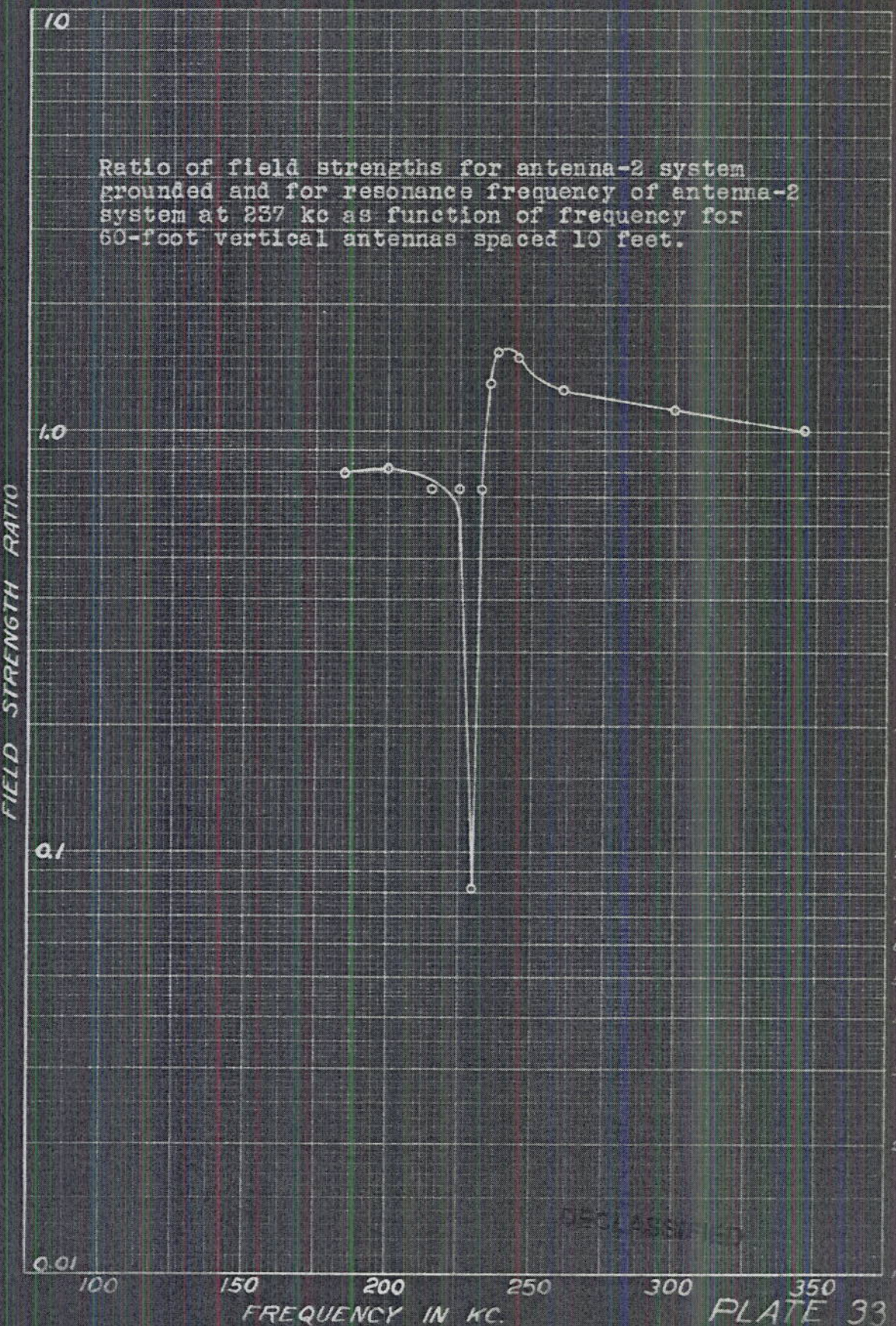

Ratio of field strengths for antenna-2 system grounded and for resonance frequency of antenna-2 system at 207 kc as function of frequency for 160-foot vertical antennas spaced 10 feet (see Plate 3).
FIELD STRENGTH RATIO
10
1
0.1
0.01
100
150
200
250
300
FREQUENCY IN KC.

PLATE 32



DECLASSIFIED

PLATE 33

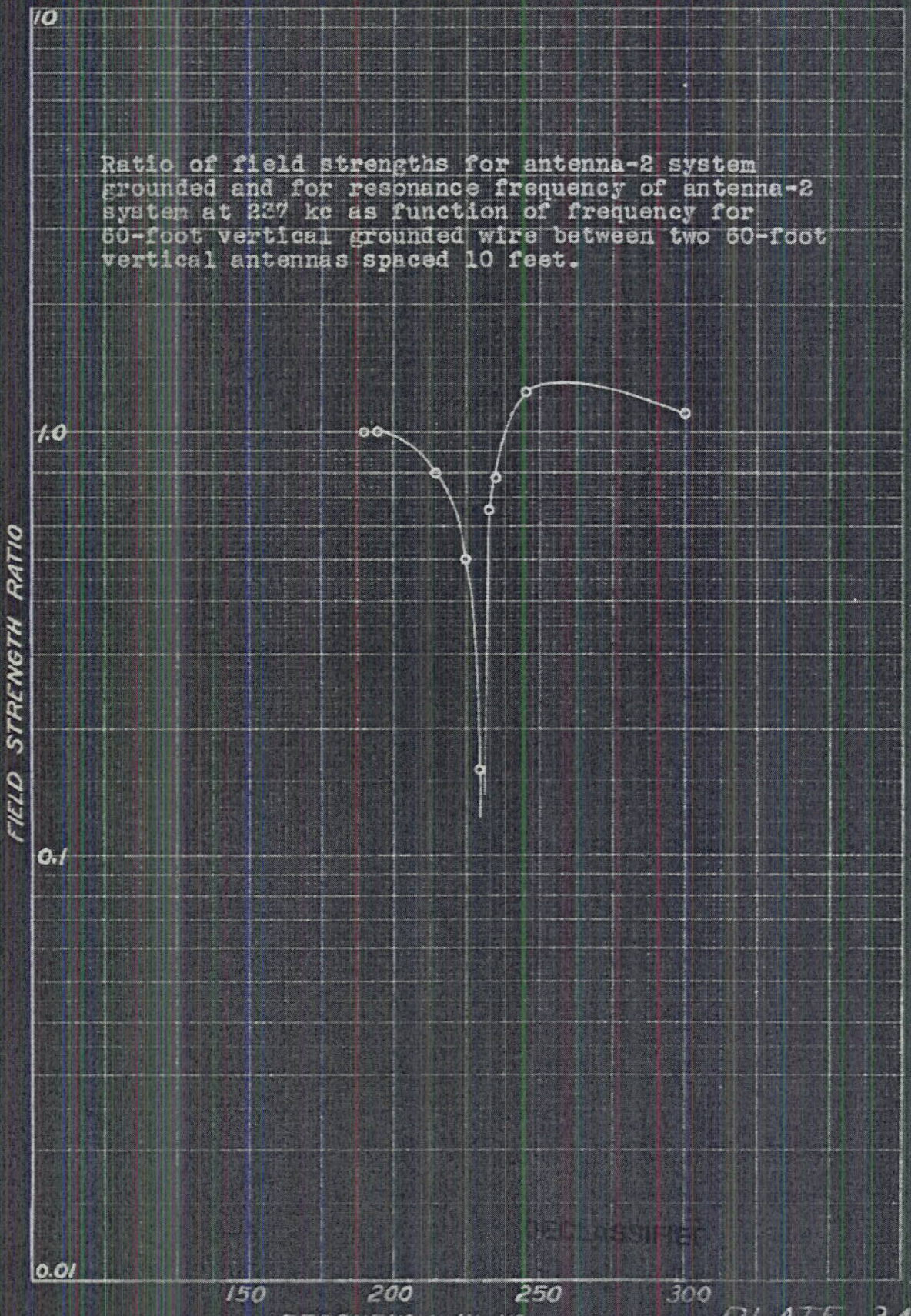
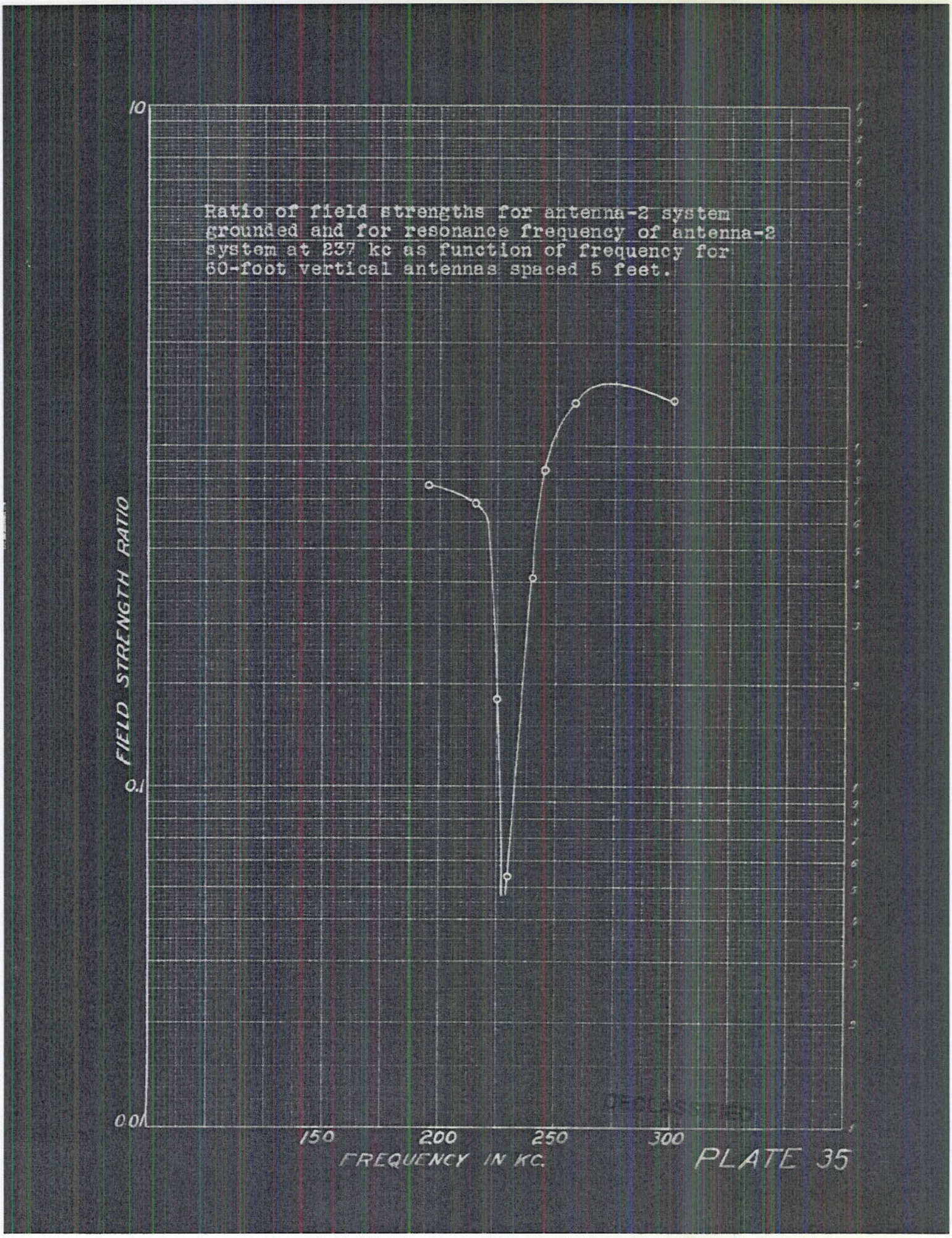
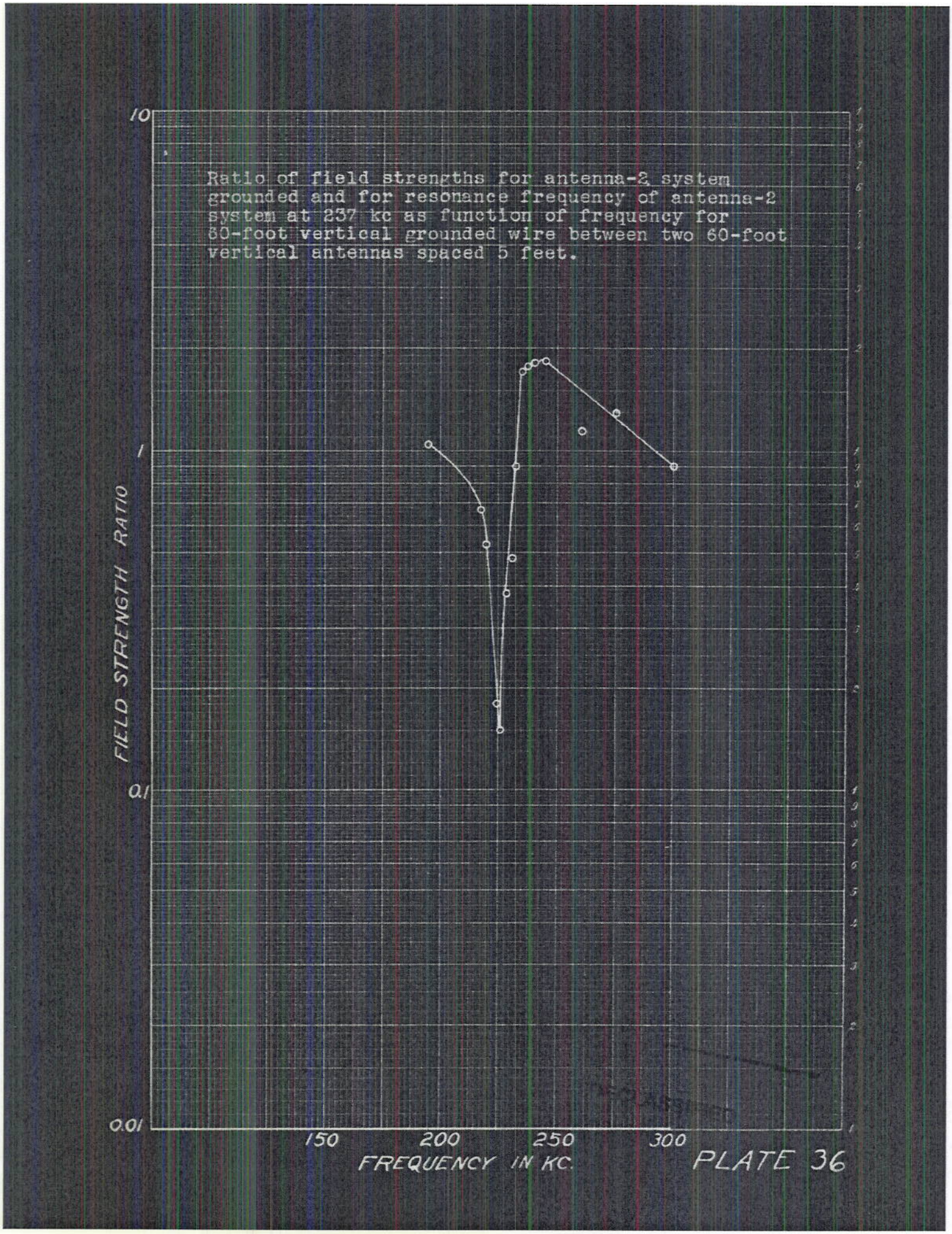

Ratio of field strengths for antenna-2 system grounded and for resonance frequency of antenna-2 system at 237 kc as function of frequency for 60-foot vertical grounded wire between two 60-foot vertical antennas spaced 10 feet.
10
1.0
0.1
0.01
FIELD STRENGTH RATIO
150
200
250
300
FREQUENCY IN KC.

PLATE 34


Ratio of field strengths for antenna-2 system grounded and for resonance frequency of antenna-2 system at 237 kc as function of frequency for 60-foot vertical antennas spaced 5 feet.
10
0.1
0.01
FIELD STRENGTH RATIO
150
200
250
300
FREQUENCY IN KC.
DECLASSIFIED
PLATE 35


Ratio of field strengths for antenna-2 system grounded and for resonance frequency of antenna-2 system at 237 kc as function of frequency for 80-foot vertical grounded wire between two 60-foot vertical antennas spaced 5 feet.
10
1
0.1
0.01
FIELD STRENGTH RATIO
150
200
250
300
FREQUENCY IN KC.
PLATE 36

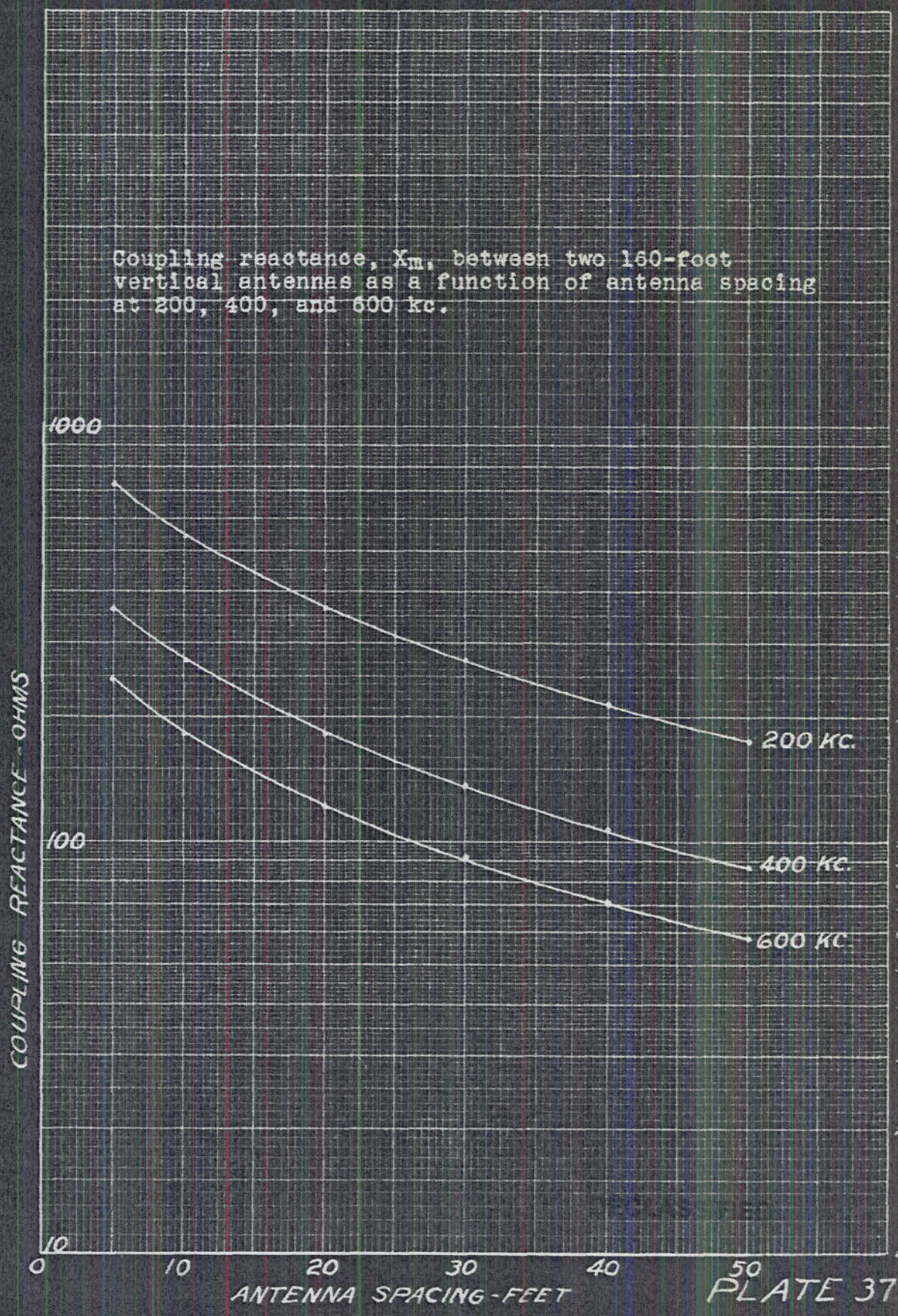

Coupling reactance, X_m, between two 160-foot vertical antennas as a function of antenna spacing at 200, 400, and 600 kc.
1000
100
10
200 KC.
400 KC.
600 KC.
COUPLING REACTANCE - OHMS
0
10
20
30
40
50
ANTENNA SPACING - FEET

PLATE 37

Coupling between two vertical antennas of the same height as a function of their height for various spacings between antennas at 200 kc.

Curves 1, 2 and 3. Coupling reactance X_m for D equals 5, 10 and 30 feet.
Curve 4. Reactance, X, of one antenna only.

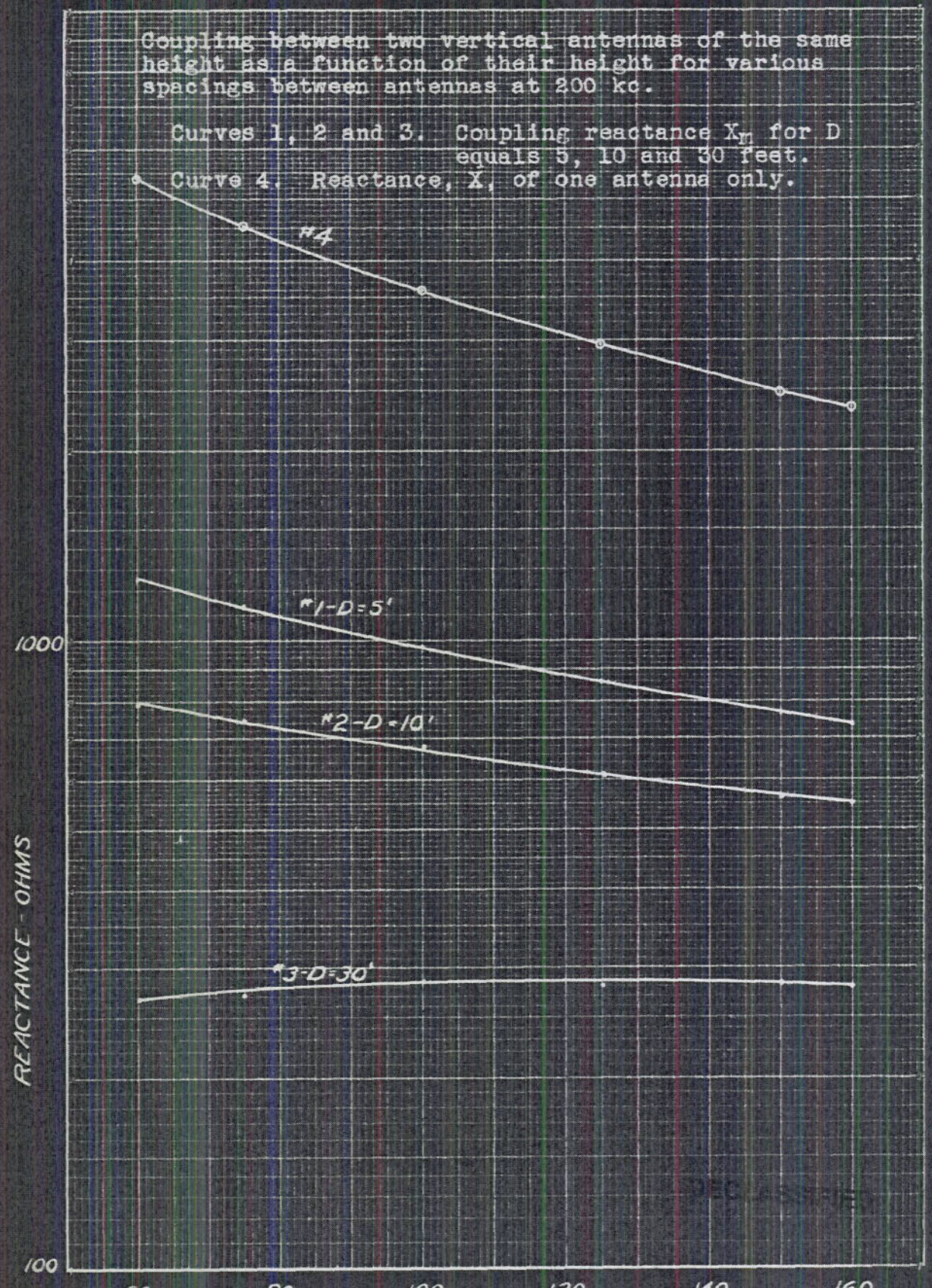


PLATE 38

Ratio of coupling reactance, X_m, between two vertical antennas of the same height to reactance, X, of antenna-1 only as a function of their heights for various spacings between antennas at 200 kc.

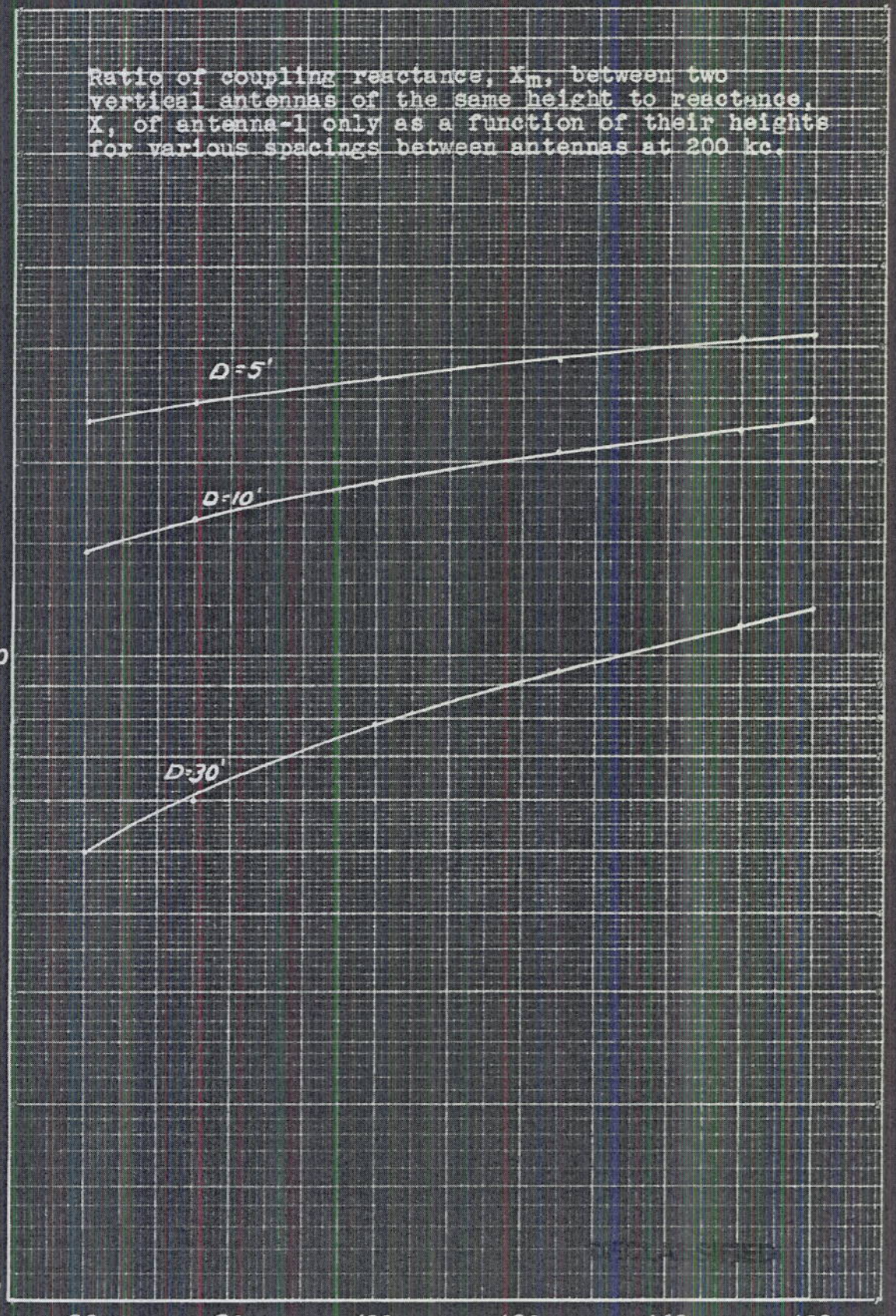


PLATE 39