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Electromagnetic Propagation Between Antennas Submerged in the Ocean

MARVIN SIEGEL AND RONOLD W. P. KING

Abstract—**Experiments are described for determining the distributions of current, the driving-point impedance, and the electromagnetic fields characteristic of dipole antennas immersed in the sea near the surface. Measured and theoretical results are compared at two frequencies with good agreement.**

Introduction

A SERIES of electrical measurements was performed to verify theoretical predictions of the properties of finite antennas submerged in the Atlantic Ocean [1]. Experiments were conducted with both the transmitting and receiving antennas located beneath the water surface at two field sites in Maine. Measurements of electric field strength, antenna current distribution, and antenna input impedance were compared with theoretical predictions at two widely separated frequencies, 100 kHz and 14 MHz. The higher frequency, 14 MHz, was chosen deliberately (despite the severe attenuation in sea water) to examine experimentally the fields in the "intermediate range" as well as the near field [2], [3]. In addition, array applications are easier to demonstrate at the higher frequencies because of the smaller physical dimensions required.

The instrumentation and equipment used in this experiment had to be capable of operating when totally submerged. Since all the measurements had to be performed over a large body of deep water, unusual restrictions were imposed on the design of the experiment. Thus in addition to discussing the specific antennas and propagation experiments associated with submerged antennas, this paper is also directed toward illuminating the practical problem of conducting electrical experiments in the ocean environment.

A laboratory and field program was undertaken to confirm experimentally asymptotic and numerical solutions for the electric fields of short dipoles and longer antennas in a dissipative half-space. Previous quantitative measurements to verify the approximate solutions for the field vectors have either attempted to verify only the slope of the far-field pattern at the water surface, or have been performed in relatively small tanks on frequency-conductivity scaled models. This experimental

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investigation was designed to be performed in the Atlantic Ocean at two widely separated frequencies (100 kHz and 14 MHz) in order to correlate the measured absolute value of the electric field with theoretical predictions. The higher frequency was chosen in order eventually to demonstrate arraying effects as well as to examine the fields in the intermediate region. (For reference to other experiments in sea water, see [8]–[10].)

To perform this experiment high power transmitters (up to 500 W CW) were required. Both the transmitter and transmitting antenna and the receiver and receiving antenna were submerged in the Atlantic Ocean. To carry out a program of radiation measurements it was necessary to do the following.

1) Design two complete high-power transmitters and sensitive receivers, one transmitter and receiver system at each frequency. Both the transmitter with its transmitting antenna and the receiver with the receiving antenna had to be designed to permit accurate calibration and monitoring while they remained totally under water.

2) Design support structures (rafts) capable of independently suspending transmitters and receivers at various depths, ranges, and orientations.

3) Characterize experimentally and analytically the impedance properties of short dipoles and longer antennas in sea water at the two selected frequencies and design suitable matching units for maximum power transfer.

Site Locations

The experiments to be described were performed in three different locations, one laboratory site and two field sites. The laboratory site included a sizable tank (10 ft × 7.5 ft × 2 ft) filled with "synthesized" sea water. This tank was useful making preliminary measurements related to impedance matching, current distribution and near-field radiation even under high power. In addition, all physical aspects of the water seals and pressurizing schemes were evaluated first in this tank before being placed into field use.

The other two sites were located in Maine; one at Rockport Harbor where deep water was readily accessible by a little-used long polyfoam floating dock, and the second, a tidal basin near Waldoboro, which had the advantage that adjustments and changes could be performed easily on the experimental apparatus when the tide receded, and the experiment run when the tide came in. Since over 1000 ft of polypropylene rope was available for the control and guidance lines, the experiment could be performed over considerable ranges in deep water. Both Maine sites had the advantages of relative isolation and little interference (both low electrical noise and low water-traffic density).

At the field sites the transmitter float (Fig. 1) was located about 30 ft off the shore line; anchor points were established up to 1000 ft into the deep water and parallel ropes were stretched between the anchor points and the transmitter location. The receiver float (Fig. 1) was arranged so that it could be guided between the parallel ropes using a third marker rope as a range measuring device. Proper antenna orientation and accurate range determination (accuracy to one third of a foot along the water surface) were ensured using this method. Field strength measurements were made from a small five-man inflatable life raft running parallel to the receiver float but sufficiently remote to minimize reflections and interference. The conductivity and relative dielectric constant of the water at all field sites were electrically tested at the field temperature.

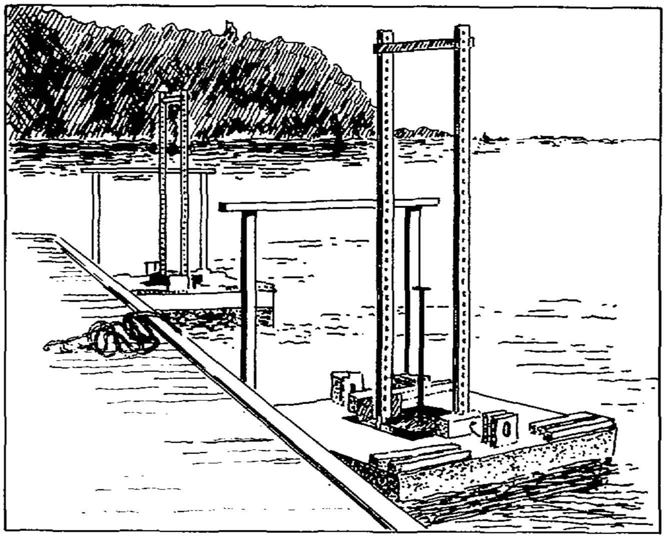
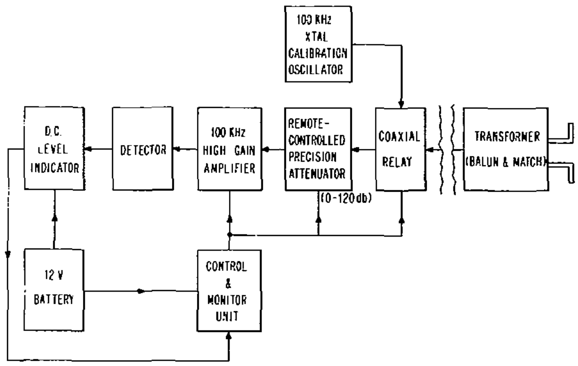


Fig. 1. Polyfoam rafts supporting antennas and electronics systems.

Physical and Electrical Design of Instrumentation

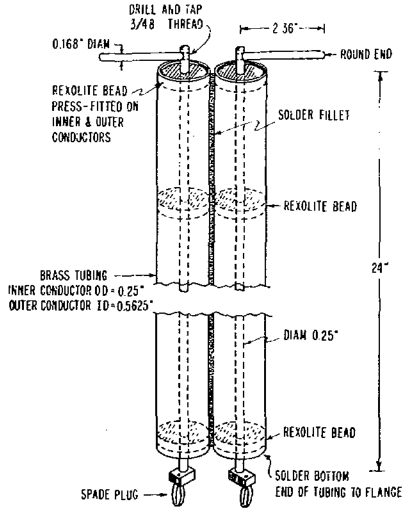
In the experiments all cables were deeply submerged, and the detector, the mixer, and the rest of the receiver were mounted directly behind the receiving antenna. Therefore, only an intermediate frequency much lower than the signal frequency was carried by cables to the surface for purposes of measurement. The entire transmitter was designed so that it could be enclosed in a stainless steel drum which was RF by-passed and then pressurized and water sealed to make it capable of being lowered if necessary to the ocean floor. It was felt that these attempts to minimize stray radiation and unbalanced currents, to provide "Gaussian surfaces" around the transmitters and to provide RF bypassing on power and control lines would greatly assist in making accurate determination of the electromagnetic field.

An additional difficulty in obtaining accurate field measurements is the necessity of maintaining overall linearity over the expected wide dynamic range (70 to 80 dB). The technique used to achieve linearity also allowed the receiver to be calibrated and sensitivity checks to be made while the entire transmitting–receiving system was submerged. A remote-controlled motorized precision attenuator was inserted behind the receiving antenna together with a coaxial remote-controlled RF



100 KHz RECEIVER

Fig. 2. Block diagram of 100-kHz receiver.



DIPOLE ANTENNA AND FEED SYSTEM

Fig. 3. Dipole antenna and feed system.

switch and a calibrated crystal-controlled oscillator (see Fig. 2). Whenever it was desired to check the performance of the receiving system from the surface, the calibrated oscillator would be switched into the receiver. Whenever actual field measurements were being made, the antenna would be switched into the receiver, and the signal level at the receiver would always be adjusted to the same level by using the remote-controlled attenuator. In this manner the mixer and remaining portions of the receiver are ensured of operating at the same operating point regardless of the signal level at the antenna. Thus signal strength is proportional to the attenuator reading and linearity is assured over a wide range of input signal levels.

The experiment's mechanical design centered around the supporting rafts and the brass cylinders containing the electronics (matching units, receiving and transmitting components, etc.). The rafts for the transmitting and receiving antennas are shown in Fig. 1. They consisted of 4-ft squares of polyfoam, 6-in thick, upon which was cemented a marine plywood cover. A square hole (1 ft on a side) was cut in the center, through which was passed a wooden support structure to raise and lower the electronics cylinders; the range of depth adjustment from the top of the antenna to the water surface was zero to 29 in in 1-in steps. This center support frame could readily handle the 50- to 75-lb brass electronics containers.

The waterproof containers for the electronics consisted of brass cylinders, 9-in diameter, 24-in long and $\frac{1}{8}$-in thick. The diameter was determined by the largest item (the motorized attenuator), the length by the number of components, and the thickness by the necessity of a water-tight seal. The electronics were mounted on a wooden "bread board" and different boards were assembled for use at each frequency. Two brass end flanges with circular grooves were placed on each end and fastened by stainless steel rods parallel to the cylinder. Silicone rubber sealant and adhesive was poured into the groove and served as an effective gasket, never leaking though subject to repeated dismantling.

All cables (power, control, and RF coaxial cables) had their own vinyl covering and were passed through the end plates by brass vacuum fittings, used as "feed-throughs." When the fitting was screwed down, a doughnut shaped insert was compressed around the cable to establish a leak-free effective means to control, monitor, and power the underwater cylinders. Since a single leak in any cylinder could prove catastrophic, it was decided to pressurize all the cylinders and cables. To accomplish this, air valves were installed on the sides of all cylinders. With the cylinders maintained at a positive pressure (10 psi) by means of a hand pump, a leak would be revealed by escaping air bubbles. Sufficient air was stored so that time was available for raising the leaking cylinder before essential components became wet. fortunately, all the seals proved to be effective in holding air in and water out.

The actual radiating (and receiving) dipole was located a short distance away from the brass cylinder containing the electronics to minimize reflections and interference. A 20-in long twin coaxial transmission line was used to feed the balanced dipole, one coaxial line for each half of the dipole (see Fig. 3). Difficulties were experienced at first with the water-sealing of the junction region between the dipole sections and the coaxial feeder lines. (For example, the feed regions of the dipole antennas were encapsulated in a waterproof dielectric, but they deteriorated after a few days of operation at the 300 W power level under the heat and stress of the high RF currents circulating in the sea water near the feed region.) It was actually possible to boil continuously the sea water if the feed gap was not made sufficiently large. High-power water-tight joints were finally made possible by press-fitting low-loss dielectric beads into the gap region.

Both transmitting and receiving antennas with their matching units were installed on similar containers and suspended from similar rafts. Since the RF power generation equipment was too large to be contained in these electronics cylinders, it was contained in a pressurized

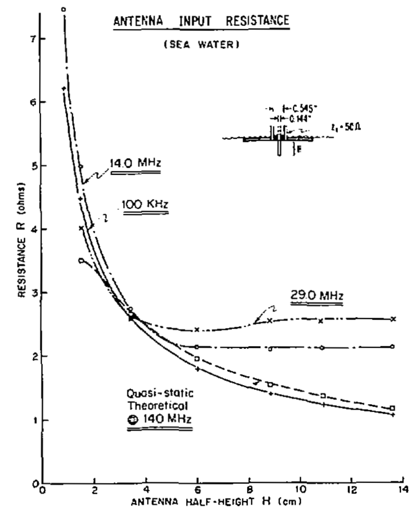


Fig. 4. Antenna input resistance versus antenna half-height (sea water).

55 gal stainless steel drum which could be totally submerged. Each transmitter (14 MHz, 100 kHz) was placed on a removable board designed for easy installation in the drum. Prime power for the transmitter was provided by a gasoline driven generator, and for the receiver by a 12-V storage battery. Thus the experiment could be performed in isolated areas.

In the main, considerable satisfaction was experienced with the mechanical design of the equipment judging by the ruggedness, durability and interchangeability of all components. A variety of hydraulic problems were solved by the selective use of O rings, RTV sealant (General Electric), vacuum fittings, and pressurization.

Short Antenna and Antenna Feed System

In order to validate experimentally theoretical solutions that had been derived, it was important to use transmitting and receiving antennas having a known dipole moment derivable from a known current distribution. Considerable investigation, both experimental and theoretical, has been performed on short dipoles immersed in an infinite dissipative medium [4]–[6]. In sea water, the antenna's electrical behavior (input impedance and current distribution) is little influenced by the medium a short distance away. Provided the antenna is submerged a sufficient distance, electrically, below the surface, the current distribution and input impedance for a dipole in a highly dissipative *half-space* will be little changed from those existing in an *infinite* medium. Actual ocean measurements confirmed this. King has shown [4, p. 16] that, for electrically short dipoles in sea water, the current distribution is essentially triangular.

$$I(z) \doteq I(0)\left\{1 - \frac{|z|}{h}\right\}$$

where $I(0)$ is the current at $z = 0$, the driving region; z is the distance along the antenna; and h is the half-height of the antenna. Expressions for the conductance G_0 and susceptance B_0 of the input admittance $Y_0 = G_0 + jB_0$ are:

$$G_0 \doteq \frac{4\pi\beta h}{\zeta_e[2\ln(h/a) - 2]},$$

$$B_0 \doteq 4\pi\left\{1 + \frac{1.08}{[2\ln(2h/a) - 3]}\right\}$$

where $\zeta = \omega\mu/\beta$, β is the phase constant and a is the radius of the antenna.

In sea water the conductance term is considerably larger than the susceptance term. By substituting the parameters of the short dipoles used in the experiment ($h = 6 \times 10^{-2}$ m, $a = 2.14 \times 10^{-3}$ m) the following results are obtained from the formulas or curves in [4]:

$$f = 10^5 \text{ Hz}$$
$$G = 3.24 \times 10^{-1} \text{ mho}$$
$$B = 1.488 \times 10^{-3} \text{ mho}$$
$$f = 1.4 \times 10^7 \text{ Hz}$$
$$G = 3.24 \times 10^{-1} \text{ mho}$$
$$B = -2.08 \times 10^{-1} \text{ mho.}$$

Note that in both cases the current distribution for electrically small antennas is essentially triangular and the input impedance is predominantly resistive and quite low (a few ohms). Because of this low input impedance some difficulty was expected in impedance matching between the antenna and the transmitter or receiver. To confirm these results, the impedance of a coaxially fed short monopole operating beneath a ground plane immersed in water was measured. Fig. 4 shows the variation in input resistance as a function of antenna length at the various frequencies of interest. The high-frequency measurements (at 14 and 29 MHz) were made with a Boonton RX meter, type 250A (transforming into the range of the meter using a section of rigid coaxial line); these measurements were later verified with a Vector Voltmeter (Hewlett-Packard 8405A) arranged to read impedance. The low frequency measurements used a RF bridge (General Radio 916-AL) and a tuned amplifier null detector (General Radio 1292-A). Note that the measurements shown in Fig. 4 are for monopoles; dipoles would have twice the input impedance.

Baluns and Impedance Matching

Although the impedance matching problem is important especially under high power, the balancing problem is also very important in preventing the entire system from carrying unbalanced circulating currents which would interfere with proper measurements. At 100 kHz the impedance matching and balancing were accomplished simultaneously by means of a transformer. A ferramic toroid (Indiana General, 0–5 material) was used as the

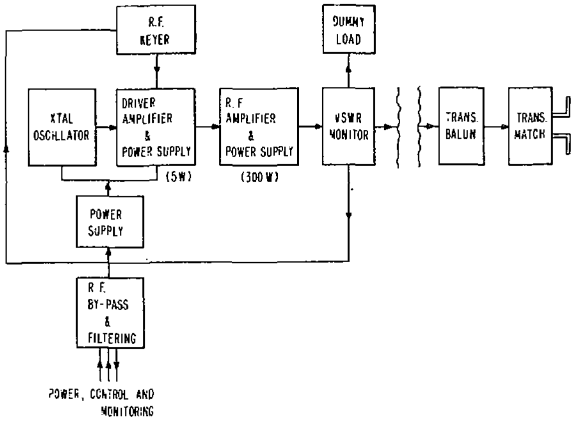


Fig. 5. Block diagram of 14-MHz transmitter.

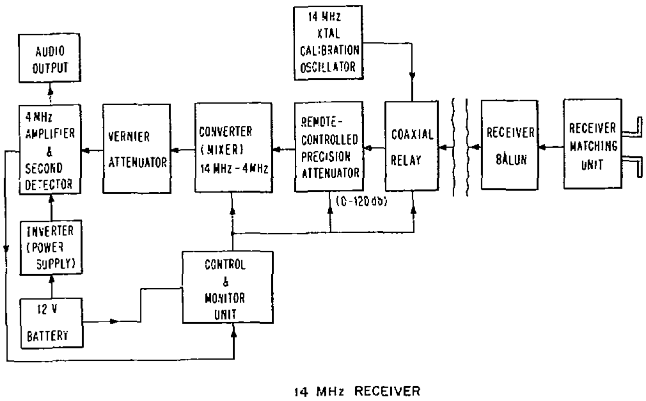


Fig. 6. Block diagram of 14-MHz receiver.

core, tightly wound with #14 magnet wire (31:9 turns ratio). Careful placement of the secondary winding symmetric with respect to the unbalanced primary's grounded side assured a well-balanced excitation to the dipole. The balance between the dipole halves was monitored by submersible probes and an oscilloscope (Tektronix 545) while the dipole was under water. In addition, the input impedance looking into the primary of the transformer was 50 Ω to within 1 percent (after the transformer primary reactance was tuned out). This transformer was capable of handling 200 W of RF power without overheating.

The 14 MHz matching and balancing network utilized a pseudo-transmission-line three-wire coil (balun) wound on a ferramic core (Indiana General, Q-2 material) to act as a 1:1 balun, and a pair of "back-to-back" Pi networks to match the 50-Ω impedance to the low input impedance of the immersed dipole. Actual measurements made at 14 MHz using the vector voltmeter confirmed that the balance was good to within 5 percent using standard component values.

Considerable care and effort went into the design of the baluns, matching networks, and the physical and electrical symmetry of the components. Electrical imbalance could cause currents to circulate on the outer shields of coaxial lines and underwater containers thereby placing in error all estimates of effective dipole moment and also providing a mechanism for extraneous fields to leak into the receiver. All matching units and baluns performed well even under high power; the only difficulty occurred in foggy weather when trimmer capacitors would "arc-over" at the 300–400 W level. Diagrams of the 14 MHz transmitter and receiver are shown in Figs. 5 and 6.

Experimental Measurements

All measurements were recorded in dB below the calibrated reference oscillator in the receiver (100 kHz, 2.21×10^{-5} W and 14 MHz, 5.52×10^{-4} W). The method chosen to normalize all theoretical and experimental results was as follows. The equivalent dipole moment of the transmitting dipole was determined from a knowledge of dipole input impedance, the antenna current distribution and the transmitter RF power (verified by antenna-gap voltage measurements). The effective field outside the receiving antenna was determined in the experimental cases by using: 1) knowledge of the dipole input impedance, 2) receiving antenna theory [7, pp. 465–470] (assuming a uniform external field along the short antenna), and 3) the equivalent voltage of the receiver derived from comparisons of meter readings in the receiver and the internal calibration oscillator. In the theoretical cases, the solutions (numerical and asymptotic) gave directly the field outside the receiving dipole.

To examine the type of behavior that is expected, two of Baños' [2] explicit formulas for the radial component of the electric field are presented. The experiments that were performed were designed by choice of frequency and horizontal range to extend over the near-field and intermediate-field formulas.

Near field:

$$E_{1r} \sim \frac{P_{1x} \cos \phi}{2\pi \xi r^3} \exp\left[ik_1(z + z_0)\right].$$

Intermediate field:

$$E_{1r} \sim \frac{P_{1x} \cos \phi}{2\pi \xi r} (-k_2^2) \left[1 + \frac{ik_2}{k_1}\left(\frac{\pi i k_2 r}{2}\right)^{1/2}\right] \cdot \exp\left[ik_2 r + ik_1(z + z_0)\right].$$

where $p_{1x} = iI(0)(\Delta x/\omega)$ is the classical Hertzian dipole [$I(0)$ is the current at the driving point, Δx is an infinitesimal height], $\xi = \epsilon + i\sigma/\omega$ is the complex dielectric constant, k_2 is the wavenumber in air, k_1 is the wavenumber in sea water, z is the depth of submergence of the receiver, and z_0 is the depth of submergence of the source (transmitter).

From the near-field formula, $\log |E_{1r}|$ versus $\log r$ should be a straight line (slope equal to -3) with its axis intercept easily determined from the constants. Alternatively, for a fixed range r, a depth test can be

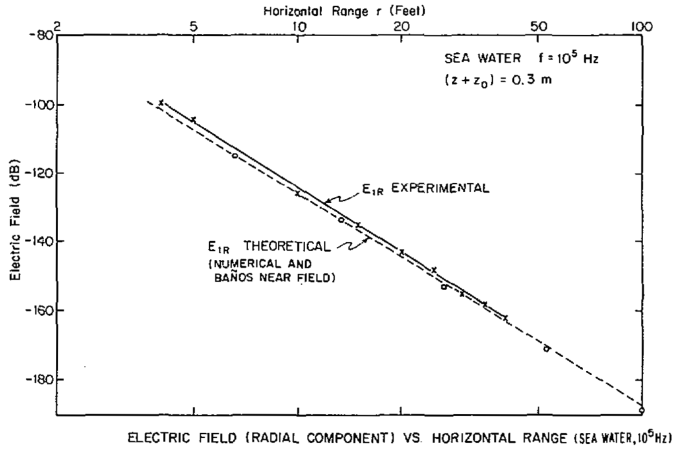


Fig. 7. Electric field versus horizontal range (radial component, 100 kHz).

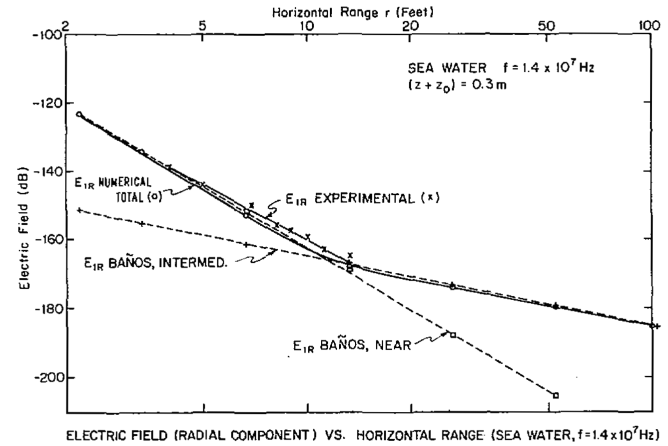


Fig. 9. Electric field versus horizontal range (radial component, 14 MHz).

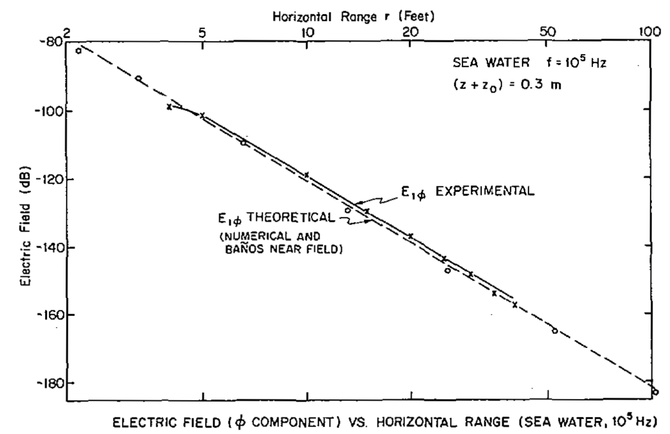


Fig. 8. Electric field versus horizontal range (azimuthal component, 100 kHz).

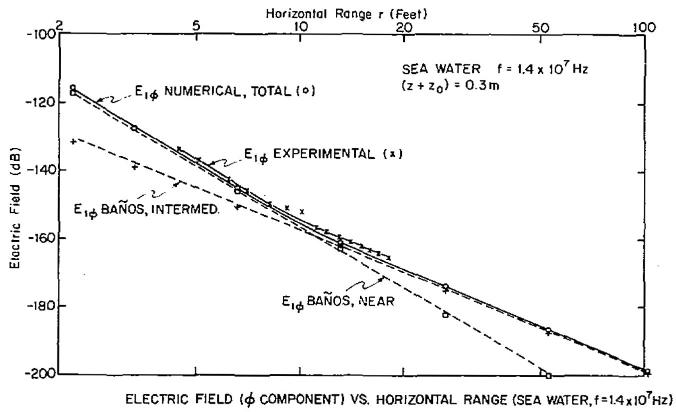


Fig. 10. Electric field versus horizontal range (azimuthal component, 14 MHz).

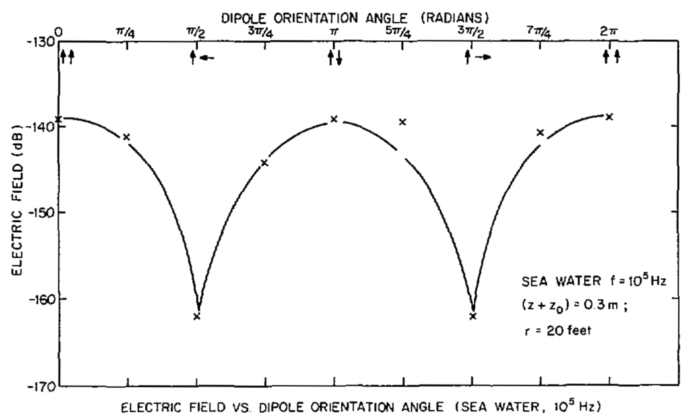


Fig. 11. Electric field versus dipole orientation angle (100 kHz).

performed and a graph of $\log|E_{1r}|$ versus $\log(z + z_0)$ constructed. The curve is also a straight line with a slope $0.434(z + z_0)\,\mathrm{Im}\,(k_1)$. Note that the logarithmic curves conveniently display the exponential behavior and the inverse power behavior as straight lines. In addition to the experimental results, the theoretical results, both from asymptotic solutions and from numerically integrated solutions, are presented for comparison.

It should be noted that sea water measurements, especially at the higher frequencies, are difficult to perform due to an extreme sensitivity to minor variations in depth (or waves); at 100 kHz the change in electric field with depth of submergence $\Delta E_{1r}/\Delta(z + z_0) = -0.109$ dB/cm, at 14 MHz $\Delta E_{1r}/\Delta(z + z_0) = -1.28$ dB/cm. A 4-in wave over the transmitter or receiver dipole at 14 MHz causes a 10 dB variation in received signal! Extreme care (and calm seas) are required.

Figs. 7 through 10 display the magnitudes of E_{1r} and $E_{1\phi}$ versus horizontal range for transmitting and receiving dipoles, each submerged 0.15 m. Note the generally good agreement between measured and theoretically predicted values. In particular, note the agreement (Fig. 10) between the experimental results and both near field and intermediate field theoretical predictions in the transition region (2 to 4 m) between near and intermediate fields. Over the first part of the range Baños' near field formula is valid; over the final part the intermediate formula applies.

Fig. 11 shows a graph of electric field versus dipole orientation angle ϕ at a fixed range $r = 20$ ft, a fixed depth $z = z_0 = 0.15$ m. Again the sinusoidal behavior

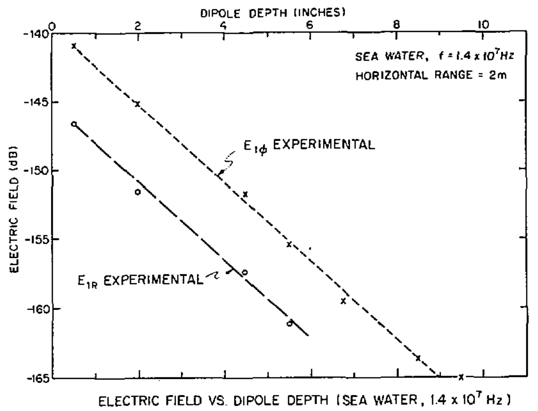


Fig. 12. Electric field versus dipole depth (14 MHz).

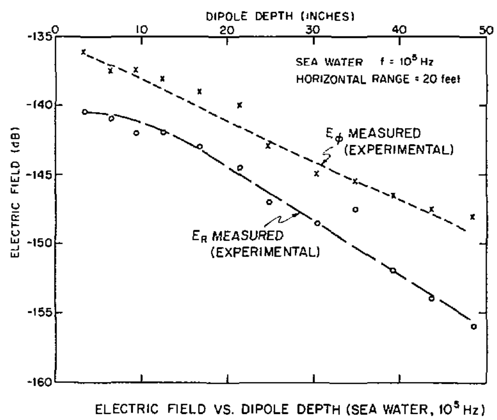


Fig. 13. Electric field versus dipole depth (100 kHz).

(with a 23-dB null) agrees well with theoretically predicted values.

Figs. 12 and 13 display graphs of electric field strength versus depth of submergence for the E_r and E_ϕ components at the two frequencies (14 MHz, 100 kHz). In the depth measurements, "reciprocity" tests confirmed that the radiation path did not include stray paths, i.e., the attenuation resulting from lowering the transmitter with the receiver depth fixed agreed exactly with that obtained by lowering the receiver with the transmitter depth fixed.

Conclusions Concerning Dipole Measurements

It has been shown that at both 14 MHz and 100 kHz in sea water, very fine experimental confirmation of asymptotic formulas in their regions of validity and numerical results has been obtained. The slopes of all the respective curves match to within a reasonable experimental error, thus verifying range and depth dependence predicted by theoretical solutions. In addition very favorable *absolute* comparisons of the theoretically determined and experimental curves indicate that the assumed model of an electrically short dipole (and dipole behavior) is a proper one, and practical results can be obtained by using asymptotic or numerical solutions over a wide range of frequencies. The absolute amplitudes of the radial and azimuthal components were related by the predicted factor of 2 (6 dB).

In addition to presenting some of the experimental results on submerged antennas and comparing these with theoretical predictions, the practical problems associated with electromagnetic measurements in the ocean have been discussed.

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