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IMPEDANCES OF SUBMERGED HORIZONTAL-WIRE ANTENNAS

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IMPEDANCES OF SUBMERGED HORIZONTAL-WIRE ANTENNAS

C. B. Appleman

December 20, 1951

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DEPARTMENT OF THE NAVY OFFICE OF NAVAL RESEARCH

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ABSTRACT

Experiments have been conducted to check the validity of the theoretical equation for the input impedance of horizontal type end-sealed and end-exposed antennas submerged in sea water. Scale model techniques were employed which required the use of a specially designed model range free of boundary effects and reflective interference. The end-sealed and end-exposed antennas are compared to open-circuited and short-circuited standard transmission lines. It is shown that the impedances of the antennas and transmission lines are of the same general characteristics. A scaling factor of twelve to one was employed over the frequency range of 0.1 to 10 Mc, which adequately embraces the full scale range of frequencies, 10 to 500 kc, considered of practical value for underwater radio systems. Good agreement is shown between the experimental and theoretical values.

PROBLEM STATUS

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

AUTHORIZATION

NRL Problem 39R11-02
BuShips S-1510
RDB Project NR 511-020

Manuscript submitted September 20, 1951

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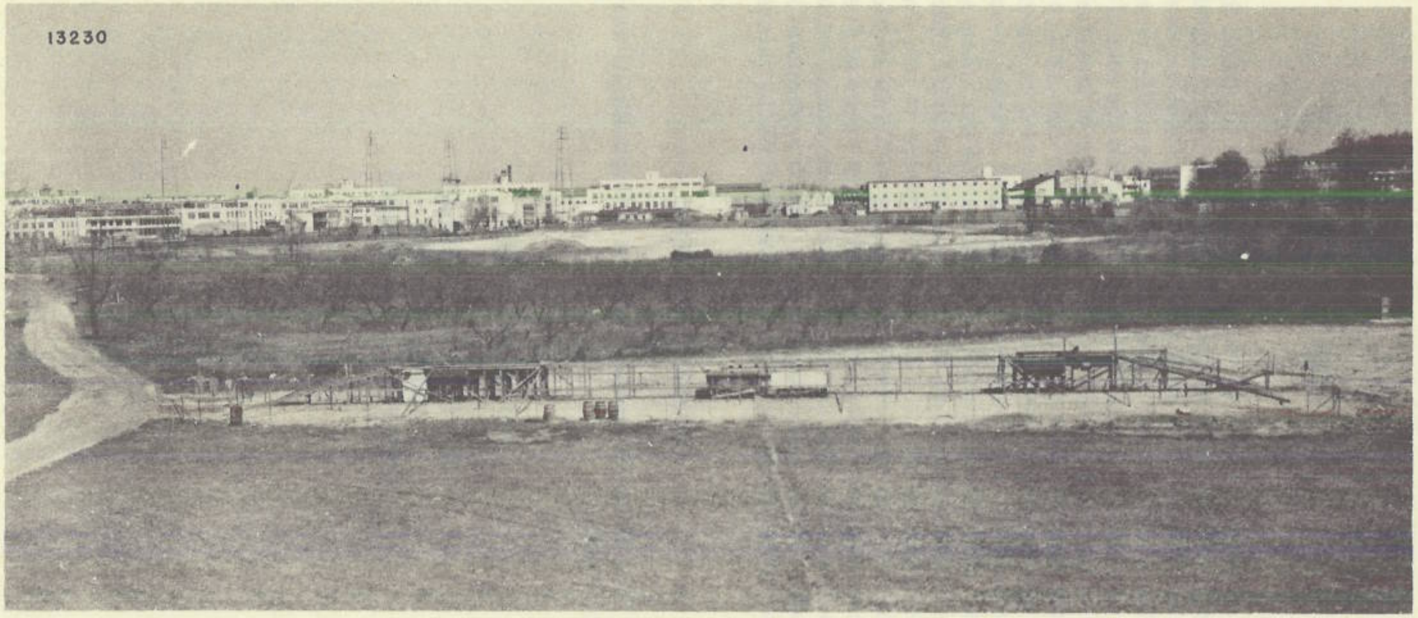

Frontispiece - Underwater-radio scale-model range with NRL in background

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IMPEDANCES OF SUBMERGED HORIZONTAL-WIRE ANTENNAS

INTRODUCTION

The general problem of radio communication between completely submerged submarines necessarily includes a study of antenna characteristics, the propagation of the radio waves between antennas, and the transmitting and receiving equipment associated with the system. In order to realize optimum performance from such a radio circuit it is necessary to determine the fundamental physical laws governing the radiation and propagation of radio waves in sea water and through the sea water-air interface. A theoretical analysis of the impedance characteristics of horizontal-wire antennas submerged in sea water or other semiconducting media is reported in reference (1).

In reducing the formulas for the input impedance of horizontal-wire antennas to a form suitable for numerical computation, it was desirable to make a number of approximations and simplifications. Several series of measurements were planned to determine the input impedance of horizontal-wire antennas over a wide range of parameters such as frequency, antenna length, diameter of antenna conductor, and thickness of the dielectric sheath surrounding the conductor for the purpose of comparing the experimental results with the theory. Practical considerations pointed out the need of a scale model range for carrying out the experimental program rather than attempting full scale measurements in sea water.

THE MODEL RANGE

An area to the south of the Naval Research Laboratory, known as Blue Plains, was selected as the site of the model range. This location was essentially free of structures which might influence the measurements and the wet, almost swampy, character of the terrain was favorable for obtaining good grounding conditions. A considerable amount of experimentation at the Naval Research Laboratory proper preceded the actual construction of the model range and indicated that it was possible to use relatively small tanks to hold the semiconducting medium and to employ wire mesh for the conducting ground between and in the immediate vicinity of the tanks. The frontispiece is a photographic view of the completed installation while Figure 1 illustrates the important details.

Various solutions for scaling the conductivity factor were considered. The final choice was an ammonium chloride (NH_4Cl) solution which produced a conductivity of 50 mhos per meter at a temperature of 37°C. This gave a scaling factor of approximately twelve to one for average sea water. Thus an antenna 24 inches long immersed in the model range tank to a depth of one inch is the equivalent of a 24-foot antenna submerged to a depth of one foot in average sea water. The other scaling factors required to compare impedances of the scale model antennas with the full-scale antennas include frequency, the diameters of the antenna conductors, and antenna insulation.

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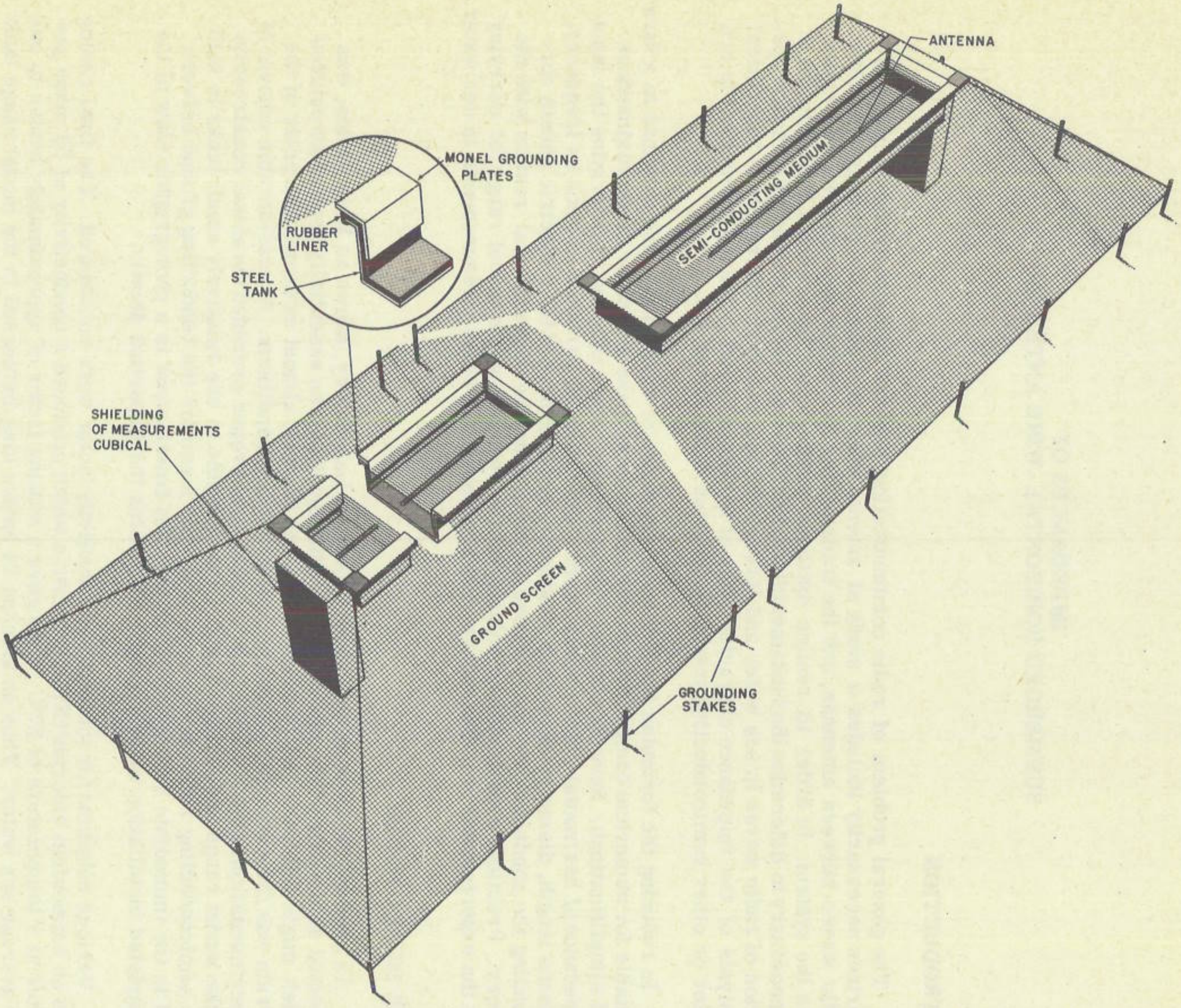

Figure 1 - Isometric drawing of scale-model range

The corrosive nature of the NH_4Cl solution and the necessity to avoid coupling between the antennas and the tank walls or other experimental components dictated the choice of construction materials and the dimensions of the tanks. The transmitting tank is 16 inches deep, 30 inches wide, and 216 inches long. The dimensions of the receiving tank are 16 inches deep, 30 inches wide, and 108 inches long. Both tanks are fabricated from 3/8-inch steel with hard-rubber liners. Monel metal plates were installed along the inside of the tanks to provide a bond between the wire mesh ground screen and the solution.

The wire mesh screen was designed to provide an essentially continous conducting ground in the immediate vicinity of the tanks. A steel cable was soldered around the entire periphery of the ground screen which in turn was connected to galvanized iron rods driven three feet into the earth at 6-foot intervals. The ground screen is further connected to the shielding of the measurement cubicles and these shields are connected to copper rods driven 6 feet into the earth. Due to the height of the small shielded houses the ground screen slopes from an elevation of 7 feet at the tanks to a height of one foot at the periphery.

The measurement cubicles, one at the end of each tank, are of the single shield type and are equipped with three feed-through tubes to provide a means of entrance into the NH_4Cl solution for antenna lead-in conductors. To minimize corrosion difficulties the tubes and tube caps were made of lucite (Figure 2). Although the return path of the r-f current from the antenna (Figure 2) is longer than was at first considered desirable, experience revealed that no difficulties were encountered from this source. Check measurements were made using metal tubes, but the differences in results were not sufficient to warrent their use or to accept the additional difficulties which would occur due to corrosion of the metallic parts.

Checks were conducted on the finished installation to determine if any boundary effects or pattern discrepancies existed. Antennas immersed in the NH_4Cl solution were moved from the center of the tank to positions close to the sides and from positions near the surface to a considerable depth. These changes caused no observable effects upon the impedance or antenna pattern characteristics. The only effect observed was the expected decrease in field strength as the antenna was lowered to a greater depth in the solution.

The model tanks were equipped with automatically controlled heaters to maintain the solution at a constant temperature and with stirring devices to maintain uniformity of the conductivity.

After thorough checks had been completed the impedance data measurements were undertaken.

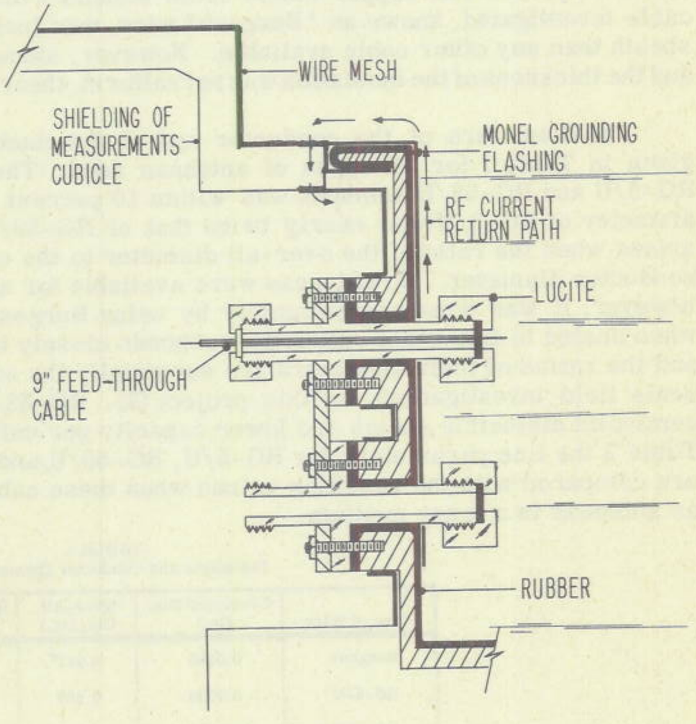

Figure 2 - Cutaway drawing of feed-through tubes

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HORIZONTAL-WIRE ANTENNAS

The term horizontal-wire antenna is used in this report to describe a copper conductor encased in a dielectric sheath and submerged in a horizontal position in a semiconducting medium. If a section of this lossy transmission line is shorted or open circuited at the far end, then the result is an end-exposed or an end-sealed antenna, respectively. The short-circuited condition was obtained by exposing one inch of the conductor to the semiconducting medium. Experiments showed that this one-inch section of exposed conductor gave essentially as effective a connection to the sea water as a flat plate or a sphere. The end-sealed condition was obtained by completely insulating the conductor from the semiconducting medium.

Antennas of this type have been analyzed in terms of a lossy coaxial transmission line of infinite length (1). The semiconducting medium is the outer conductor for this transmission line. Formulas for evaluating the parameters α, β, R, L, C, and Z_0 for such a transmission line are also given in reference (1). All of these parameters except the capacity (C) are a function of the frequency because of the lossy outer conductor (semiconducting medium). The analysis also included the conditions of lossy coaxial transmission line of finite length for the end-exposed and end-sealed conditions. The impedance characteristics of the end-exposed or end-sealed horizontal wire antenna are calculated from the formulas for the input impedance of a short-circuited or open-circuited transmission line, respectively. The appropriate line parameters for the lossy coaxial transmission line must be used in the impedance formulas.

Three of the antennas, whose line parameters are tabulated, were made by removing the vinyl jacket and copper shield from standard coaxial transmission lines. The fourth cable investigated, known as "Burgess" wire, was included since it had a thinner dielectric sheath than any other cable available. However, since the dielectric constant was unknown and the thickness of the insulation was not uniform, theoretical calculations were impossible.

The diameters of the conductor and of the conductor and the dielectric sheath are given in Table 1 for all types of antennas used. The ratio of the two diameters for the RG-5/U and RG-58/U antennas was within 10 percent of being the same but the over-all diameter of RG-5/U was nearly twice that of RG-58/U. Another interesting situation arises when the ratio of the over-all diameter to the conductor diameter varies for a given conductor diameter. No antennas were available for accurately making this comparison; however, it was done approximately by using Burgess wire and RG-63/U. The RG-58/U when scaled to full-scale values corresponds closely to the same size of cable as RG-19/U and the ratios of their diameters are essentially the same. RG-19/U has been used on full-scale field investigations on this project (2). RG-63/U cable was chosen since it has a semisolid dielectric sheath and lower capacity per unit length than the other cables. In Table 2 the line parameters for RG-5/U, RG-58/U, and RG-63/U standard coaxial cables are compared with the resulting values when these cables, properly modified, are employed as antennas in a lossy medium.

TABLE 1
Dielectric and Conductor Diameters

Type of Wire	Conductor Dia. (in.)	Over-All Dia. (in.)	Ratio of Over-All to Conductor
Burgess	0.0195	0.041*	2.1
RG-5/U	0.0508	0.185	3.71
RG-58/U	0.0320	0.116	3.64
RG-63/U	0.0254	0.285	11.3

* An approximate value

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TABLE 2
Line Parameters For Low-Loss and Lossy Transmission Lines

Cable	Frequency (Mc)	R (ohms/meter)	L (henries/meter)	C (farads/meter)	β (radians/meter)	α (nepers/meter)	Z_0 (ohms)
RG-5/U	0.1	0.0226	0.27×10^{-6}	93.5×10^{-12}	0.316×10^{-2}	0.0208×10^{-2}	53.5
RG-5/U as an antenna	0.1	0.1188	1.15×10^{-6}	93.5×10^{-12}	0.651×10^{-2}	0.0535×10^{-2}	111-j36.5
	1.0	1.05	0.907×10^{-6}	93.5×10^{-12}	5.76×10^{-2}	0.531×10^{-2}	966-j35.6
	10.0	10.07	0.667×10^{-6}	93.5×10^{-12}	49.6×10^{-2}	5.95×10^{-2}	84.5-j40.8
RG-58/U	0.1	0.0239	0.27×10^{-6}	93.5×10^{-12}	0.316×10^{-2}	0.0223×10^{-2}	53.5
RG-58/U as an antenna	0.1	0.1306	1.27×10^{-6}	93.5×10^{-12}	0.688×10^{-2}	0.0564×10^{-2}	116-j38.2
	1.0	1.05	1.01×10^{-6}	93.5×10^{-12}	6.12×10^{-2}	0.525×10^{-2}	104-j34.4
	10.0	10.18	0.761×10^{-6}	93.5×10^{-12}	53.0×10^{-2}	5.63×10^{-2}	90.3-j38.4
RG-63/U	0.1	0.0452	0.497×10^{-6}	32.8×10^{-12}	0.249×10^{-2}	0.0181×10^{-2}	125
RG-63/U as an antenna	0.1	0.1396	1.32×10^{-6}	32.8×10^{-12}	0.4132×10^{-2}	0.03478×10^{-2}	205-j67.4
	1.0	1.115	1.05×10^{-6}	32.8×10^{-12}	3.686×10^{-2}	0.3118×10^{-2}	179-j60.5
	10.0	10.27	0.803×10^{-6}	32.8×10^{-12}	32.22×10^{-2}	3.282×10^{-2}	156.5-j63.4

The capacity per unit length of the lossy line is the same as the capacity per unit length of the standard coaxial transmission line and is independent of the frequency. The inductance per unit length of the lossy line is approximately 4 times the inductance of the standard coaxial transmission line at 0.1 Mc and decreases as the frequency increases. This frequency effect is due to the lossy outer conductor now surrounding the dielectric sheath.

The lossy outer conductor also affects the resistance of the submerged line. The resistance is approximately 5 times the value of the standard line with a lossless outer conductor. Since R and L of the lossy line change with frequency, the α, β, and Z_0 are frequency dependent also. The α and β of the lossy line are nearly twice the value of the standard coaxial transmission line at 0.1 Mc. The resistance parameter now cannot be neglected in deriving characteristic impedance equations for this lossy line. The inclusion of this parameter causes the expression for Z_0 to be complex.

The values of the parameters have been tabulated for 3 frequencies for the lossy line. These frequencies, 0.1, 1.0, and 10 Mc, when scaled, more than cover the range of frequencies of primary interest in full scale operations for underwater radio—namely 10 to 500 kc. The experimental and theoretical work that has been done indicates that the above frequency range is of the greatest importance for underwater radio systems.

The theoretical formulas for the computation of the input impedance of these antennas are

$$Z_{(\text{End-exposed})} = \frac{Z_0}{2}\left\{\frac{\text{Sin}\,\alpha\ell + j\text{Sin}\,2\beta\ell}{\text{Cos}^2\beta\ell + (\alpha\ell)^2\text{Sin}^2\beta\ell}\right\}$$

and

$$Z_{(\text{End-sealed})} = \frac{Z_0}{2}\left\{\frac{2\alpha\ell - j\text{Sin}\,2\beta\ell}{(\alpha\ell)^2\,\text{Cos}^2\beta\ell + \text{Sin}^2\beta\ell}\right\}$$

where

$Z_{(\text{End-exposed})}$ = input impedance to end-exposed antenna,

$Z_{(\text{End-sealed})}$ = input impedance to end-sealed antenna,

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$$Z_0 = \text{characteristic impedance} = \sqrt{\frac{R + j\omega L}{j\omega C}} \cong \sqrt{\frac{L}{C}}\left\{1 - j\left(\frac{R}{2\omega L}\right)\right\},$$

R = resistance per unit length in ohms per meter,

L = inductance per unit length in henries per meter,

C = capacity per unit length in farads per meter,

$\omega = 2\pi f$ where f is the frequency in cycles per second,

β = phase-shift constant per unit length = $\omega\sqrt{LC}$ in radians per meter,

α = attenuation constant per uint length = $\left(\frac{R}{2\omega L}\right)\left(\omega\sqrt{LC}\right)$ in nepers per meter,

ℓ = the physical length in meters.

MODEL RANGE MEASUREMENTS

Most of the data recorded at the Blue Plains model range were measured using a General Radio LP-5 Signal Generator, General Radio 916-A and 916-AL impedance bridges, RBA, RBB, and RBC Navy receivers as detectors, and a 3-inch oscilloscope as an indicator. This set of equipment (Figure 3) could be used for all measurements except the low-frequency measurements on end-sealed antennas where the capacitive reactance exceeded the range of the bridge.

At these lower frequencies it was necessary to use a Q-meter with a small variable air dielectric capacitor and a decade resistance box. The Q-meter circuit with an associated coil was resonated and the capacity recorded. Then, by attaching the antenna to the Q-meter and resonating the circuit again, the value of the antenna capacity was obtained as the difference of these two capacities. Also by attaching the antenna to the Q-meter, a Q of the combined coil and antenna circuit could be obtained. By substituting a variable air dielectric capacitor and a decade resistance box for the antenna, this Q could again be duplicated by proper adjustments of the two variables and the value of resistance of the antenna could be obtained. This method could be used between 0.150 and 1.0 Mc with good accuracy. At 1.0 Mc the bridge range was also adequate and the two methods could be used with very little discontinuity in the data.

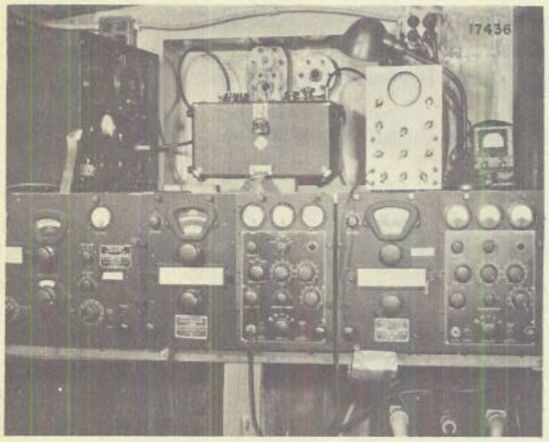

Figure 3 - Measuring equipment

The recorded data were obtained on antennas formed from the following cables: RG-5/U, RG-58/U, RG-63/U, and Burgess wire. The transmission lines (RG-5/U, RG-58/U, and RG-63/U) were stripped of their outer vinyl jacket and copper shield leaving only the inner copper conductor and dielectric sheath. Burgess wire was already of this form. These, then, were submerged in the semiconducting medium and the impedance measured over the frequency range of 0.1 to 10 Mc. These measurements were to be made with antenna lengths of 8, 6, 4, 2,

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and 1 foot for both end-sealed and end-exposed terminations. All the end-exposed antennas were one inch longer to provide contact with the medium at the termination. It was discovered that the resistance component of the end-sealed type of antennas was difficult to measure for antenna lengths less than four feet at the low frequencies. This difficulty was due to the high Q of the antenna circuit. Since such an antenna could not be fed efficiently and since the radiation efficiency would be low, accurate resistance measurements on the short lengths of end-sealed antennas were not considered worth the necessary additional effort.

In order to make the measurements it was necessary to use a connecting lead between the antenna and the measuring instrument. A 9-inch section of the antenna wire (Figure 2) was used for this feed-line. Sufficient measurements were made on the connecting lead so that the measured value of the antenna impedance could be corrected to give the input impedance to the antenna.

The antenna input impedance was computed for the following antennas to correct for the connecting lead in the measured data:

(a) For the 8-, 6-, 4-, 2-, and 1-foot lengths of the end-exposed type of antenna for the four antenna cables.

(b) For the 8-, 6-, and 4-foot lengths of the end-sealed type of antenna for the four antenna cables.

DATA AND RESULTS

The input impedance data (Tables 3 through 10) are shown as broken-line curves (Figures 4 through 19) except where theoretical curves are given for the same length antennas. Symbols indicate the measured points. It should be noted that the frequency range is 0.1 to 10 Mc for all the impedance data and that the electrical lengths of the antennas were both longer and shorter than would be of practical value to an underwater communication system. This was done to get as good a check as possible on the theoretical formulas for the calculation of the antenna impedance.

TABLE 3
Measured Input Impedance Values For RG-5/U End-Exposed Antennas

Frequency (Kc)	Antenna Length (ft) 8	6	4	2	1
100	0.45 + j 2.0	0.23 + j 1.8	0.14 + j 0.8	0.01 + j 0.53	+ j 0.3
195	0.60 + j 3.35	0.40 + j 2.4	0.25 + j 1.66	-0.1 + j 0.96	+ j 0.56
300	0.77 + j 5.19	0.57 + j 4.5	0.41 + j 2.4	0.24 + j 1.44	0.02 + j 0.8
434	0.98 + j 7.07	0.77 + j 5.0	0.52 + j 3.47	0.27 + j 1.9	0.07 + j 1.17
524	1.16 + j 8.4	0.86 + j 5.9	0.61 + j 4.05	0.31 + j 2.3	0.1 + j 1.28
750	1.6 + j 12.3	1.24 + j 8.0	0.88 + j 5.54	0.43 + j 3.22	0.17 + j 1.89
900	1.91 + j 14.5	1.51 + j 9.5	1.06 + j 6.88	0.51 + j 3.7	0.21 + j 2.2
1550	4.27 + j 21.6	2.62 + j 15.7	1.82 + j11.4	0.82 + j 5.2	0.37 + j 3.54
2000	5.9 + j 26.8	3.35 + j 19.6	2.25 + j13.0	1.15 + j 7.7	0.43 + j 4.2
4000	15.0 + j 53.7	7.3 + j 37.8	4.3 + j26.2	1.82 + j15.0	0,57 + j 8.2
6000	25.8 + j 86.5	12.5 + j 56.5	6.8 + j36.5	2.65 + j20.8	0.75 + j11.5
10000	148.0 + j207.5	39.8 + j114.5	14.7 + j60.5	4.6 + j33.1	1.15 + j16.5

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TABLE 4
Measured Input Impedance Values for RG-58/U End-Exposed Antennas

Frenquency	Antenna Length (ft)				
(Kc)	8	6	4	2	1
100	0.37 + j 1.8	0.22 + j 1.4	0.17 + j 0.8	0.13 + j 0.56	0.07 + j 0.3
195	0.70 + j 3.46	0.60 + j 2.7	0.35 + j 1.9	0.17 + j 1.06	0.10 + j 0.6
300	0.90 + j 5.40	0.82 + j 4.1	0.47 + j 2.9	0.21 + j 1.6	0.12 + j 0.8
434	1.3 + j 7.34	1.0 + j 5.8	0.55 + j 3.74	0.25 + j 2.13	0.13 + j 1.0
524	1.53 + j 8.95	1.18 + j 6.75	0.73 + j 4.96	0.28 + j 2.55	0.15 + j 1.4
750	2.09 + j 12.5	1.59 + j 9.4	0.94 + j 6.5	0.34 + j 3.6	0.18 + j 1.9
900	2.56 + j 14.5	1.96 + j 11.2	1.11 + j 7.5	0.38 + j 4.3	0.19 + j 2.0
1550	4.1 + j 20.0	3.1 + j 18.2	1.9 + j12.4	0.70 + j 6.6	0.25 + j 3.1
2000	5.28 + j 29.9	3.78 + j 22.9	2.4 + j15.4	1.03 + j 7.9	0.28 + j 3.9
4000	11.75 + j 61.8	9.0 + j 46.8	4.4 + j30.8	1.65 + j16.8	0.40 + j 7.3
6000	26.0 + j100.0	14.5 + j 78.0	7.0 + j46.0	2.25 + j24.8	0.55 + j11.1
10000	227.0 + j260.0	47.0 + j141.0	15.8 + j74.5	4.55 + j37.0	0.70 + j14.4

TABLE 5
Measured Input Impedance Values For RG-63/U End-Exposed Antennas

Frequency	Antenna Length (ft)				
(Kc)	8	6	4	2	1
100	0.42 + j 1.76	0.27 + j 1.26	0.07 + j 1.06	+ j 0.36	+ j 0.26
195	0.69 + j 4.15	0.47 + j 2.45	0.19 + j 1.91	0.07 + j 1.07	+ j 0.47
300	0.96 + j 6.12	0.71 + j 3.8	0.36 + j 2.82	0.18 + j 1.82	0.01 + j 0.64
434	1.34 + j 8.33	0.99 + j 5.33	0.59 + j 4.13	0.32 + j 2.49	0.10 + j 0.88
524	1.68 + j 9.7	1.18 + j 6.4	0.73 + j 5.05	0.41 + j 2.92	0.15 + j 1.05
750	2.25 + j 13.0	1.55 + j 9.4	1.08 + j 6.5	0.59 + j 4.1	0.3 + j 1.5
900	2.63 + j 15.1	2.0 + j 11.1	1.28 + j 8.1	0.70 + j 4.6	0.38 + j 1.7
1550	4.3 + j 23.6	3.4 + j 17.8	2.2 + j12.7	1.1 + j 6.15	0.7 + j 2.7
2000	5.55 + j 30.9	4.05 + j 23.4	2.75 + j15.9	1.35 + j 8.7	0.9 + j 3.3
4000	11.8 + j 61.2	7.9 + j 43.2	5.05 + j30.2	2.2 + j14.7	1.65 + j 6.2
6000	19.6 + j 88.5	11.9 + j 61.5	7.50 + j43.5	3.15 + j20.5	2.35 + j 8.5
10000	42.2 + j171.0	21.7 + j103.0	13.3 + j70.5	5.4 + j30.5	3.7 + j13.0

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TABLE 6
Measured Impedance Input Values For Burgess Wire End-Exposed Antennas

Frequency (Kc)	Antenna Length (ft)				
	8	6	4	2	1
100	0.61 + j 2.36	0.51 + j 1.63	0.48 + j 0.63	0.26 + j 0.18	0.22 + j0.13
195	0.95 + j 3.69	0.70 + j 2.33	0.60 + j 1.28	0.35 + j 0.35	0.25 + j0.25
300	1.21 + j 5.5	0.91 + j 3.6	0.73 + j 2.1	0.38 + j 0.68	0.27 + j0.35
434	1.42 + j 7.73	1.07 + j 4.8	0.9 + j 3.2	0.47 + j 2.06	0.32 + j0.53
524	1.9 + j 9.2	1.35 + j 8.1	1.1 + j 4.0	0.5 + j 3.42	0.33 + j0.6
750	2.57 + j 13.1	1.77 + j 9.6	1.3 + j 5.5	0.62 + j 4.47	0.38 + j0.85
900	2.95 + j 15.1	2.15 + j 13.9	1.5 + j 7.3	0.75 + j 5.65	0.42 + j1.0
1550	4.86 + j 26.1	3.36 + j 24.0	2.3 + j 12.2	1.11 + j10.0	0.59 + j1.7
2000	6.39 + j 33.3	4.39 + j 24.9	2.8 + j 16.6	1.39 + j12.3	0.71 + j2.1
4000	19.45 + j 77.5	10.35 + j 61.8	5.6 + j 33.0	2.25 + j23.7	1.2 + j4.0
6000	91.6 + j168.0	26.2 + j104.0	10.3 + j 49.5	3.5 + j34.6	1.7 + j6.0
10000	Above Resonance	Resonant	34.5 + j102.0	7.05 + j57.0	2.9 + j9.0

TABLE 7
Measured Impedance Input Values For RG-5/U End-Sealed Antennas

Frequency (Kc)	Antenna Length (ft)		
	8	6	4
100	- j7270	- j8440	- j12700
195	0.7 - j3720	0.25 - j4400	- j 6330
300	0.71 - j2450	0.49 - j2160	- j 4150
434	0.79 - j1750	0.55 - j1950	0.92 - j 2830
524	0.86 - j1190	0.65 - j1610	0.93 - j 2400
750	1.01 - j 940	0.72 - j1120	0.98 - j 1650
900	1.09 - j 758	0.8 - j 923	1.05 - j 1340
1550	1.47 - j 387	1.1 - j 534	1.15 - j 768
2000	1.72 - j 315	1.35 - j 409	1.22 - j 586
4000	3.0 - j 150	2.15 - j 200	1.65 - j 288
6000	4.8 - j 83.4	3.2 - j 117	2.3 - j 184
10000	10.3 - j Resonant	6.0 - j 40	3.9 - j 85.4

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TABLE 8
Measured Input Impedance Values For RG-58/U End-Sealed Antennas

Frequency	Antenna Length (ft)		
(Kc)	8	6	4
100	- j6450	- j8600	- j14000
195	- j3310	- j4410	- j 7100
300	- j2150	- j2870	- j 4500
434	- j1485	- j1985	- j 3050
524	- j1230	- j1645	- j 2550
750	- j 875	1.09 - j1145	- j 1750
900	2.02 - j 710	1.3 - j 950	- j 1440
1550	2.13 - j 406	1.5 - j 550	- j 830
2000	2.4 - j 310	1.7 - j 420	- j 630
4000	3.7 - j 150	2.7 - j 200	1.68 - j 300
6000	5.3 - j 83.0	3.7 - j 120	2.3 - j 183
10000	10.7 + j 3.7	6.7 - j 40	3.8 - j 85

TABLE 9
Measured Input Impedance Values For RG-63/U End-Sealed Antennas

Frequency	Antenna Length (ft)		
(Kc)	8	6	4
100	- j18500	- j24000	- j42000
195	- j 9500	- j12500	- j21500
300	- j 6100	- j 7950	- j13800
434	- j 4250	- j 5450	- j 9300
525	- j 3440	- j 4440	- j 7400
750	1.3 - j 2430	- j 3120	- j 5050
900	1.5 - j 2000	- j 2610	- j 4150
1550	2.25 - j 1170	1.75 - j 1485	- j 2300
2000	2.65 - j 900	2.05 - j 1160	- j 1725
4000	4.0 - j 440	2.75 - j 570	- j 825
6000	5.2 - j 280	3.25 - j 375	3.3 - j 530
10000	7.6 - j 125	4.9 - j 195	3.5 - j 295

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TABLE 10
Measured Input Impedance Values for Burgess Wire End-Sealed Antennas

Frequency (kc)	Antenna Length (ft)		
	8	6	4
100	- j3800	- j5000	- j7900
195	- j2000	- j2550	- j4050
300	- j1300	- j1680	- j2630
434	- j 900	- j1150	- j1960
524	- j 750	- j 954	- j1620
750	- j 513	- j 670	- j1080
900	- j 435	0.95 - j 555	- j 910
1550	3.1 - j 248	1.4 - j 323	- j 516
2000	3.3 - j 198	1.65 - j 250	1.2 - j 400
4000	4.4 - j 87.5	2.8 - j 112	2.1 - j 195
6000	6.2 - j 33.3	4.1 - j 50.0	2.8 - j 130
10000	16.0 + j 34.0	8.7 + j 21.5	4.8 - j 40

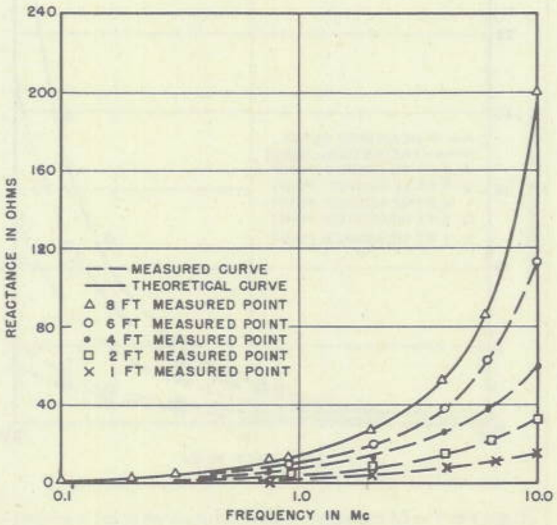

Figure 4 - Measured and theoretical reactance vs. frequency curves for RG-5/U end-exposed antennas

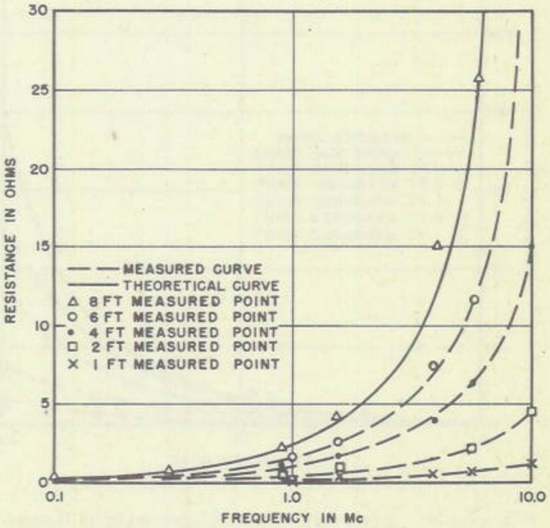

Figure 5 - Measured and theoretical resistance vs. frequency curves for RG-5/U end-exposed antennas

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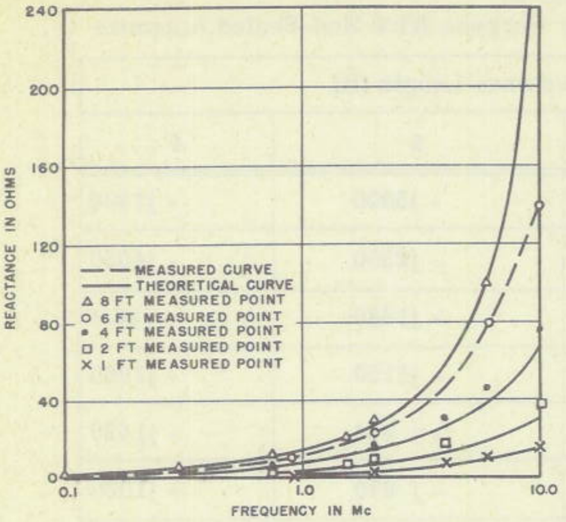

Figure 6 - Measured and theoretical reactance vs. frequency curves for RG-58/U end-exposed antennas

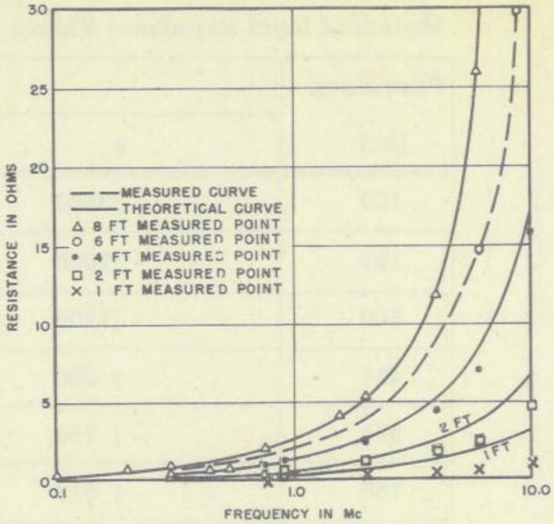

Figure 7 - Measured and theoretical resistance vs. frequency curves for RG-58/U end-exposed antennas

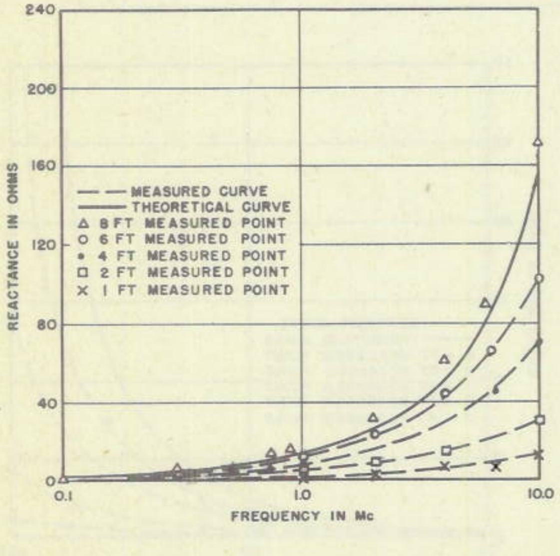

Figure 8 - Measured and theoretical reactance vs. frequency curves for RG-63/U end-exposed antennas

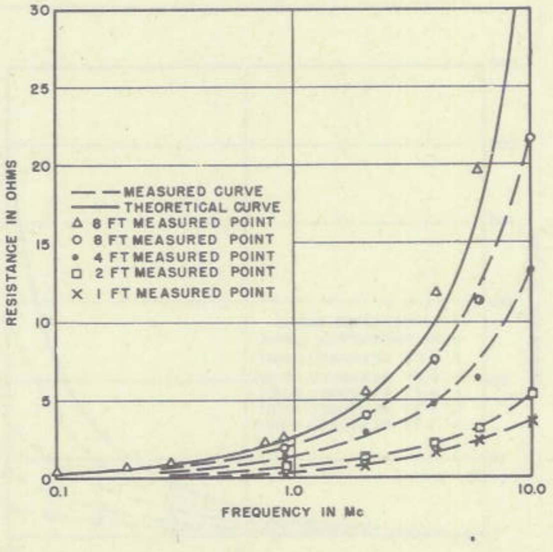

Figure 9 - Measured and theoretical resistance vs. frequency curves for RG-63/U end-exposed antennas

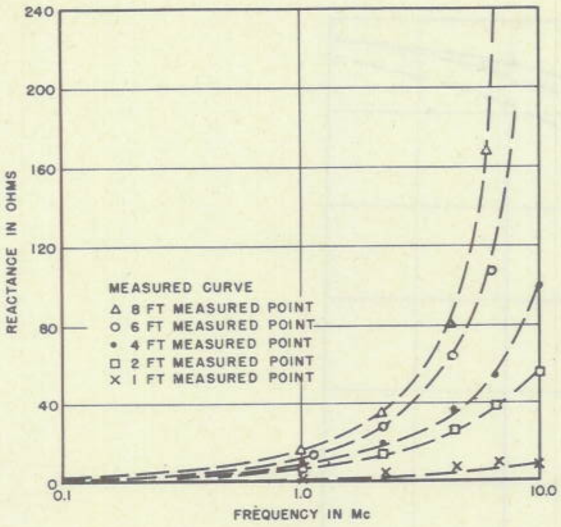

Figure 10 - Measured reactance vs. frequency curves for Burgess wire end-exposed antennas

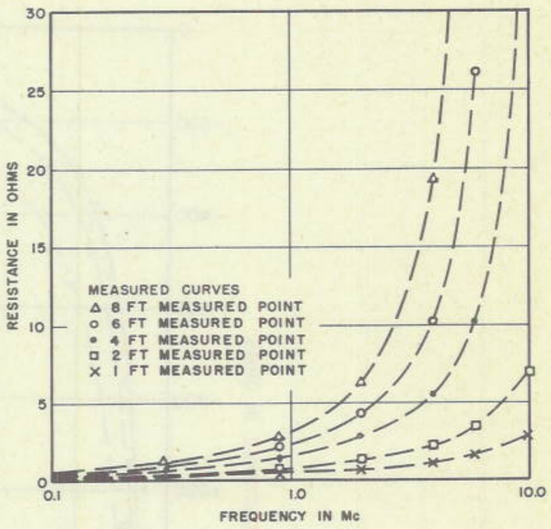

Figure 11 - Measured resistance vs. frequency curves for Burgess wire end-exposed antennas

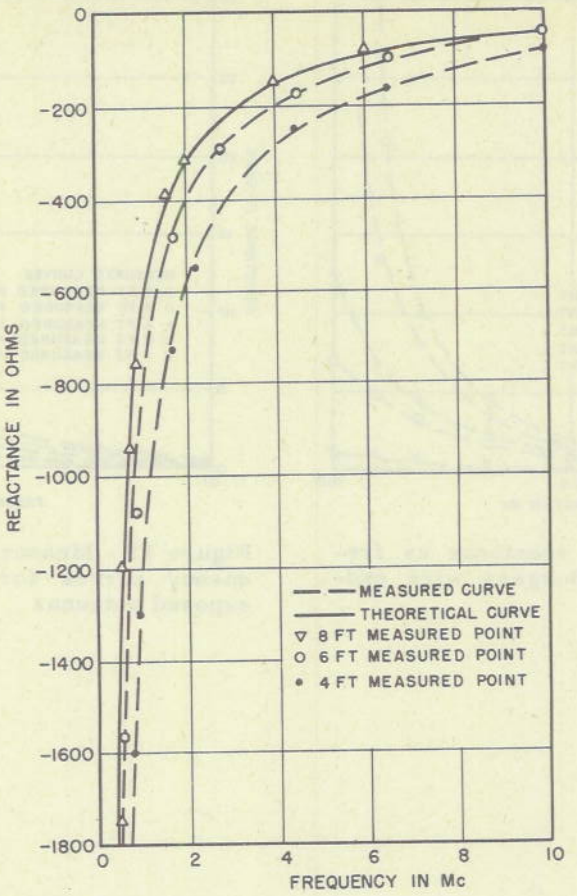

Figure 12 - Measured and theoretical reactance vs. frequency curves for RG-5/U end-sealed antennas

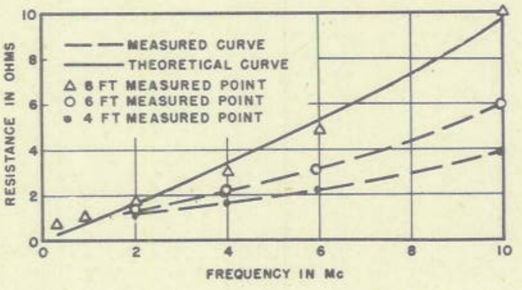

Figure 13 - Measured and theoretical resistance vs. frequency curves for RG-5/U end-sealed antennas

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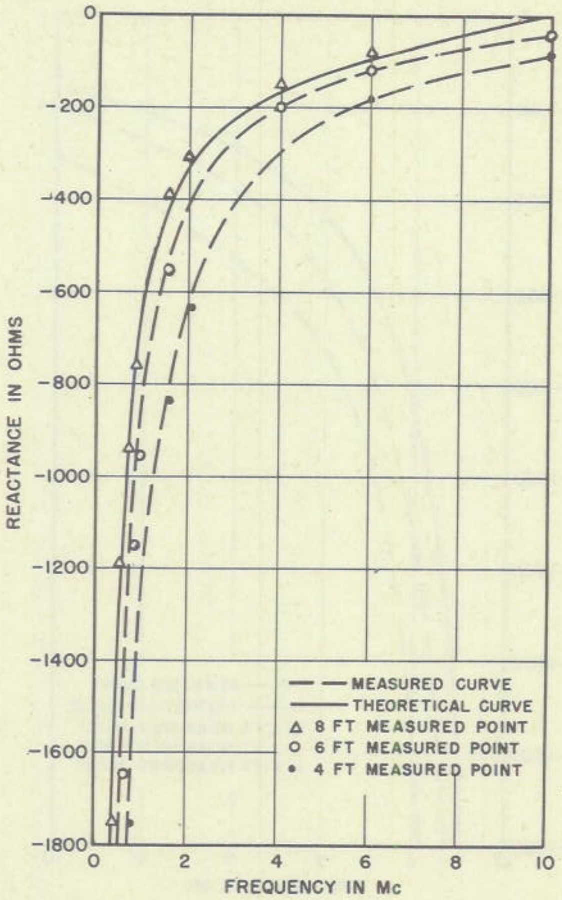

Figure 14 - Measured and theoretical reactance vs. frequency curves for RG-58/U end-sealed antennas

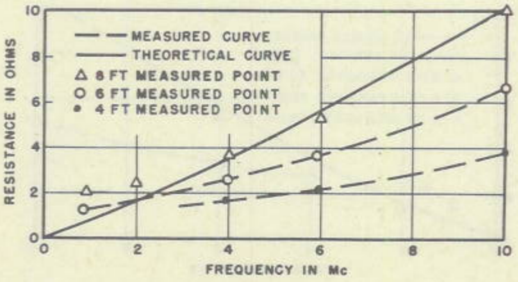

Figure 15 - Measured and theoretical resistance vs. frequency curves for RG-58/U end-sealed antennas

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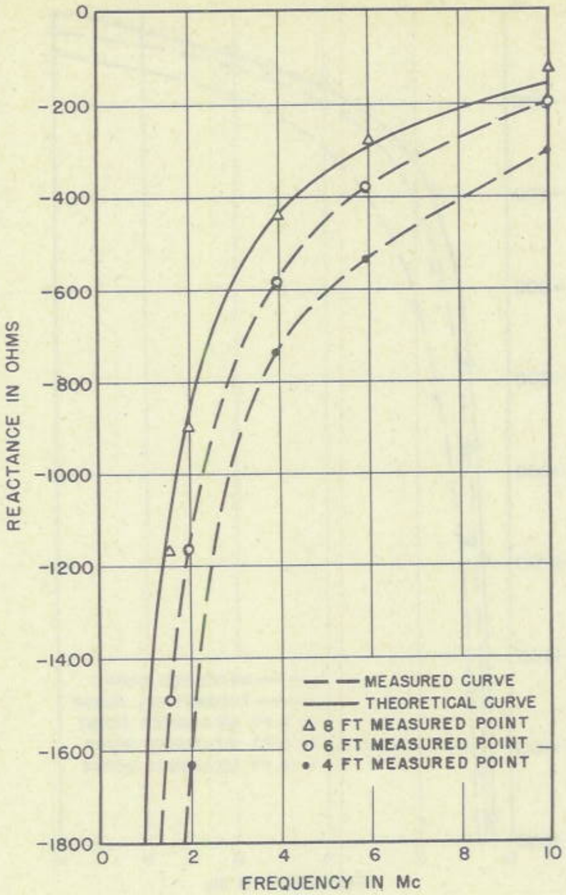

Figure 16 - Measured and theoretical reactance vs. frequency curves for RG-63/U end-sealed antennas

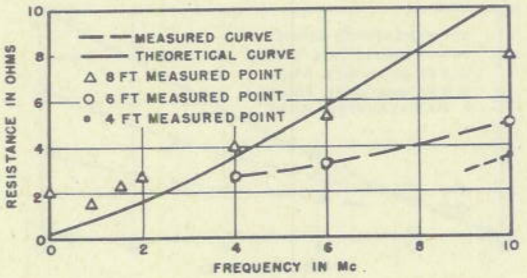

Figure 17 - Measured and theoretical resistance vs. frequency curves for RG-63/U end-sealed antennas

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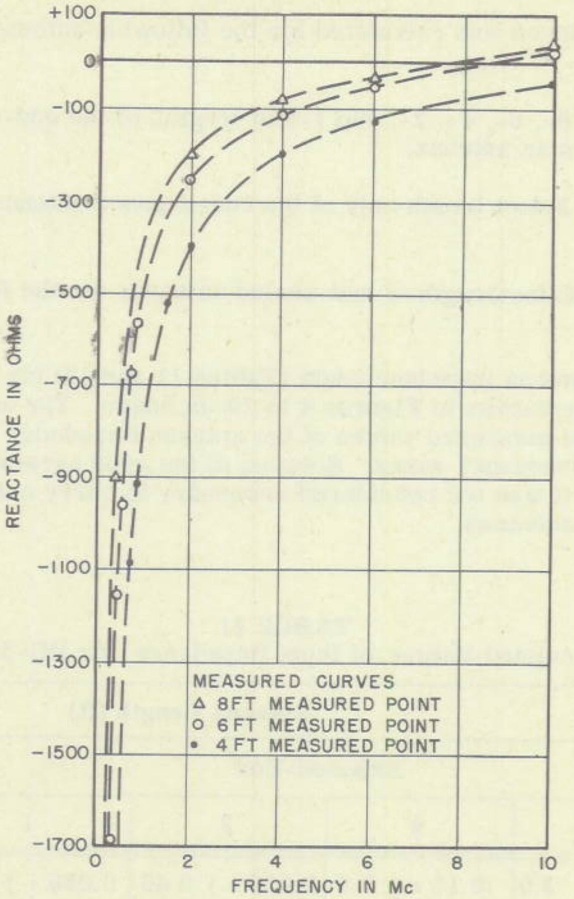

Figure 18 - Measured reactance vs. frequency curves for Burgess wire end-sealed antennas

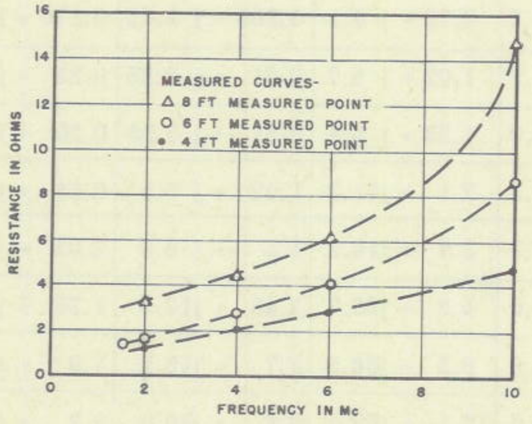

Figure 19 - Measured resistance vs. frequency curves for Burgess wire end-sealed antennas

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The antenna impedance was calculated for the following antennas by the method outlined in reference (1).

(a) For the 8-, 6-, 4-, 2-, and 1-foot lengths of the end-exposed antennas when using RG-58/U cable as an antenna,

(b) For the 8-foot length only of the end-exposed antennas when using RG-5/U and RG-63/U cables,

(c) For the 8-foot length of end-sealed antennas for the RG-5/U, RG-58/U, and RG-63/U cables.

The theoretical antenna impedance data (Tables 11 and 12) for all the above antennas are shown as solid-line curves in Figures 4 to 19 inclusive. The agreement between the theorectical curves and measured values of the antenna impedance is good for all antennas over the 0.1 to 10 Mc frequency range. Because of the good agreement between the theory and experimental data it was not considered necessary to carry out these extensive calculations on the other antennas.

TABLE 11
Calculated Values of Input Impedance for RG-58/U

Frequency (kc)	Antenna Length (ft)				
	Exposed-End				End-Sealed
	8	4	2	1	8
100	0.32 + j 2.0	0.15 + j 0.9	0.076 + j 0.46	0.039 + j 0.25	0.105 - j6630
195	0.55 + j 3.4	0.27 + j 1.7	0.142 + j 0.83	0.068 + j 0.45	0.195 - j3400
300	0.82 + j 4.9	0.41 + j 2.5	0.215 + j 1.24	0.104 + j 0.65	0.282 - j2420
434	1.17 + j 6.9	0.59 + j 3.5	0.305 + j 1.72	0.148 + j 0.9	0.40 - j1530
524	1.38 + j 8.2	0.72 + j 4.1	0.365 + j 2.05	0.178 + j 1.06	0.47 - j1280
750	1.95 + j 11.1	1.02 + j 5.7	0.51 + j 2.85	0.25 + j 1.45	0.66 - j 890
900	2.32 + j 13.0	1.23 + j 6.8	0.61 + j 3.35	0.30 + j 1.7	0.78 - j 740
1550	4.0 + j 21.2	2.1 + j11.2	1.02 + j 5.5	0.51 + j 2.75	1.35 - j 430
2000	5.25 + j 27.2	2.7 + j14.2	1.3 + j 6.9	0.65 + j 3.4	1.75 - j 335
4000	12.2 + j 58.0	5.3 + j26.7	2.48 + j12.8	1.28 + j 4.9	3.6 - j 164
6000	26.0 + j101.0	8.3 + j38.5	3.7 + j18.5	1.9 + j 8.9	5.7 - j 93
10000	215.0 + j496.0	17.1 + j67.5	6.8 + j30.0	3.2 + j14.8	10.8 - j 2.3

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TABLE 12
Calculated Values of Input Impedance for RG-5/U and RG-63/U

Frequency (kc)	RG-5/U 8-ft End-Exposed	RG-5/U 8-ft End-Sealed	RG-63/U 8-ft End-Exposed	RG-63/U 8-ft End-Sealed
100	0.28 + J 1.74	0.095 - j6617	0.34 + j 2.02	0.155 - j17200
195	0.52 + j 3.0	0.17 - j3350	0.58 + j 2.55	0.26 - j 8800
300	0.78 + j 4.3	0.26 - j2200	0.85 + j 4.45	0.36 - j 5750
434	1.12 + j 6.2	0.37 - j1500	1.2 + j 6.2	0.475 - j 4000
524	1.32 + j 7.3	0.45 - j1250	1.45 + j 7.3	0.56 - j 3300
750	1.85 + j 10.3	0.63 - j 870	2.10 + j 10.2	0.68 - j 2310
900	2.22 + j 12.2	0.77 - j 720	2.5 + j 12.2	0.75 - j 1920
1550	3.9 + j 20.5	1.3 - j 420	3.8 + j 20.5	1.25 - j 1120
2000	5.1 + j 26.0	1.68 - j 325	5.1 + j 26.0	1.45 - j 870
4000	12.0 + j 53.0	3.4 - j 153	10.6 + j 52.0	3.6 - j 435
6000	26.0 + j 87.0	5.3 - j 94	16.7 + j 81.0	5.7 - j 290
10000	122.0 + j195.0	9.7 - j 44	42.0 + j155.0	10.5 - j 156

The over-all accuracy of the impedance measurements was about 10 percent and the majority of the experimentally measured points were within 10 percent of the theoretical curves.

The antenna resistance of three different diameter conductors having different dielectric thicknesses is plotted as a function of frequency in Figure 20. It is not until resonance frequency is approached that the resistance of the three antennas becomes appreciably different. This indicates that the diameter of both the conductor and the dielectric sheath does not markedly affect the input resistance. The loss and radiation resistances, which are primary factors in the antenna resistance are, therefore, essentially independent of the diameter of the conductor. The divergence of the antenna resistances near the resonant frequency is dependent on the phase-shift constant, β. This results from the fact that β is a function of frequency and is shown as such in Figure 21.

In considering the performance of these antennas in a communication system, practical limitations require greatest emphasis on short antennas. An electrically short end-exposed antenna has a low Q, a factor which makes it possible for this length of antenna to be employed efficiently in a system due to the low-loss antenna matching network which can be used.

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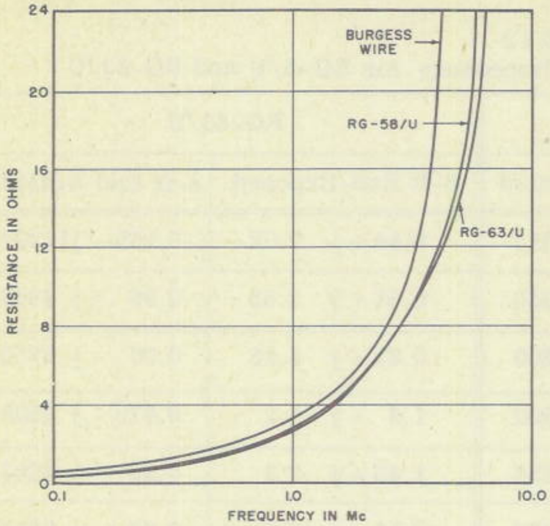

Figure 20 - Measured resistance vs. frequency curves for RG-58/U, RG-63/U, and Burgess wire for end-exposed antennas

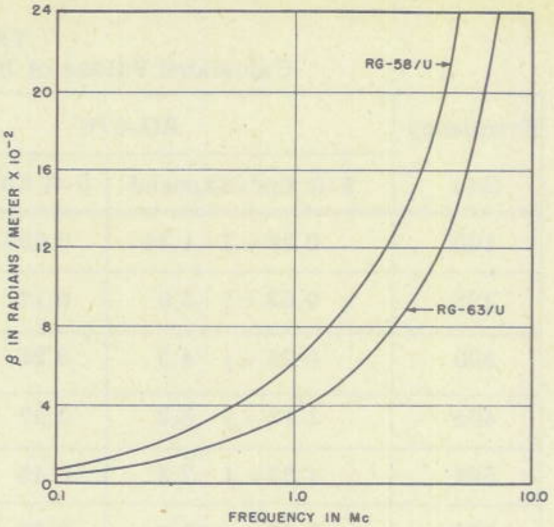

Figure 21 - Phase-shift constant vs. frequency curves for RG-58/U and RG-63/U end-exposed antennas

CONCLUSIONS

It can be concluded that the theoretical formulas for the computation of the resistance and reactance of horizontal-wire antennas, as reported in reference (1), are accurate over the wide range of frequencies and antenna types checked by these experimental measurements.

* * *

REFERENCES

1. Flath, E. H., Jr., and Norgorden, Oscar, "Expressions for Input Impedance and Power Dissipation in Lossy Concentric Lines," NRL Report R 3436 (Unclassified), March 24, 1949

2. Musselman, M. L., "Key West Experiments on Horizontal-Wire Antennas," NRL Report 3841 (Secret), August 6, 1951

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