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THE TRANSMISSION OF RADIO SIGNALS FROM A SUBMERGED ANTENNA

By Dr. R. B. Quinn and
Dr. O. Norgorden

- Report R-3006 - [redacted]

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SHIP-SHORE RADIO DIVISION - TRANSMITTER SECTION

6 November 1946

THE TRANSMISSION OF RADIO SIGNALS FROM A SUBMERGED ANTENNA

By Dr. R. B. Quinn and
Dr. O. Norgorden

- Report R-3006 -

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ABSTRACT

The possibility of transmitting radio signals from one submerged antenna to another along a path from one antenna to the surface, along the surface to a point directly over the second antenna, and down to that antenna is considered. Larger distances may be linked than if the transmission is entirely within sea water. The reciprocal theorem is applied to develop a simple theory for the field which can be obtained from a submerged loop antenna. The final field value is the product of three factors: the primary field of the antenna, the refraction coefficient at each penetration of the surface, and an exponential factor giving the field after attenuation by the sea water. Experiments were conducted at Fort Pond Bay which demonstrated the reception in air of signals from a submerged loop and gave data in satisfactory agreement with the theoretical predictions. These loops were as large as 65 feet by 10 feet, and powers as high as three kilowatts at 100 kilocycles per second were used. The radiation efficiencies were not high, and efforts are being directed toward reducing the loss resistance of the loops.

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INTRODUCTION

1. The transmission of radio signals from one antenna submerged in sea water, such as might be the case on a submarine, to a second antenna also submerged, is viewed as having important military applications. There are two possible propagation paths between the two submerged antennas: (a) directly from one antenna to the other, entirely within sea water; and (b) vertically upward from the transmitting antenna to the sea water surface, in air along the surface to a point directly over the submerged receiving antenna, and finally downward to the antenna. For the direct, all sea water propagation path the attenuation is extremely high, limiting the range of operation for radiated radio frequency signals to too short distances to be of practical value. Less attenuation is suffered at audio frequencies but the radiation efficiency of practical radiators is then very low. Special short-range applications may still find these frequencies advantageous. However, because of the severe range limitation no further consideration will be given in this report to the all sea water propagation path. The "composite", air-sea water propagation path is suggested by the known submerged reception of signals which have originated in air, an analysis of which is presented in reference (a). If the antennas are not deeply submerged the attenuation suffered is not excessive. Although the small fraction of energy penetrating the sea surface reduces the advantage over the all sea water path there is still a large net gain in operating range. In one instance (100 kc/sec) involving two antennas submerged eight feet and separated a mile, the field at the receiving antenna should be 10^{867} times larger for the composite path than for the all sea water path.

2. Under authority of reference (b) the analysis of reference (a) has been extended to include the reception in air of signals generated by a submerged loop antenna, and experiments have been conducted to observe the fields under various conditions. This theoretical analysis and the experimental data are the subject of the present report. It is shown that the applicability of the reciprocal theorem makes possible a simple calculation of the field to be expected, in terms of antenna current.

3. The efficiency of generation of the fields with the loops used in the experiments is low, the radiation resistance being small compared to the loss resistance. The characteristics of submerged loops are being investigated in further experiments with a view to reducing the components of the loss resistance to minimum practical values and obtaining the greatest possible radiation efficiency. The maximum capability of a radio link using the composite propagation path may then be readily determined.

THEORY

4. When electromagnetic radiation is propagated through a conducting medium such as sea water, a propagation constant may be defined as

$$k = \omega\sqrt{\mu(\epsilon - j\sigma/\omega)} \qquad (1)$$

where

$\omega = 2\pi$ x frequency in cycles/second
$\mu =$ magnetic permeability x μ_o ($= 4\pi \times 10^{-7}$ henry/meter)
$\epsilon =$ dielectric constant x ϵ_o ($= 10^{-9}/36\pi$ farad/meter)

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σ = conductivity in mhos/meter
$j = \sqrt{-1}$

For the propagation constant defined thus, a plane wave may be represented by

$$e = E_m \exp j\,(\omega t - kR) \qquad (2)$$

where e is the instantaneous value of the field, E_m is the amplitude, and R is the distance traversed in meters. For sea water for which the dielectric constant is 80 and the standard conductivity is four mhos per meter, $\sigma = \omega\epsilon$ at a frequency of 900 megacycles per second. At much lower frequencies the dielectric constant term in equation (1) may be neglected and the propagation constant then becomes

$$k = \sqrt{-j\,\sigma\mu\omega} = (1-j)\sqrt{\sigma\mu\omega/2} \qquad (3)$$

The field expression (2) then takes the form

$$e = E_m \exp\left(-R\sqrt{\sigma\mu\omega/2}\right) \quad \exp j\left(\omega t - R\sqrt{\sigma\mu\omega/2}\right) \qquad (4)$$

E_m is thus attenuated exponentially with distance R. The attenuating factor will be designated as A and has the value, since $\mu = \mu o$,

$$A = \exp\left(-2\pi \times 10^{-4} R \sqrt{10\,\sigma f}\right) \qquad (4a)$$

5. The general plan of the radiation source to be considered is shown on Plate 6, where a rectangular loop is supported in a vertical plane below the surface of the sea. It may be expected that only radiation incident nearly normally on the surface can emerge, so that only radiation from the top and bottom sides of the loop needs to be considered. Radiation from the bottom side may be neglected if the loop height is appreciable, due to the greater attenuation in traversing the greater distance to the surface. Thus, for a 10-foot loop height, radiation at 100 kc/sec from the bottom side contributes only about two percent to the resultant field. The remaining top side may be viewed as the only source of useful radiation. As such it will be regarded as a straight wire of length a carrying a traveling current wave.

6. The analysis of the radiation from such a non-resonant wire enclosed in a thin dielectric sheath and submerged in sea water and, in addition, of the refraction of the radiation is somewhat more complex than that of the inverse process treated in reference (a). A simple solution is obtained by application of the Rayleigh-Carson Reciprocal Theorem, a derived form of which may be stated as follows: if a current I_A flowing in antenna A results in a voltage V_B being induced in antenna B, then the same current I_A flowing in antenna B results in the same voltage V_B being induced in antenna A. The induced voltage for a very short antenna (compared to the wavelength) may be taken as the product of field strength E and antenna length a. Then the theorem may be represented by the equation

$$E_A \cdot a_A \cdot I_A = E_B \cdot a_B \cdot I_B \qquad (5)$$

If then a vertical wire of length equal to the loop length, and carrying a traveling current wave of the same strength as that in the submerged loop, were located at the point above the sea surface at which the field strength

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due to the submerged loop is to be observed, then the field strength produced at the position of the top side of the loop by this antenna should equal the field strength to be obtained from the radiating submerged loop.

7. The field due to an isolated, non-resonant wire can be obtained from reference (c). It is convenient to have the wire, of length a, coincide in position with the z-axis in a cylindrical coordinate system as shown in Figure 1 on Plate 7, and to represent the current as

$$i = I_m \exp j \left[\omega t - k_o (a - z') \right] \qquad (6)$$

where I_m is the current amplitude, z' is the z-coordinate of a current element on the wire, and k_o is the free-space propagation constant $\omega\sqrt{\mu_o\epsilon_o}$ or $2\pi/\lambda_o$, λ_o being the free-space wavelength. Then the field of interest is

$$e_z = -\frac{k_o}{4\pi\epsilon_o\omega} I_m \left\{ \frac{e^{-jk_oR_a}}{R_a} \left[\left(1-\frac{z-1}{R_a}\right) + j\left(\frac{z-1}{k_oR_a^2}\right) \right] - \frac{e^{-jk_oR_o}}{R_o} \left[\left(1-\frac{z}{R_o}\right) + j\left(\frac{z}{k_oR_o^2}\right) \right] e^{-jk_oa} \right\} e^{j\omega t} \qquad (7)$$

In the present investigation the value of e_z for $z = o$ is desired. Since a is of the order of 65 feet, R_o of the order of 500 yards or more, and λ_o of the order of 1000 yards or more, the following relationships are sufficiently valid:

$$a^2 \ll R_o^2 \qquad (k_oa)^2 \ll 1 \qquad (8a, b)$$

Then

$$e_z = -\frac{k_o^2}{4\pi\epsilon_o\omega} \frac{aI_m}{R_o} \left\{ \frac{1}{k_oR_o} + j\left[1 - \left(\frac{1}{k_oR_o}\right)^2\right] \right\} e^{j(\omega t - k_oR_o)} \qquad (9)$$

The amplitude of this field will be designated as E_m and is given by

$$E_m = \frac{\mu_o\omega}{4\pi} \frac{aI_m}{R_o} \sqrt{1 - \left(\frac{1}{k_oR_o}\right)^2 + \left(\frac{1}{k_oR_o}\right)^4} \text{ peak volts/meter} \qquad (10)$$

The last factor in the expression (10) for E_m may be regarded as a correction factor on the inverse distance variation of the field, to represent the contributions of the $1/R_o^2$ and $1/R_o^3$ terms. Plate 1 is a plot of this factor, designated as F, against R_o/λ_o for values of the latter from 0.01 to 10. No correction on the inverse distance field value is required at distances greater than λ_o, and the correction at distances only slightly greater than $\lambda_o/2\pi$ is not large. In military applications greatest interest attaches to the maximum range at which the field strength is still sufficient to permit reliable operation of a system. In most cases no correction will be required at this maximum range, and the factor may be dropped. Equation (10) becomes, dropping the factor and using r-m-s values,

$$E_o = 2\pi \times 10^{-7} \frac{faI}{R_o} \text{ r-m-s volts/meter} \qquad (10a)$$

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where the frequency f is in cycles per second, dimensions a and R_o are in meters, and the current is in r-m-s amperes. The field represented by this equation is the primary field effective in producing the refracted wave in the sea water.

8. If the space corresponding to $z < o$ in paragraph 7 is filled with a conducting medium such as sea water, the radiation represented by equation (9) will be just grazing the sea water surface. Energy is then absorbed from the radiation at every point on the surface if the medium is not a perfect conductor. The energy absorbed from the radiation is contained in a refracted wave traveling nearly vertically downward from the surface and being rapidly attenuated. The field in this refracted wave is then readily determined in terms of the Fresnel refraction coefficient, which for plane waves polarized in the plane of incidence is, from reference (d),

$$t_{\parallel} = \frac{2\,\mu_1 k_1 k_o \cos\theta_o}{\mu_o k_1^2 \cos\theta_o + \mu_1 k_o \sqrt{k_1^2 - k_o^2 \sin^2\theta_o}} \tag{11}$$

where the subscript 1 refers to sea water, θ_o is the angle of incidence, and the k's have already been defined. Since $\mu_1 = \mu_o$ and $|k_1| \gg k_o$,

$$t_{\parallel} = \frac{2k_o \cos\theta_o}{k_1 \cos\theta_o + k_o} \tag{12}$$

The value of $\cos\theta_o$ is readily established from the fact that no reflected wave is produced in the course of the absorption of energy from the original radiation. Thus the Fresnel reflection coefficient is zero. For plane waves polarized in the plane of incidence, the reflection coefficient is

$$r = \frac{k_1 \cos\theta_o - k_o}{k_1 \cos\theta_o + k_o} \tag{13}$$

For $r_{\parallel} = 0$,

$$\cos\theta_o = k_o/k_1 \tag{14}$$

and, from equation (12),

$$t_{\parallel} = k_o/k_1 = \sqrt{\frac{\epsilon_o\,\omega}{\sigma_1}}\, e^{j\frac{\pi}{4}} \tag{15}$$

Only the magnitude of this refraction coefficient is of interest in determining the field strength of the refracted wave. From equation (15),

$$|t_{\parallel}| = \frac{1}{6 \times 10^{5}} \sqrt{\frac{20f}{\sigma_1}} \tag{15a}$$

where the frequency f is in cycles per second and the conductivity σ_1 is in mhos per meter. Closer to the antenna than λ_o some departure from the value given by equation (15) may be expected. The angle θ_o, and θ_1, the angle of refraction, are shown in Figure 2 on Plate 7. The significance

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of the complex nature of these angles is discussed in reference (d). It is shown that at the surface of the conducting medium the real angle of incidence ψ_o and the real angle of refraction ψ_1 are given by

$$\psi_o = \tan^{-1} \sqrt{2\sigma_1/\epsilon_o\omega} \qquad (16a)$$

$$\psi_1 = \tan^{-1} \sqrt{2\epsilon_o\omega/\sigma_1} \qquad (16b)$$

For standard sea water conductivity and a frequency of 100 kc/sec, ψ_o is 89°57' and ψ_1 is about six minutes.

9. The field (r-m-s) observed then at the position of the submerged loop is, using equations (4a), (10a), and (15a),

$$E = E_o \text{ x } |t_{\parallel}| \text{ x } A \qquad (17)$$

$$= 2\pi \text{ x } 10^{-7} \frac{faI}{R_o} \text{ x } \frac{1}{6\text{x}10^5} \sqrt{\frac{20f}{\sigma_1}} \text{ x } \exp\left(-2\pi \text{ x}10^{-4}\text{x}d\sqrt{10\sigma_1 f}\right) \qquad (17a)$$

where d is the submergence depth (meters), assumed small compared to R_o. The thickness of the dielectric sheath about the loop conductor is not sufficient to produce appreciable disturbance of the field and equation (17) then gives the field at the loop conductor. This field is then also the field which should be observed at a point in the plane of the loop just above the sea surface, and at a distance R_o, when a current I flows in the submerged loop.

10. If the loop has n turns, the total induced voltage is n times as great as for a single turn, and the reciprocal theorem then requires that the radiated field should be n times as large as for a single turn.

11. If the loop is turned an angle α (still vertical), the induced voltage is cos α times as great. If the loop radiates, the same factor should apply to the vertically polarized field observed above the surface. At a point "broadside" to the loop the observed field should be zero. The horizontal field pattern above the sea surface is thus a "figure-eight" pattern, with the maximum field "end-on" to the loop.

12. In the case of a very small loop operating at low frequencies, the effect of the bottom side of the loop may not be neglected. If E_d is the field produced at the top side of the loop by an antenna above the sea surface, the field E_{d+b} at the bottom side is $E_d \exp(-jk_1 b)$. Assuming very short loop length, the resultant voltage induced in the loop is

$$V_{loop} = a E_d \left| 1-\exp(-jk_1 b) \right| \qquad (18)$$

If the loop radiates, this same voltage will be induced in the antenna of length a above the sea surface. The radiated field given by equation (17) should then be modified by the factor

$$\left| 1-\exp(-jk_1 b) \right| = \left\{ 1-\exp\left[-(1+j)b\sqrt{\sigma_1\mu_1\omega/2} \right] \right\} \qquad (19)$$

This correction is not large, amounting to only eight percent in one instance in which the radiation from the bottom side of the loop was one-fourth that

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from the top side.

PRELIMINARY EXPERIMENTS

13. Preliminary experiments were conducted in the Potomac River using a 7-foot by 73-foot loop supported at the NRL pier. The loop was constructed of Navy type 62001 submarine cable, which consists of seven conductors of A.W.G. #9 with rubber insulation 1.5 inches in diameter; and was energized by a Model TBL transmitter at two frequencies; namely, 175 and 250 kilocycles/second. The loop current was seven amperes. Only loop depths of one foot and two feet were practicable. Field strengths were measured with a Model OF meter, at distances up to 2900 yards.

14. Table 1 contains the field strength data obtained in these experiments. The field strength measured "end on" (in the plane of the loop) was three to five times the field strength measured "broadside" (normal to the plane of the loop), a sufficiently close approximation to the theoretical field strength pattern. The observed field value of 1.2 millivolts/meter at 2700 yards for a loop depth of two feet and a current of 6.7 amperes is sufficiently large to encourage further experimentation.

15. Samples of the water in the Potomac River had an average conductivity at about 40°F of the order of 0.01 mhos/meter. For so low a conductivity, $\sigma = \omega\epsilon$ at only 2.25 megacycles/second and the approximations made in paragraphs 4 and 8 are barely valid. Since the conductivity is not representative of sea water conditions, the experimental data have not been analyzed further.

FORT POND BAY EXPERIMENTS

16. Fort Pond Bay, on the north side of Long Island, near Montauk, was selected as a site for further experiments. The bay is roughly semicircular, about a mile wide, and 40 feet deep. Some protection is afforded by the surrounding hills from winds, except northwest winds, which can make the water surface too rough to conduct the experiments to be described. No rivers empty fresh water into the bay and reduce the conductivity to a value unrepresentative of average sea water. Good pier facilities were available from the USN Magazine at the spot marked on Plate 9. This plate shows the bay and the adjacent portion of Block Island Sound.

17. The Sonar Training Barge YNg-22 was made available at the USN Submarine Base, New London, to carry and power the transmitters required. A Model TAB-7 transmitter and a Model QCO-2 Sonar Driver, and coupling units, were mounted on the aft deck and surrounded by a sheet metal enclosure. The barge was moored to the Navy pier as shown on Plates 10 and 11. Between the barge and a buoy anchored in the bay a chain of pontoon rafts, which may be seen on Plate 12, supported the submerged loop. The loop depth was adjusted by means of the two supporting ropes on each raft. Plate 13 shows the experimental disposition of the barge, transmitters, loop, and field measuring craft.

18. The "lead" from the bottom side of the loop, entering the transmitter enclosure through one of the hawseholes, was grounded to the hull of the barge. The lead from the top side was connected to a series capacitor bank containing six 2000-μμf type PL mica capacitors, four 1000-μμf capacitors

of the same type, and four one-microfarad mica capacitors. The bank was connected in turn to the antenna terminal of the Model TAB-7 transmitter for operation at 100 kc/sec or higher. For operation at 26.8 and at 40 kc/sec the bank was connected to the appropriate, usually the 2/3-ohm, secondary of a special transformer designed to match the loop resistance to the 100-ohm output circuit of the Model QCO-3 driver unit. Reference to Figure 1 on Plate 8 should make the connections clear. The optimum series capacitance should just neutralize the inductive reactance of the loop in the case of operation from the Model QCO-3 driver. Values of the order of one-quarter microfarad were used. For operation from the Model TAB-7 transmitter the net reactance "seen" by the transmitter should be that of a capacitance of the order of 2000-$\mu\mu$f. The Model QCO-3 driver unit was modified to provide somewhat higher frequency output than the original 20 kc/sec by transferring the connections to interstage transformer T-401 to taps nearer the coil center.

19. The yard patrol craft YP-253 and later YP-256 were provided for the field strength measurements. In order to measure small field values (frequently less than 16 μV/m) a Model RAK-7 receiver was used instead of a standard field intensity meter. A 16-foot whip antenna was installed on the deck of the YP-253 and connected to the receiver. The field strength being the quotient of the receiver r-f input voltage from the antenna and the effective height of the latter, the input voltage was determined for each field strength measurement by a substitution method. The receiver was connected to a Model LP-2 signal generator through a capacitance equal to that of the antenna, and the signal generator voltage adjusted to give the same a-f output from the receiver as when the latter was connected to the antenna. The effective height of this 16-foot whip antenna was determined in a preliminary experiment to be 2.0 meters by measuring the receiver r-f input voltage from such stations as NSS and WEEI, and measuring the field strength using an RCA Model 308A Field Intensity Meter. On the YP-256 a 20-foot whip antenna already installed was used. The effective height was measured and found to be 2.0 meters.

20. Distances were measured by means of a coincidence type optical range finder.

FORT POND BAY CONDUCTIVITY

21. Fourteen samples of the bay water were collected near the barge at temperatures ranging from 45°F to 50°F. The conductivity of four of these has been measured and is given in Table 2. The variation in conductivity among the samples is observed to be small, the probable average at 47°F being 2.0 mhos/meter assuming a temperature coefficient of 0.014 per °F.

22. For 2 mhos/meter the refraction coefficient becomes (equation (15a))

$$|t_{||}| = \sqrt{f}/(6 \times 10^3) \qquad (15b)$$

where f is now in kc/sec. This coefficient is plotted on Plate 2 for frequencies from 10 kc/sec to 1000 kc/sec, a representative value being 1.67 x 10^{-3} at 100 kc/sec.

23. The attenuating factor (equation (4a)) becomes

$$A = \exp\,(-2\pi \times 10^{-2} \times 0.3048 \times d\sqrt{2f}) \qquad (4b)$$

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where d is in feet and f is in kc/sec. Plate 3 shows the variation of this factor with depth for the frequencies used in the experiments. It is observed that at 100 kc/sec penetration of the radiation through 10 feet of Fort Pond Bay water reduces the field to about 0.07 of its initial value.

LOOP CHARACTERISTICS

24. Five different loops, constructed of the same submarine cable used in the preliminary experiments, were used. The loop sizes follow:

Loop A: 20 feet x 7 feet - single turn
Loop B: 65 feet x 10 feet - single turn
Loop C: 65 feet x 10 feet - 2-turn, closely spaced
Loop D: 65 feet x 10 feet - 2-turn, spaced 3 feet
Loop E: 141 feet x 10 feet - single turn

The loop leads in each case were about 25 feet long and were laced together.

25. The capacitance between the loop leads was found to make the loop near-resonant at the upper frequencies planned for the experiments. At these frequencies the load impedance presented to the Model TAB-7 transmitter was outside the design range of the transmitter so that the latter could not deliver full power. The resulting "line" current to the loop was lower than at frequencies far from resonance. In the case of loop B the line current, as indicated by the ammeter at the series capacitor bank, was quite small at frequencies above 300 kc/sec. At the same time the "circulating" current in the loop, which will be designated as I_L, is larger than the line current I_T. Referring to Figure 2 on Plate 8 it may be seen that if L represents the effective inductance of the submerged loop, C the loop capacitance, and R the resistance,

$$I_L = I_T / \left[(1 - \omega^2 LC) + j\omega CR \right] \tag{20}$$

If the frequency of operation is not too close to the resonant frequency $(\omega^2 LC < 1)$, and if $R << 1/\omega C$,

$$I_L = I_T / (1 - \omega^2 LC) \tag{21}$$

The capacitance between loop leads was of the order of 30 $\mu\mu f/ft$. Assuming this to be a large part of C, $1/\omega C$ is of the order of 2000 ohms at 100 kc/sec. The loop resistance will be shown to be of the order of one to twenty-five ohms, so that the approximation (21) is sufficiently good.

26. The terminal impedance of the loops represented as in Figure 2 on Plate 8 may be given in terms of the equivalent series resistance R' and inductance L' as

$$R' + j\omega L' = \frac{R + j\omega \left[L (1 - \omega^2 LC) - CR^2 \right]}{(1 - \omega^2 LC)^2 + (\omega CR)^2} \tag{22}$$

If, in addition to the previous conditions, $R^2 << L/C$,

$$R' + j\omega L' = \frac{R + j\omega L (1 - \omega^2 LC)}{(1 - \omega^2 LC)^2} \tag{23}$$

and

$$L' = L/(1 - \omega^2 LC) \qquad (24a)$$

$$R' = R/(1 - \omega^2 LC)^2 \qquad (24b)$$

L will be shown to be of the order of 20 to 150 μh. For 75 μh, $L/C = 10^5$ so that the approximations (24) are good. Then, from relations (21) and (24),

$$I_L = I_T L'/L \qquad (25)$$

and the measured current I_T may be simply "corrected" to obtain the current I_L.

27. The equivalent series inductance L' and resistance R' were measured over the relevant frequency range using a G-R Type 516-C Impedance Bridge.

(a) Plate 4 presents graphically the measured values of L' for the five submerged loops. Some difficulty was experienced at the lower frequencies in making accurate measurements because of the constants of some of the accessory capacitors used, and experimental errors are evident. However, reasonable values of L can be obtained from the curves. They are presented in Table 3. The value 51.5 μh for the inductance of the submerged loop B (65' x 10') is not greatly different from the calculated inductance of the same loop in air, which is 59.6 μh, indicating that the effect on the inductance of submergence in sea water is not large. Spacing the turns of a multi-turn loop, as in the case of loop D, is shown to result in lower loop inductance (than for loop C) and a resonant frequency farther removed from the desired operating frequency.

(b) Plate 5 presents the measured values of R'. From these the true loop resistance R may be computed using equation (24). R consists of loss resistance and loop radiation resistance, both of which vary with frequency. Included in Table 3 are the computed values of R for the five submerged loops at a frequency of 100 kc/sec. At lower frequencies the values of R are smaller. The resistance of the two-turn loop C is shown to be about four times that of the single-turn loop B. If the turns are spaced the resistance is somewhat less than for turns close together, and is close to the value for a single-turn loop with the same total length of cable. The radiation resistance can be shown to be only a small fraction of the total resistance. In the case of loop B at 100 kc/sec, the radiation resistance is of the order of 0.1 ohm, while the total resistance is given in Table 3 as 5.8 ohms. The radiation efficiency of the loops used is seen to be low, but would be improved by a reduction of the loss resistance, An analysis of the loss resistance is desirable in order to obtain the maximum possible radiation efficiency.

28. The power P required from the transmitter may be taken as $R'I_T^2$ or as RI_L^2. The former expression will be used in deriving the transmitter power requirement in the experiments described.

COMPUTED FIELD

29. The primary field E_0 given by equation (10a) becomes, in more useful units and with the factor F restored to include distances even less than $\lambda_0/2\pi$,

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$$E_o = \frac{200}{3} \pi \frac{nfaI_L}{R_o} F \text{ microvolts/meter} \qquad (10b)$$

where n is the number of turns in the loop, f is in kc/sec, a (loop length) is in feet, R_o is in yards, I_L is in r-m-s amperes, and F can be obtained from Plate 1.

30. E_o/I_L is tabulated, along with $|t|$, A, and the product which is the final field value E/I_L, for the loops, submergence depths, frequencies, and distances used experimentally, in Tables 4 through 8. The factor F has been included in the tabulation to emphasize the rapid variation of primary field at close range. A final field value representative of the general order of magnitude obtained is 1.1 µV/m/amp at 100 kc/sec at 1500 yards from a two-turn, 65 x 10-foot loop submerged six feet.

MEASURED FIELD VALUES

31. Tables 9 through 13 present the measured field values, the loop currents, the transmitter powers, the reduced field (per ampere of loop current) values, and the computed values for comparison. As introduced in paragraph 25, I_T is the current indicated by the r-f ammeter shown in Figure 1 on Plate 8, while I_L is the computed current circulating in the loop.

32. The frequency range obtained in the experiments was limited by the near-resonance effects at the higher frequencies and by interference at the low frequencies. On the YP-256, supplementary power supplies, including a gasoline engine generator, were required to operate the receiver and a transceiver used for communication with the YNg-22. These supplies required treatment to reduce noise which was initially troublesome. During the period of use the YP-253 a transformer failure in the Model QCO-3 driver prevented tests with 26.8 and 40 kc/sec.

33. The agreement between computed and measured values is satisfactory except at very close range at the lowest frequencies. At 40 kc/sec and distances of 500 yards or less the computed values considerably exceed the measured values. This is not surprising in view of the possible error in the refraction coefficient at close range.

(a) All submergence depth settings are subject to some error, the loop supporting ropes having been marked for the various depths when dry. The markers were disturbed during the assembly of the loops. Distances larger than about 3000 yards are subject to some uncertainty due to limitations of the optical range finder used. All antenna current values at the highest frequencies are subject to some error in reading the small value on the meter.

(b) In the cases of loop A submerged two and four feet, discrepancies are evident at 355 kc/sec which have not been completely accounted for. During the measurements with this loop the water was quite rough, presenting some difficulty with uniformity of submergence depth of the loop. Furthermore, for these measurements, the YP-256 could not be prevented from drifting from the desired measurement spot. Apart from these difficulties the effect of the rough sea surface was not sufficiently large to be observed in the measurements made. This might be expected since the wavelength of the radiation was

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large compared to the length of the water waves.

(c) Discrepancies are also observed in the case of loop E submerged eight feet and operating at 250 kc/sec. In this case the measurements were made aboard the YP-256 before the power supplies had been adequately filtered. Field strength values less than 20 μV/m were then largely estimations. Efforts were promptly made to reduce the interfering noise.

34. Included in the tables are measurements of the field obtained when the loop B was partially surfaced, i.e., when the top side of the loop was about one foot above the sea surface. These values are roughly twice those for the loop submerged one foot, confirming an expectation that no abrupt change in field should be observed.

35. Four measurements were recorded of the field at a position roughly "broadside" to the loop. These were with loops B and E at frequencies of 40, 100 and 250 kc/sec. The field was about one-third that measured "end-on". Other unrecorded observations of the broadside field gave ratios of one-third to one-fifth. Shallow water made it impossible to take a position more than about 80° from the "end-on" position. For such positions the ratios obtained are considered sufficient assurance that the radiation is primarily from the submerged loop and that no appreciable contribution is from the transmitter equipment above the sea surface.

36. For the same loop current, loops C and D are shown to produce the same field. Somewhat larger currents I_T and I_L were observed for the spaced-turn loop (D) than for the close-turn loop (C), which should be the case if the same power is available (R' is less for loop D). For the same available power, then, the final field value is larger for the spaced-turn than for a loop with the turns close together. The radiation efficiency is thus greater for the spaced-turns loop. The greater radiation efficiency for the spaced-turns loop was to be expected since the radiation resistance is essentially unchanged by varying the turn spacing while the loop resistance R is shown to be decreased by spreading the turns.

CONCLUSIONS

37. The experiments have demonstrated the detection above the sea surface of radiation from a submerged antenna. The field strength can be calculated quite simply from an application of the reciprocal theorem, with assurance of good agreement with measured values except at close range. At any greater distances the field from a submerged loop is given sufficiently accurately by

$$E = 0.0495 \frac{naIf^{3/2}}{R_o\sqrt{\sigma}} \exp\left(-0.019\, d\sqrt{\sigma f}\right) \quad \mu V/m \tag{17b}$$

where n is the number of turns in the loop, f is in kc/sec, a is the loop length in feet, R_o is the distance in yards, I is the loop current in r-m-s amperes, σ is the sea water conductivity in mhos/meter (usually taken as 4), and d is the submergence depth of the antenna in feet.

38. As an illustration of the order of magnitudes to be expected under conditions of "standard" sea water conductivity, it may be determined from

relation (17b) that a transmitting loop submerged 8 feet and radiating at a frequency of 100 kc/sec should produce at a distance of 10,000 yards a field above the sea surface of 116 μμ V/m/ampere-turn-foot. If the loop is a 4-turn loop 75 feet long, and if it carries a current of 40 amperes, the field should be 1.4 μ V/m. Following reference (a), the field at the position of a receiving loop submerged 8 feet should be 77μμ V/m. If the receiving loop is 7-1/2 feet square, has 50 turns, and a Q of 50, the input voltage to the receiver should be 1.4 microvolts.

39. For a radiation resistance for this transmitting loop of the order of one-half ohm, the total radiated power is of the order of one kilowatt. The actual loop resistance, if no special attention is given to the design of the loop for maximum radiation efficiency, might be 25 ohms. The transmitter power required is then 40 kilowatts, most of which is dissipated in resistive and dielectric losses. The desirability of reducing these losses is evident. A substantial reduction in the losses has been demonstrated in the experiments by the simple device of spacing the loop turns. Further reductions should be realized by attention to other design features.

ACKNOWLEDGMENTS

It is desired to acknowledge the cooperation and assistance given by the personnel of the United States Naval Submarine Base and of the United States Naval Underwater Sound Laboratory, both at New London, Connecticut, in the preparation for these experiments and in their prosecution. An ideal site for the experiments was afforded by the facilities of the United States Naval Magazine at Montauk, Long Island. The services of Lt. R. F. Van Wye, BuOrd Liaison Officer, of his relief Cmdr. R. Berthrong, and of Ens. W. L. Olson, Commanding Officer of Sonar Barge YNg-22, were invaluable.

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(a) NRL Report R-1669, December 1940; Submerged Reception.

(b) NRL Problem N34R-S, "Propagation Characteristics of Frequencies Below 500 kc."

(c) Harrison, C.W., "The Calculation of the Mutual and Self Impedance of Wires on which Traveling Wave Systems Exist," XA-8874A.

(d) Stratton, J. A., Electromagnetic Theory, McGraw-Hill Book Company, 1941, Chapter IX.

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TABLE 1

Field Strength From Submerged Loop

(Preliminary Experiments in Potomac River)

Frequency (kc/sec)	Loop Current (amps)	Loop Depth (feet)	Distance (yards)	Field Strength (mV/m)
175	6.4	1	257	40
			1700	1.9
			2400	1.3
			1750	1.9
			365	9.6
175	6.5	1	274	14
			1750	1.7
			2900	1.2
			367	9
175	6.7	2	318	10
			1700	1.7
			2700	1.2
			318	11.6
250	7.0	1		30
				2
			2700	1.4
			1700	1.96
			375	6.6
250	7.0	2	410	8
			1700	2
			2650	1.5
			1750	2
			450	5.6

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TABLE 2

Fort Pond Bay Conductivity
(Four of Fourteen Samples)

Collection Date	Temperature (°F)	Conductivity (mho/m)	Probable Conductivity at 47°F
23 April	47	1.99	1.99
25 April	46	1.90	1.93
7 May	48.5	2.11	2.07
9 May	50	2.14	2.05

Average probable conductivity at 47°F = 2.01 mhos/meter

Temperature coefficient = 0.014 per °F

TABLE 3

Inductance and Resistance of Submerged Loops

Loop	L (uh)	R_{100}* (ohms)
A - 20' x 7'	21.2	1.4
B - 65' x 10'	51.5	5.8
C - 65' x 10' - 2 turns, close	158	24.2
D - 65' x 10' - 2 turns, spaced	114	18.9
E - 141' x 10'	101	15.6

* R_{100} is the loop resistance computed from R' at 100 kc/sec.

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TABLE 4

Computed Field From Submerged Loop A

$20' \times 7'$ - a = 20 ft.

d = 2 ft

f (kc/sec)	R_o (yds)	F	E_o/I_L (μV/m/amp) x 10^{-2}	$\lvert t \rvert$ x 10^3	A	E/I_L (μV/m/amp)
100	432	1.3	12.5	1.667	0.582	1.21
	952	0.88	3.85			0.37
	1447	0.94	2.7			0.26
200	442	0.87	16.5	2.357	0.465	1.81
	1097	0.97	7.4			0.81
	1497	0.98	5.5			0.61
355	297	0.90	45.0	3.14	0.361	5.1
	697	0.97	20.7			2.34
	1097	0.99	13.4			1.52
			d = 4 ft			
100	407	1.4	14.4	1.667	0.338	0.81
	762	0.85	4.6			0.26
	1072	0.90	3.5			0.19
200	397	0.86	18.1	2.357	0.216	0.92
	877	0.96	9.3			0.47
	1072	0.97	7.6			0.38
355	507	0.96	28.1	3.14	0.130	1.15
	682	0.97	21.1			0.86
	987	0.99	14.9			0.61
			d = 6 ft			
100	412	1.38	14.0	1.667	0.197	0.46
	767	0.85	4.6			0.15
	907	0.88	4.0			0.13
200	460	0.88	16.0	2.357	0.100	0.38
	657	0.92	11.7			0.27
	1000	0.97	8.1			0.19
355	360	0.92	38.0	3.14	0.047	0.56
	832	0.98	17.5			0.26
	1050	0.99	14.1			0.21

E_o/I_L is the primary field (in free space) per ampere of loop current.
$\lvert t \rvert$ is the refraction coefficient magnitude
A is the attenuation factor.
E/I_L is the final field per ampere.

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TABLE 5

Computed Field From Submerged Loop B

65' x 10' - a = 65 ft

d = 1 ft

f (kc/sec)	R_0 (yds)	F	E_0/I_L (μV/m/amp) x 10^{-2}	$\lvert t_{11} \rvert$ x 10^3	A	E/I_L (μV/m/amp)
26.8	495	15.0	111.5	0.863	0.869	8.29
40.	500	6.4	69.7	1.054	0.843	6.19
100	500	1.05	28.6	1.667	0.763	3.64
	970	0.89	12.5			1.59
	1670	0.95	7.7			0.99
150	500	0.85	34.7	2.042	0.718	5.58
	975	0.94	19.7			2.89
	1640	0.98	12.2			1.79
200	500	0.90	49.0	2.357	0.682	7.87
	975	0.96	26.8			4.31
	1610	0.99	16.7			2.69
	3500	0.99	7.7			1.23
250	500	0.92	62.6	2.635	0.652	10.7
	975	0.98	34.2			5.87
	1630	0.99	20.6			3.54
			d = 2 ft			
100	600	0.90	20.4	1.667	0.582	1.98
	1050	0.90	11.6			1.13
	1890	0.96	6.9			0.67
	4500	0.99	3.0			0.29
150	585	0.87	30.3	2.042	0.515	3.19
	1080	0.95	17.9			1.88
	1960	0.98	10.2			1.07
	4500	0.99	4.5			0.47
200	575	0.91	43.1	2.357	0.465	4.72
	1075	0.97	24.5			2.58
	1990	0.99	13.5			1.48
	4500	0.99	6.0			0.66
250	555	0.93	57.0	2.635	0.425	6.39
	1075	0.98	31.0			3.47
	1990	0.99	16.9			1.90
	4500	0.99	7.5			0.84
			d = 3 ft			
100	530	0.98	25.1	1.667	0.434	1.82
	1070	0.90	12.4			0.90
	1950	0.96	6.7			0.48
	3000	0.98	4.4			0.32

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TABLE 5 (Continued)

Computed Field - Loop B

f (kc/sec)	R_o (yds)	F	E_o/I_L (μV/m/amp) $\times 10^{-2}$	$\lvert t \rvert \times 10^3$	A	E/I_L (μV/m/amp)
			d = 3 ft			
150	535	0.86	32.8	2.042	0.369	2.47
	1070	0.95	18.1			1.37
	1950	0.98	10.2			0.77
	3000	0.99	6.7			0.51
200	535	0.90	45.8	2.357	0.316	3.41
	1070	0.97	24.7			1.84
	2000	0.99	13.5			1.00
	2900	0.99	9.3			0.69
250	535	0.93	59.1	2.635	0.277	4.32
	1050	0.98	31.7			2.32
	2000	0.99	16.8			1.23
	2900	0.99	11.6			0.84
			d = 4 ft			
40	490	6.6	73.3	1.054	0.504	3.89
100	475	1.10	31.5	1.667	0.338	1.78
	565	0.94	22.6			1.27
	1060	0.90	11.5			0.65
	1740	0.96	7.5			0.42
150	475	0.85	36.5	2.042	0.265	1.98
	565	0.87	31.4			1.70
	1070	0.95	18.1			0.98
	1740	0.98	11.5			0.62
200	565	0.91	43.8	2.357	0.216	2.24
	1070	0.97	24.7			1.25
	1940	0.99	13.9			0.71
250	565	0.94	56.6	2.635	0.18	2.68
	1070	0.98	31.1			1.47
	1940	0.99	17.3			0.82
			d = 6 ft			
100	445	1.23	37.6	1.667	0.197	1.23
	870	0.87	13.6			0.44
150	445	0.86	39.4	2.042	0.136	1.09
	870	0.92	21.6			0.60
200	445	0.87	53.2	2.357	0.100	1.25
	875	0.96	29.8			0.70

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TABLE 5 (Continued)

Computed Field - Loop B

d = 6 ft: (Cont'd)

f (kc/sec)	R_o (yds)	F	E_o/I_L (μV/m/amp) x 10^{-2}	t x 10^3	A	E/I_L (μV/m/amp)
250	445	0.90	68.8	2.635	0.077	1.39
	840	0.97	39.3			0.79
			d = 8 ft			
100	242	4.25	239.0	1.667	0.114	4.54
	580	0.94	22.0			0.42
150	252	1.65	133.7	2.042	0.070	1.91
	555	0.87	32.0			0.45
200	276	0.94	92.7	2.357	0.047	1.02
	470	0.88	51.0			0.56
250	268	0.86	109.2	2.635	0.033	0.95
	605	0.94	52.9			0.46

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TABLE 6

Computed Field from Submerged Loop C

65' x 10' - 2 turns close - a = 65 ft

d = 2 ft

f (kc/sec)	R_o (yds)	F	E_o/I_L (μV/m/amp) x 10^{-2}	t x 10^3	A	E/I_L (μV/m/amp)
40	315	16.5	570.5	1.054	0.710	42.7
	498	6.4	139.9			10.5
	565	4.9	94.5			7.07
100	325	2.25	188.5	1.667	0.582	18.3
	580	0.91	42.7			4.14
	1140	0.91	21.7			2.10
	1790	0.96	14.6			1.42

d = 4 ft

f (kc/sec)	R_o (yds)	F	E_o/I_L (μV/m/amp) x 10^{-2}	t x 10^3	A	E/I_L (μV/m/amp)
40	268	22.5	917.3	1.054	0.504	48.7
	420	9.3	241.2			12.8
	560	5.0	97.2			5.16
100	510	1.1	58.7	1.667	0.338	3.31
	1150	0.91	21.5			1.21
	1890	0.96	13.8			0.78

d = 6 ft

f (kc/sec)	R_o (yds)	F	E_o/I_L (μV/m/amp) x 10^{-2}	t x 10^3	A	E/I_L (μV/m/amp)
40	320	15.5	527.5	1.054	0.358	19.9
	410	9.7	257.7			9.7
100	460	1.15	68.1	1.667	0.197	2.24
	890	0.87	26.6			0.87
	1490	0.94	17.2			0.56

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TABLE 7

Computed Field From Submerged Loop D

65' x 10' - 2 turns spaced 3 ft.

d = 2 ft

f (kc/sec)	R_o (yds)	F	E_o/I_L (µV/m/amp) x 10^{-2}	$\lvert t_\mu \rvert$ x 10^3	A	E/I_L (µV/m/amp)
100	375	1.65	119.8	1.667	0.582	11.6
	745	0.85	31.0			3.01
	1450	0.94	17.6			1.71
	1930	0.96	13.5			1.31
			d = 4 ft			
100	268	3.4	345.5	1.667	0.338	19.5
	477	1.1	67.0			3.78
	890	0.87	26.6			1.50
	1640	0.95	15.8			0.89
			d = 6 ft			
100	250	4.0	435.6	1.667	0.197	14.3
	625	0.88	38.4			1.26
	1190	0.91	20.8			0.68

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TABLE 8

Computed Field From Submerged Loop E

141' x 10' - a = 141 ft.

d = 1 ft

f (kc/sec)	R_o (yds)	F	E_o/I_L (µV/m/amp) x 10^{-2}	$\|t_E\|$ x 10^3	A	E/I_L (µV/m/amp)
40	526	5.8	130.2	1.054	0.843	11.5
	1000	1.45	17.1			1.52
	1276	1.02	9.4			0.84
100	626	0.88	41.5	1.667	0.763	5.28
	1306	0.92	20.8			2.65
	2176	0.97	13.1			1.67
	2926	0.98	9.9			1.26
			d = 2 ft.			
40	436	8.6	233.0	1.054	0.710	17.4
	776	2.5	38.0			2.84
	1126	1.22	12.8			0.96
100	526	0.98	55.0	1.667	0.582	5.33
	1076	0.90	24.7			2.39
	1926	0.96	14.7			1.42
	13000	0.99	2.2			0.22
			d = 4 ft			
40	466	7.4	187.6	1.054	0.504	9.96
	626	4.0	75.5			4.01
	1026	1.4	16.1			0.85
100	676	0.86	37.5	1.667	0.338	2.11
	1151	0.91	23.3			1.31
	1926	0.96	14.7			0.83
			d = 6 ft			
40	526	5.8	130.1	1.054	0.358	4.91
	726	2.85	41.3			1.75
100	526	0.98	55.0	1.667	0.197	1.80
	1276	0.92	21.3			0.70
	1826	0.96	15.5			0.51
	2476	0.98	11.7			0.38

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TABLE 8 (Continued)

Computed Field - Loop E

d = 8 ft

f (kc/sec)	R_o (yds)	F	E_o/I_L (μV/m/amp) x 10^{-2}	$\|t_u\|$ x 10^3	A	E/I_L (μV/m/amp)
100	526	0.98	55.0	1.667	0.1145	1.05
	1026	0.90	25.9			0.49
	1376	0.93	19.9			0.38

d = 10 ft.

f (kc/sec)	R_o (yds)	F	E_o/I_L (μV/m/amp) x 10^{-2}	$\|t_u\|$ x 10^3	A	E/I_L (μV/m/amp)
100	516	0.99	56.6	1.667	0.067	0.63
	756	0.85	33.2			0.37
	1076	0.90	24.7			0.27

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TABLE 9

Measured Field From Submerged Loop A

f (kc/sec)	R_0 (yds)	I_T (amps)	Transmitter Power (kw)	I_L (amps)	Measured E ($\mu V/m$)	Measured E/I_L	Computed E/I_L
			d = 2 ft				
100	432	21.2	0.67	21.8	33.0	1.51	1.22
	952				8.5	0.39	0.37
	1447				5.0	0.23	0.26
200	442	21.7	1.65	22.9	88.0	3.84	1.81
	1097				36.0	1.57	0.81
	1497				20.0	0.87	0.61
355	297	14.1	2.0	16.0	36.0	2.25	5.10
	697				9.0	0.56	2.34
	1097				6.0	0.38	1.52
430		8.5			Interference Strong		
			d = 4 ft				
100	407	21.2	0.67	21.8	18.0	0.83	0.81
	762				7.5	0.34	0.26
	1072				3.8	0.17	0.19
200	397	21.7	1.65	22.9	38.0	1.66	0.92
	877				18.0	0.79	0.47
	1072				11.0	0.48	0.38
355	507	14.1	2.0	16.0	6.5	0.41	1.15
	682				4.3	0.27	0.86
	987				2.0	0.125	0.61
			d = 6 ft				
100	412	21.2	0.67	21.8	14.0	0.64	0.46
	767				6.5	0.30	0.15
	907				3.0	0.14	0.13
200	460	21.7	1.65	22.9	12.0	0.52	0.38
	657				5.5	0.24	0.27
	1000				3.0	0.13	0.19
355	360	13.6	1.9	15.4	15.0	0.98	0.56
	832				9.0	0.59	0.26
	1050				5.0	0.33	0.21

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TABLE 10

Measured Field from Submerged Loop B

d = 1 ft.

					Measured		Computed
f (kc/sec)	R_o (yds)	I_T (amps)	Transmitter Power (kw)	I_L (amps)	E (μV/m)	E/I_L	E/I_L
26.8	495	21.7	0.6	21.8	50	2.28	8.29
	1020	21.0		QCO failure			
40	500	14.2	0.4	14.32	57	3.98	6.19
100	500	21.7	3.1	22.8	148	6.49	3.64
	970				50	2.19	1.59
	1670				25	1.10	0.98
150	500	16.5	3.2	17.9	165	9.22	5.08
	975	16.2		17.6	65	3.69	2.89
	1640	16.2		17.6	32	1.82	1.79
200	500	12.3	3.3	15.78	180	11.4	7.87
	975	12.1		15.52	130	8.38	4.31
	1610	12.3		15.78	40	2.53	2.69
	3500	12.3		15.78	32	2.03	1.23
250	500	5.4	1.4	8.72	125	14.33	10.7
	975	6.5	2.0	10.50	65	6.19	5.87
	1630	6.5		10.50	30	2.86	3.54
40	505	15.0		15.15	23	1.5	Pattern*

d = 2 ft

f (kc/sec)	R_o (yds)	I_T (amps)	Transmitter Power (kw)	I_L (amps)	E (μV/m)	E/I_L	E/I_L
100	600	21.7	3.1	22.7	77	3.39	1.98
	1050				35	1.54	1.13
	1890				14	0.62	0.67
	4500				7	0.31	0.29
150	585	16.6	3.2	18.0	89	4.94	3.19
	1080	16.5		17.9	43	2.40	1.88
	1960	16.2		17.6	19	1.08	1.07
	4500	16.2		17.6	10	0.57	0.47
200	575	10.8	2.6	13.85	75	5.41	4.72
	1075	10.8		13.85	47	3.39	2.58
	1990	10.8		13.85	19	1.37	1.48
	4500	11.9		15.25	9	0.59	0.66
250	555	6.5	2.0	10.50	75	7.15	6.39
	1075				48	4.57	3.47
	1990				18	1.72	1.90
	4500				8	0.76	0.84
250	536	6.5		10.50	26	2.48	Pattern*

* Position broadside to loop.

[redacted]

(Continued)

[redacted]

TABLE 10 (Continued)

Measured Field - Loop B

d = 3 ft.

f (kc/sec)	R_o (yds)	I_T (amps)	Transmitter Power (kw)	I_L (amps)	Measured		Computed
					E (μV/m)	E/I_L	E/I_L
100	530	21.7	3.1	22.7	92	4.05	1.82
	1070				33	1.45	0.90
	1950				12	0.53	0.48
	3000				9	0.40	0.32
150	535	12.9	2.0	14.0	60	4.28	2.47
	1070	16.7		18.1	31	1.71	1.37
	1950	16.6		18.0	17	0.94	0.77
	3000	16.5	3.2	17.9	9	0.50	0.51
200	535	9.2		11.80	59	5.00	3.41
	1070	10.8	2.6	13.86	32	2.31	1.84
	2000	10.8		13.86	17	1.23	1.00
	2900	10.8		13.86	8	0.58	0.69
250	535	6.5	2.0	10.50	57	5.52	4.32
	1050				29	2.76	2.32
	2000				14	1.33	1.23
	2900				9	0.86	0.84

d = 4 ft.

f (kc/sec)	R_o (yds)	I_T (amps)	Transmitter Power (kw)	I_L (amps)	E (μV/m)	Measured E/I_L	Computed E/I_L
40	490	11.3	0.26	11.41	24	2.10	3.89
100	475	21.7	3.1	22.7	50	2.20	1.78
	565				50	2.20	1.27
	1060				21	0.92	0.65
	1740				9	0.40	0.42
150	475	16.8	3.3	18.3	47	2.57	1.98
	565	16.7		18.1	46	2.54	1.70
	1070	16.7		18.1	23	1.27	0.98
	1740	16.7		18.1	11	0.61	0.62
200	565	10.8	2.6	13.86	41	3.0	2.24
	1070				21	1.52	1.25
	1940				9	0.65	0.71
250	565	6.5	2.0	10.50	45	4.28	2.68
	1070				19	1.81	1.47
	1940				10	0.95	0.82

[redacted]

(Continued)

[redacted]

TABLE 10 (Continued)

Measured Field - Loop B

d = 6 ft

f (kc/sec)	R_o (yds)	I_T (amps)	Transmitter Power (kw)	I_L (amps)	Measured E (μV/m)	Measured E/I_L	Computed E/I_L
26.8	445	15.2	Strong Interference				
40	445	14.8					
100	445	21.7	3.1	22.7	32.5	1.43	1.23
	870				14.5	0.64	0.44
150	445	16.7	3.2	18.1	33	1.82	1.09
	870				14.5	0.80	0.60
200	445	10.8	2.6	13.86	30	2.16	1.25
	875				13.5	0.97	0.70
250	445	6.5	2.0	10.50	29	2.76	1.39
	840				12.5	1.19	0.79

d = 8 ft.

f (kc/sec)	R_o (yds)	I_T (amps)	Transmitter Power (kw)	I_L (amps)	Measured E (μV/m)	Measured E/I_L	Computed E/I_L
100	242	21.7	3.1	22.7	32.5	1.43	4.54
	580				14.0	0.62	0.42
150	252	16.7	3.2	18.1	31	1.71	1.91
	555				16.5	0.91	0.45
200	276	10.8	2.6	13.86	32.5	2.34	1.02
	470				13.5	0.97	0.56
250	268	6.5	2.0	10.50	33	3.14	0.95
	605				15	1.43	0.46

d = -1 ft (partially surfaced)

f (kc/sec)	R_o (yds)	I_T (amps)	Transmitter Power (kw)	I_L (amps)	Measured E (μV/m)	Measured E/I_L	Computed E/I_L
100	620	21.7	3.1	22.7	233	10.26	—
	1150	21.7		22.7	83	3.65	—
	1815	21.2		22.2	43	1.94	—
	2500	21.2		22.2	35	1.58	—
150	640	16.5	3.2	17.9	265	14.80	—
	1090	16.4		17.8	138	7.75	—
	1790	16.3		17.7	75	4.23	—
	2500	16.3		17.7	50	2.82	—

[redacted]

(Continued)

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TABLE 10 (Continued)

Measured Field - Loop B

d =-1 ft

f (kc/sec)	R_o (yds)	I_T (amps)	Transmitter Power (kw)	I_L (amps)	Measured E (μV/m)	Measured E/I_L	Computed E/I_L
200	635	10.8	2.6	13.86	330	23.8	—
	1090				180	13.0	—
	1790				90	6.50	—
	2500				65	4.69	—
250	680	6.5	2.0	10.50	375	35.7	—
	1090				215	20.5	—
	1790				120	11.43	—
	2500				75	7.15	—

[redacted]

[redacted]

TABLE 11

Measured Field From Submerged Loop C

d = 2 ft

f (kc/sec)	R_o (yds)	I_T (amps)	Transmitter Power (kc)	I_L (amps)	Measured E (µV/m)	Measured E/I_L	Computed E/I_L
40	315	7.5	0.37	7.69	50	6.5	42.7
	498				18	2.34	10.5
	565				13	1.69	7.07
100	325	7.0	2.2	9.62	120	12.46	18.3
	580				45	4.67	4.14
	1140				18	1.87	2.10
	1790				10	1.04	1.42
			d = 4 ft				
40	268	7.5	0.37	7.69	38	4.94	48.7
	420				28	3.64	12.81
	560				18	2.34	5.16
100	510	7.0	2.2	9.62	35	3.64	3.31
	1150				13	1.35	1.21
	1890				8	0.83	0.78
			d = 6 ft				
40	320	7.8	0.4	8.0	20	2.50	19.9
	410				15	1.88	9.7
100	460	7.0	2.2	9.62	21	2.18	2.24
	890				10	1.04	0.87
	1490				5	0.52	0.56

[redacted]

[redacted]

TABLE 12

Measured Field From Submerged Loop D

d = 2 ft

f (kc/sec)	R_o (yds)	I_T (amps)	Transmitter Power (kw)	I_L (amps)	Measured E (μV/m)	Measured E/I_L	Computed E/I_L
100	375	9.2	2.1	10.65	118	11.09	11.6
	745				30.8	2.89	3.01
	1450				16.4	1.54	1.71
	1930				13.3	1.25	1.31
			d = 4 ft				
100	268	9.3		10.77	102.5	9.53	19.5
	477	9.3		10.77	38.4	3.57	3.78
	890	9.3		10.77	19.0	1.76	1.50
	1640	9.2	2.1	10.65	10.2	0.95	0.89
			d = 6 ft				
100	250	9.7	2.3	11.23	144	12.81	14.3
	625				27.2	2.42	1.26
	1190				13.8	1.23	0.68

[redacted]

[redacted]

TABLE 13

Measured Field From Submerged Loop E

f (kc/sec)	R_o (yds)	I_T (amps)	Transmitter Power (kw)	I_L (amps)	Measured E (μV/m)	Measured E/I_L	Computed E/I_L
			d = 1 ft				
40	526	7.5	0.3	7.72	47	6.08	11.5
	1000				21	2.72	1.52
	1276				18	2.33	0.84
100	626	10.2	2.4	12.73	160	12.57	5.28
	1306				65	5.10	2.65
	2176				36	2.83	1.67
	2926				27	2.12	1.26
			d = 2 ft				
40	436	7.5	0.3	7.72	44	5.69	17.4
	776				30	3.88	2.84
	1126				20	2.59	0.96
100	526	10.5	2.5	13.1	140	10.7	5.33
	1076				58	4.42	2.39
	1926				28	2.14	1.42
	13000				5.0	0.38	0.22
			d ≐ 4 ft				
40	466	7.9	0.3	8.15	44	5.40	9.96
	626				27	3.31	4.01
	1026				15	1.84	0.85
100	676	10.5	2.5	13.1	55	4.20	2.12
	1151				25	1.91	1.31
	1926				16	1.22	0.83
40	491	7.9		8.15	11	1.35	Pattern*
			d = 6 ft				
40	526	8.1	0.3	8.34	20	2.40	4.91
	726				12	1.44	1.75
100	526	10.5	2.5	13.1	42	3.21	1.80
	1276				17	1.30	0.70
	1826				9	0.69	0.51
	2476				5.0	0.38	0.39

* Position broadside to loop.

(Continued)

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TABLE 13 (Continued)

Measured Field - Loop E

d = 8 ft

f (kc/sec)	R_o (yds)	I_T (amps)	Transmitter Power (kw)	I_L (amps)	Measured E (μV/m)	Measured E/I_L	Computed E/I_L
40	Excessive noise interference						
100	526	10.5	2.5	13.1	21	1.60	1.05
	1026				6	0.46	0.49
	1376				4.0	0.31	0.38

d = 10 ft

f (kc/sec)	R_o (yds)	I_T (amps)	Transmitter Power (kw)	I_L (amps)	Measured E (μV/m)	Measured E/I_L	Computed E/I_L
100	516	10.7	2.6	13.35	5.5	0.41	0.63
	756				3.5	0.26	0.37
	1076				2.0	0.15	0.27
100	263	10.7		13.35	10	0.75	Pattern*

* Position broadside to antenna.

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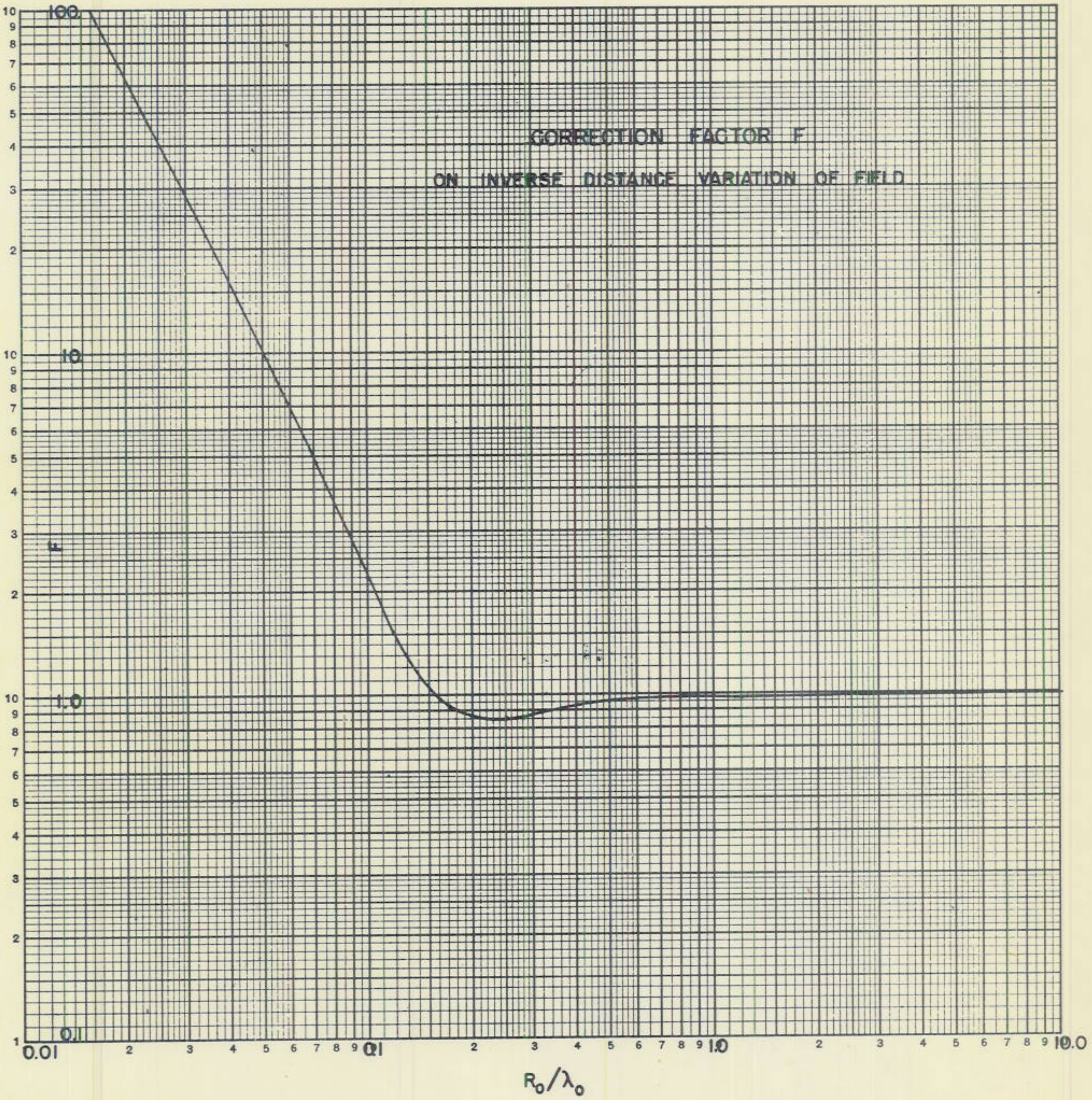
[redacted]

DECLASSIFIED



[redacted] R-3006 PLATE I

DECLASSIFIED [redacted]

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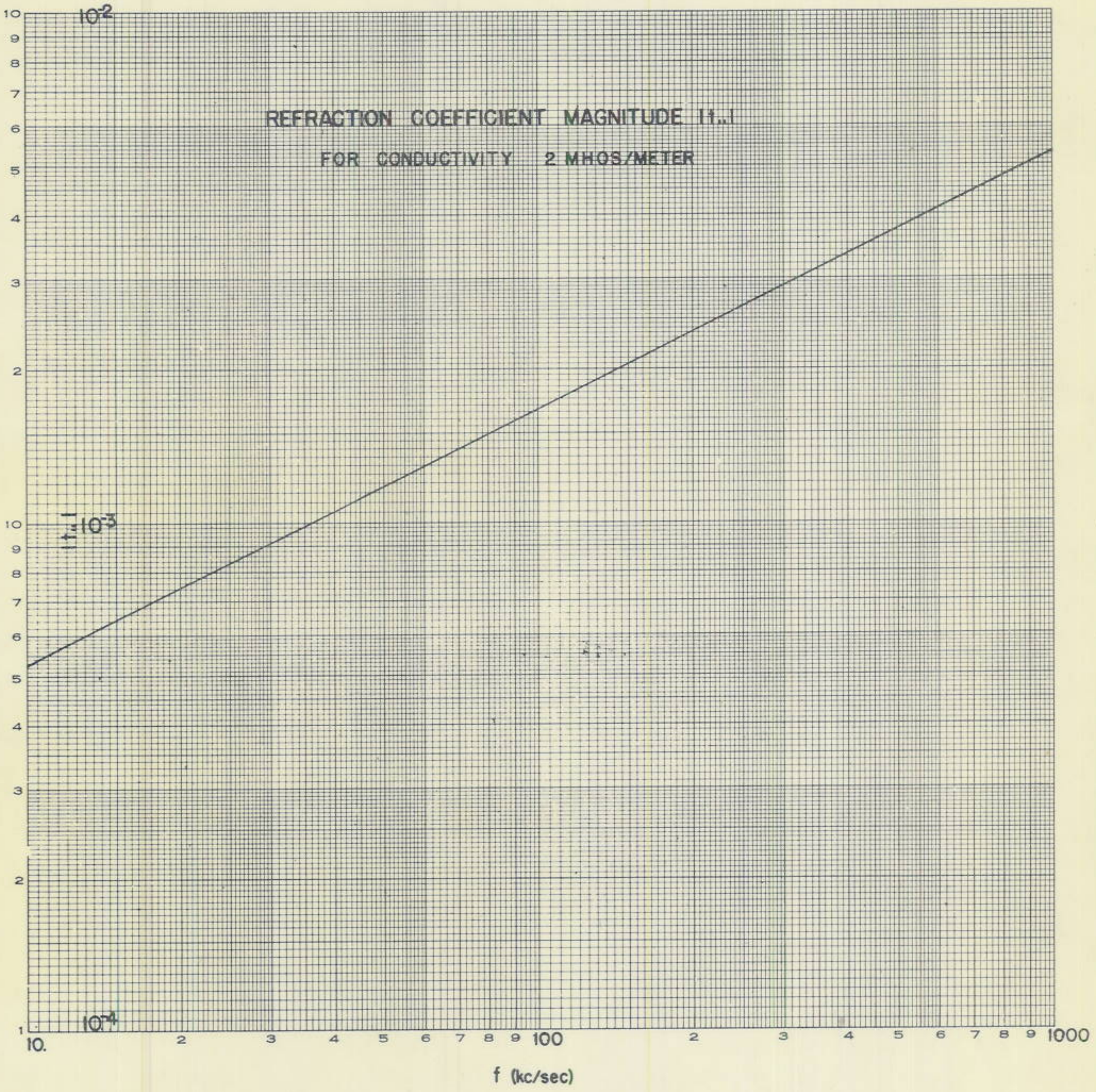
REFRACTION COEFFICIENT MAGNITUDE $|t_{12}|$

FOR CONDUCTIVITY 2 MHOS/METER

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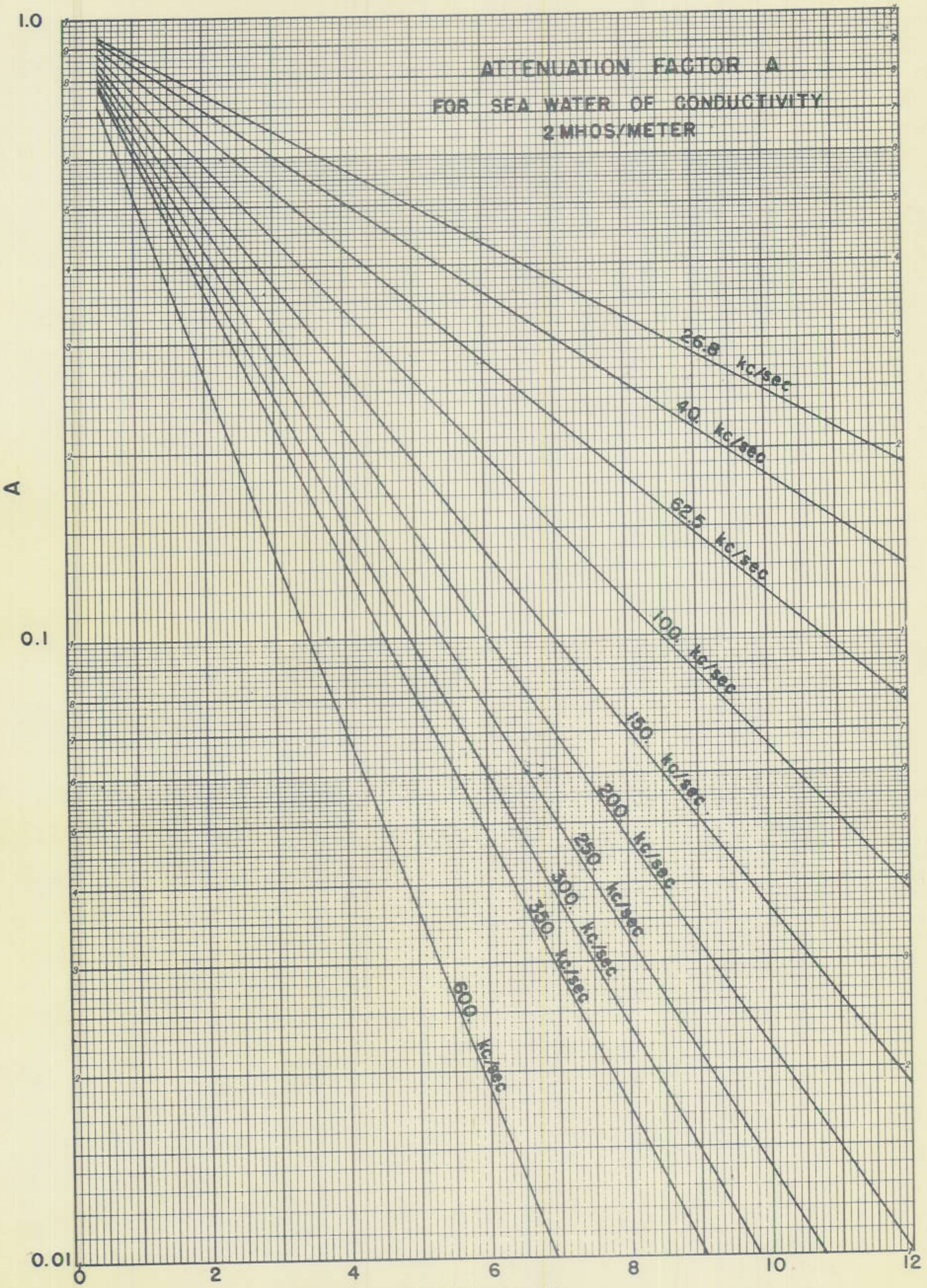

PLATE 3

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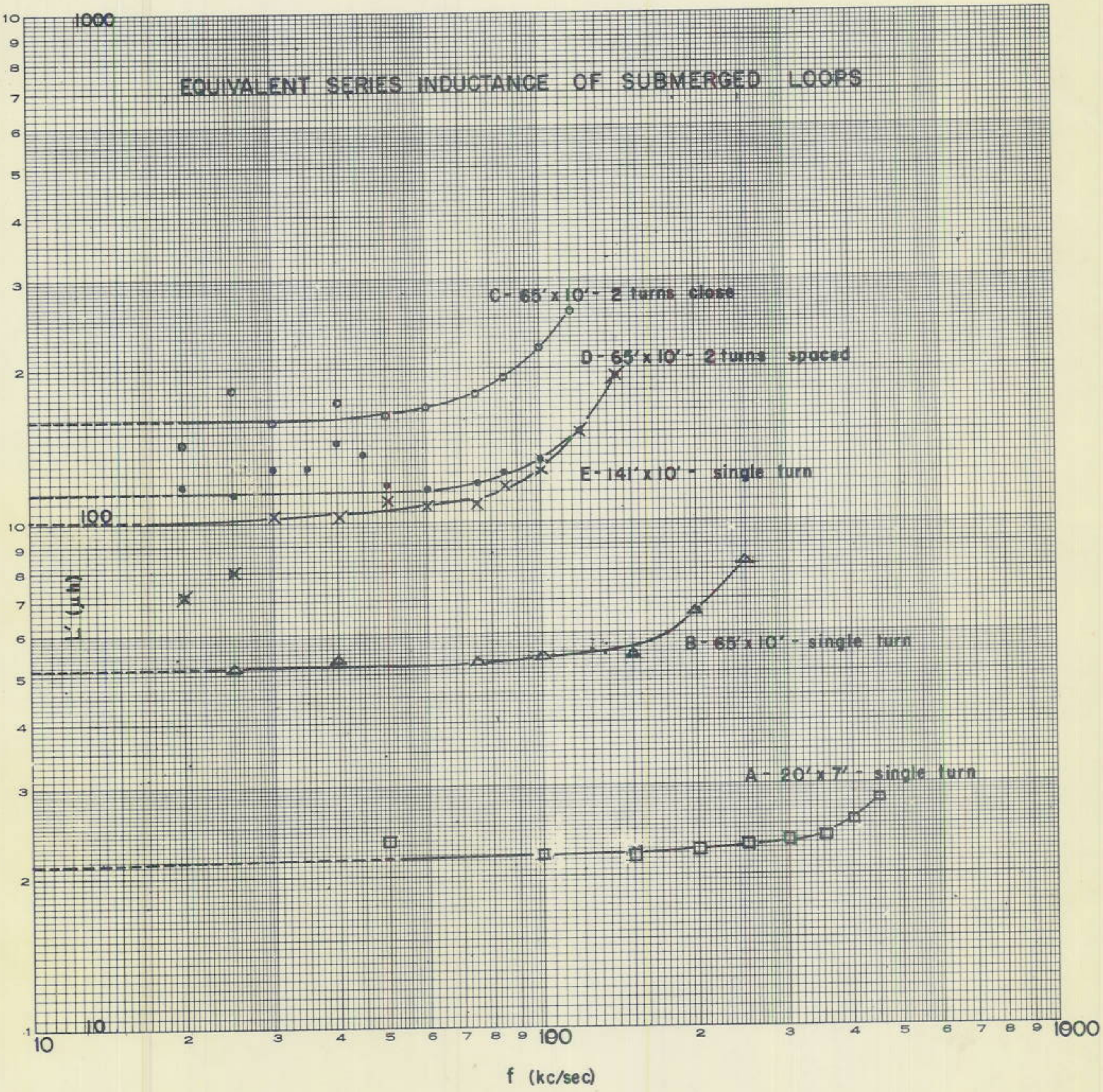

EQUIVALENT SERIES INDUCTANCE OF SUBMERGED LOOPS

~~SECRET~~

R-3006

PLATE 4

DECLASSIFIED [redacted]

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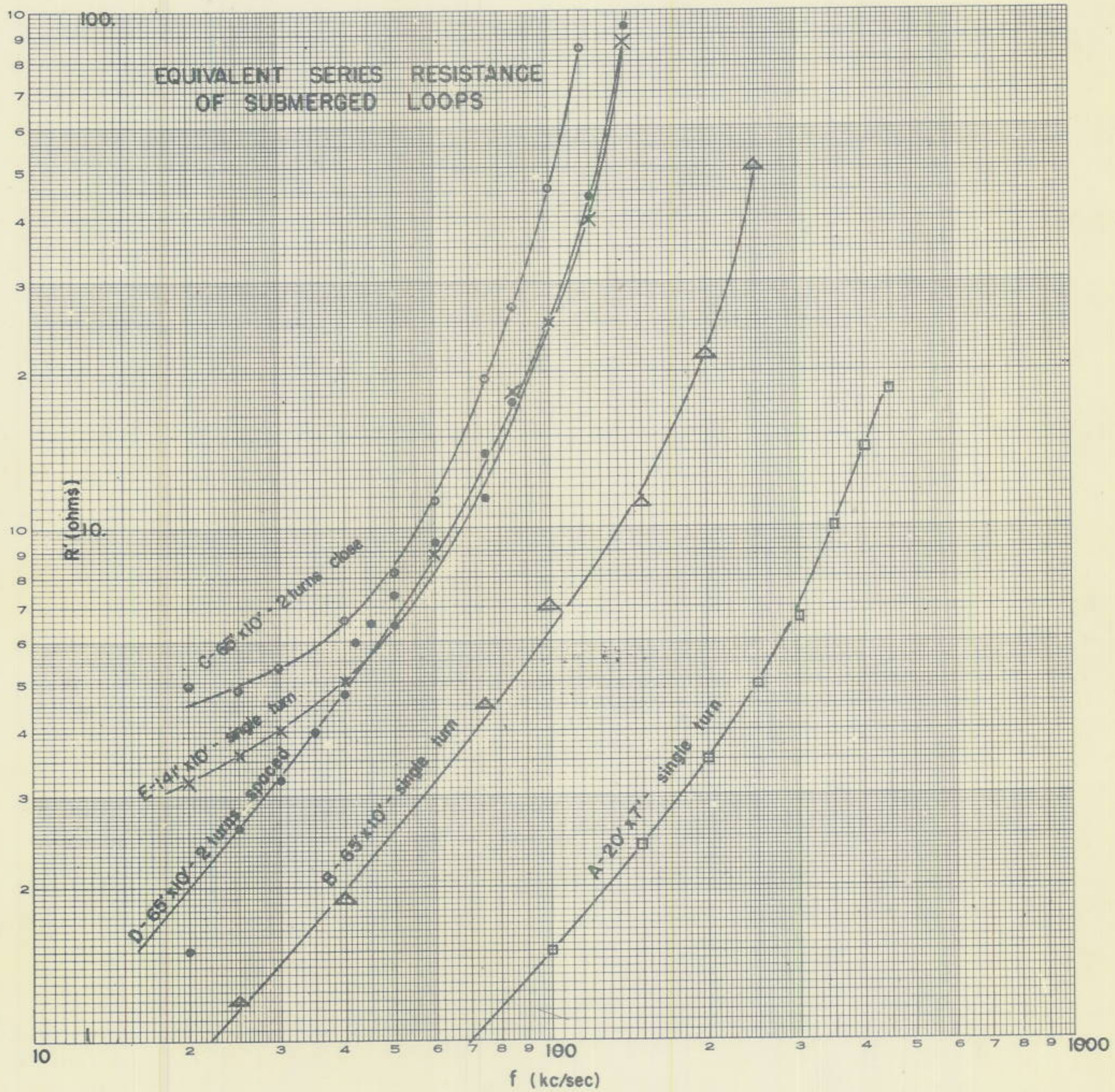

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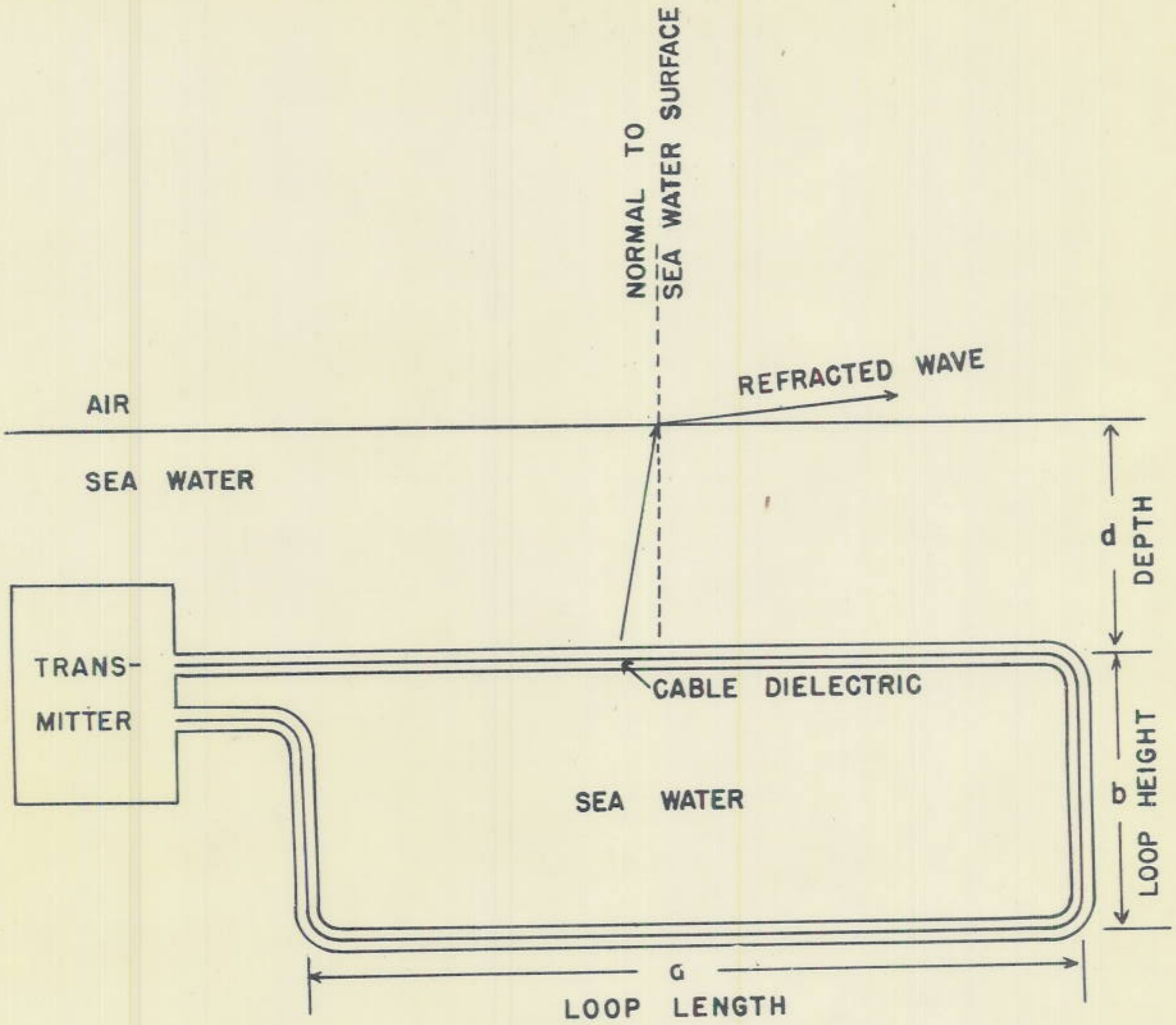

PLAN OF RADIATION SOURCE

[redacted]

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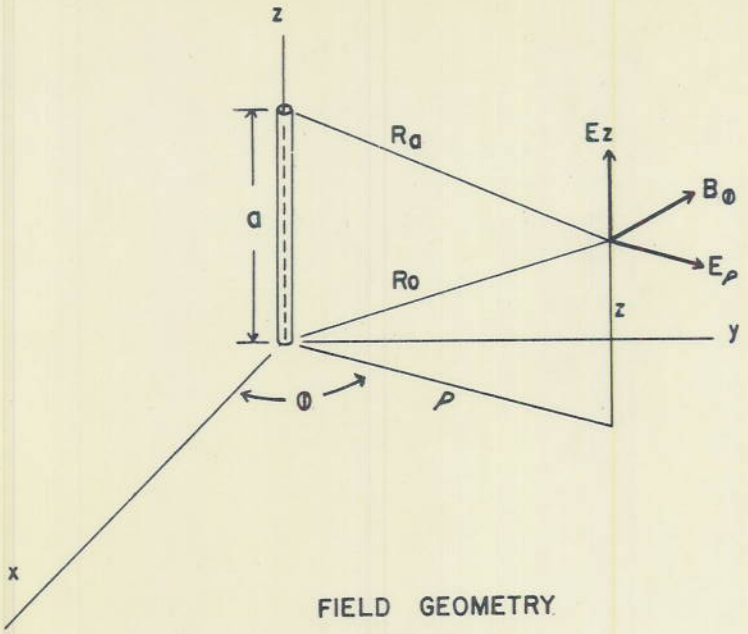
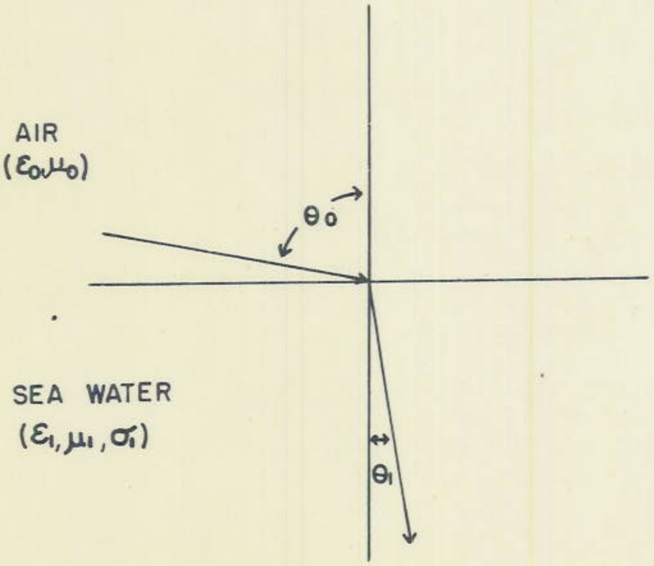


FIELD GEOMETRY
FIGURE I



REFRACTION OF SURFACE WAVE
FIGURE 2

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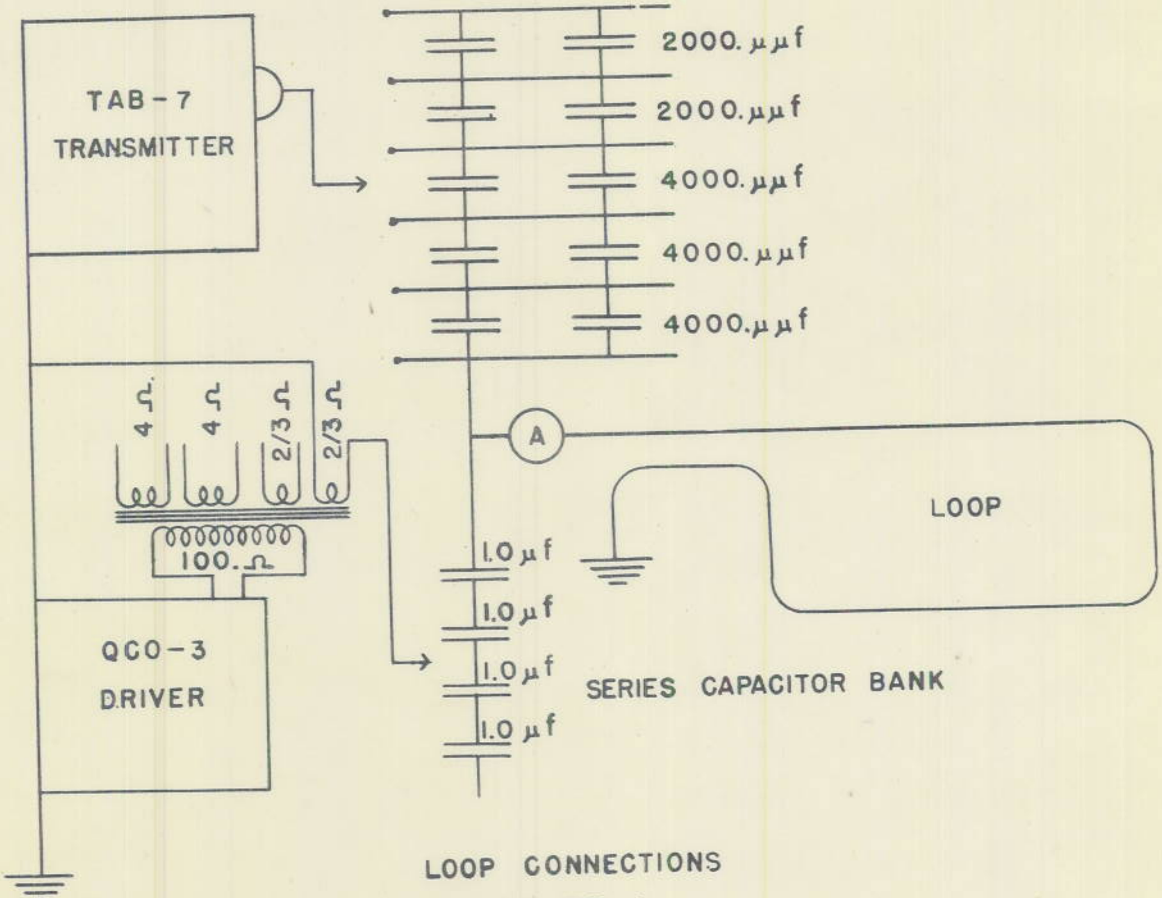
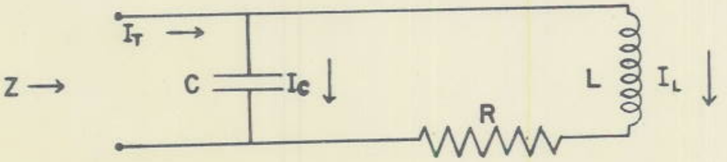


LOOP CONNECTIONS
FIGURE 1



EQUIVALENT LOOP CIRCUIT
FIGURE 2

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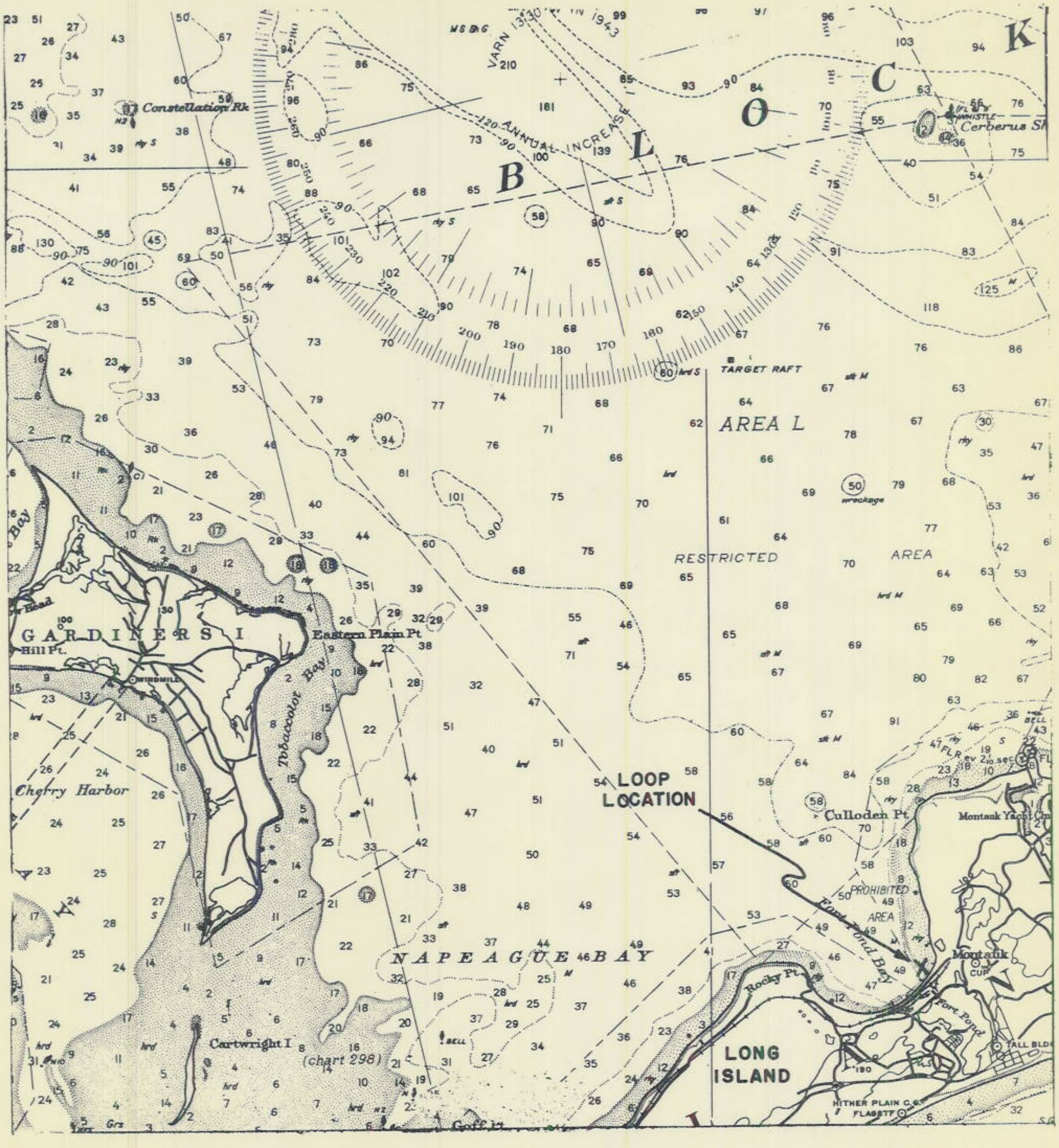

OPERATIONAL AREA FOR EXPERIMENT
BLOCK ISLAND SOUND NEAR FORT POND BAY

DISTANCE SCALE

YARDS

1000 0 5000 10000

PLATE 9

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R-3006

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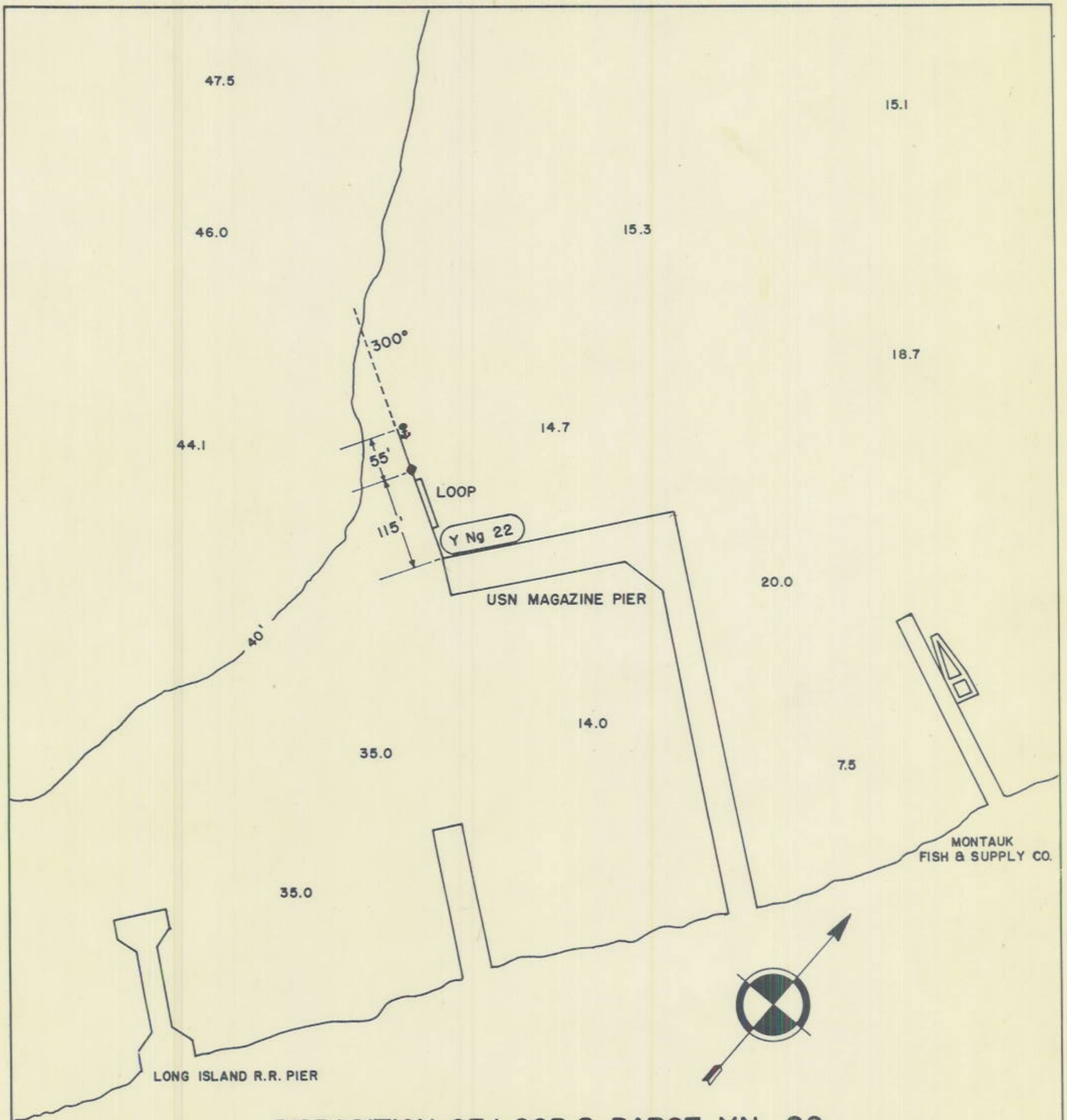


DISPOSITION OF LOOP & BARGE YNg 22
FORT POND BAY, L.I.

DISTANCE SCALE
SCALE = 17"/32 = 50'
0 50 100 150 200 250 300 350 400

[redacted]

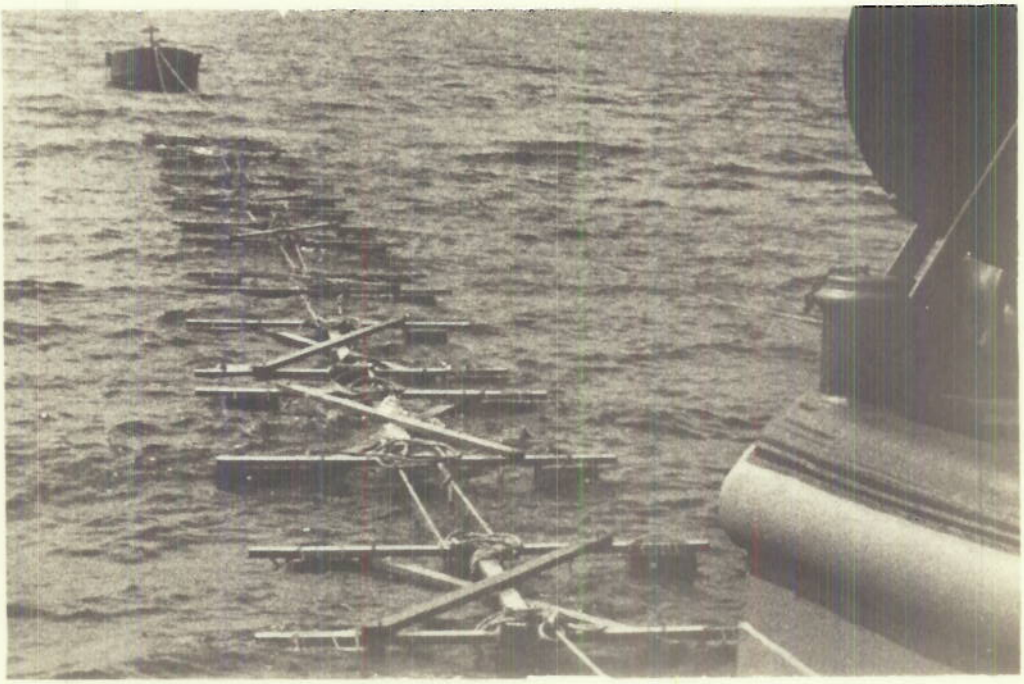
PLATE 10

[redacted]

SONAR BARGE YNg 22 MOORED TO USN PIER
FORT POND BAY, L. I.

[redacted]

[redacted]



RAFTS SUPPORTING SUBMERGED LOOP
MOORED TO BARGE YNg 22 IN FOREGROUND,
TO BOUY IN BACKGROUND

[redacted]

EXPERIMENTAL ARRANGEMENT FOR MEASUREMENT OF RADIATION FROM A SUBMERGED LOOP.

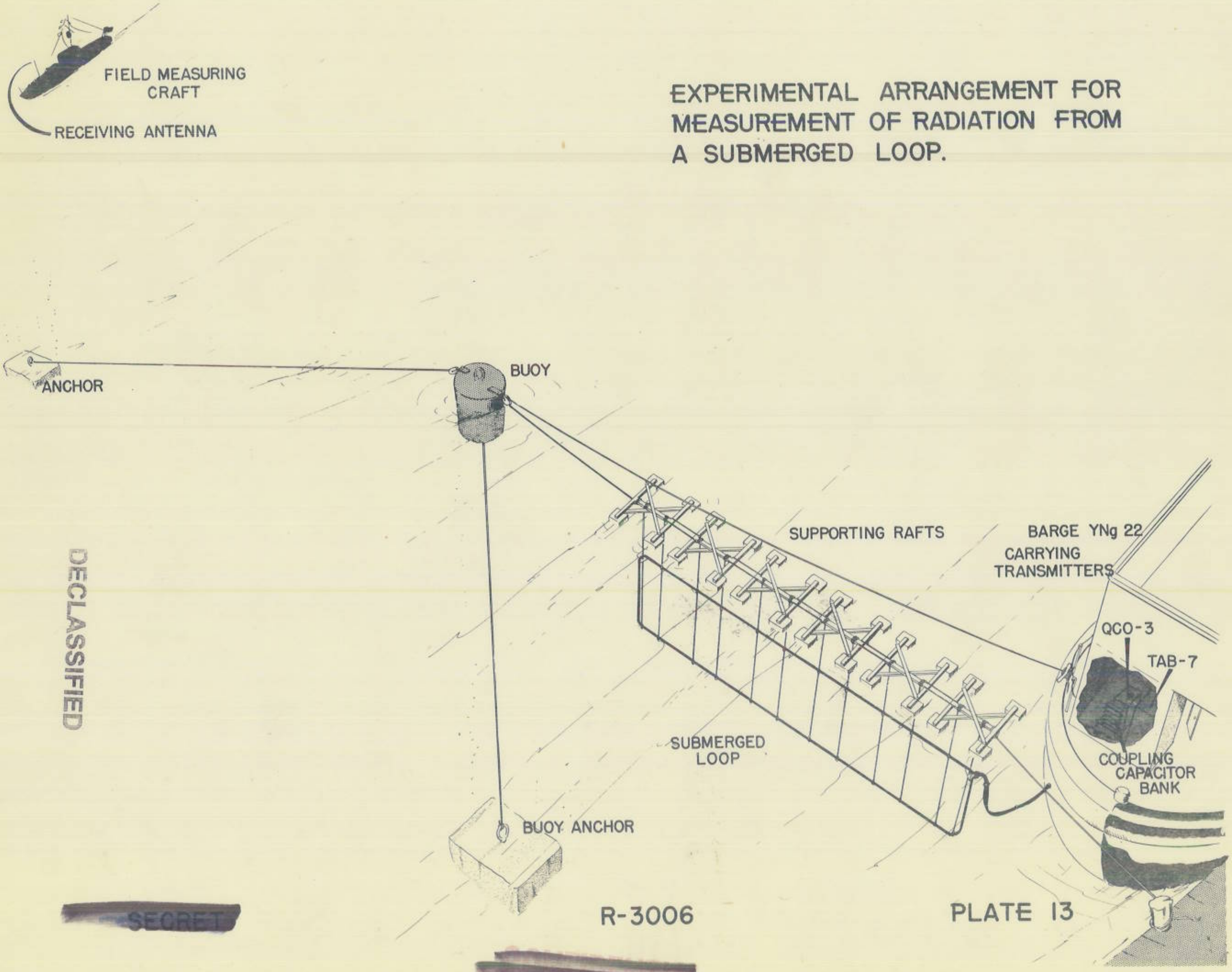


PLATE 13

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DISTRIBUTION

BuOrd - Re4b - 10
ONR - Chief - 1
ONR - Technical Information Center - 29
ONR - Project Status - 1
ONR - Subsurface Section - 1
ONR - Electronic Section - 1
ONR - Boston - 1
CNO - Op 413 - 5
CNO - Op 34H - 2
CNO - Op 31 - 1
CNO - Op 414C3 - 1
BuShips - Code 910 - 5
BuAer - EL - 5
NOL - 2
USN/USL - 2
NEL - 3

[redacted]

[redacted]