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Final Scientific Report

ANTENNAS IN DISSIPATIVE MEDIA AND IN SUBSURFACE COMMUNICATION

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GOALS

The researches under this Contract have sought to provide new quantitative information about the properties of transmitting and receiving antennas and arrays when immersed in or located near a general dissipative medium like the earth, the sea, a large lake, the sand of a desert, arctic terrain consisting of snow and ice, or a living organism. Primary emphasis has been placed on the problems associated with subsurface communication between missile sites, submerged submarines, divers, and observers in mine shafts but significant new information has also been obtained relating to over-the-surface communication, radiation hazards in biological systems, and plasma diagnostics.

The specific research goals have been centered on the determination and optimization of the conditions underlying electromagnetic communication between antennas located beneath the surface of the earth including sea and lake water, soil ranging from very moist to very dry, sand, rock, snow and ice. The investiagtions have been concerned with the following principal problems:

A. The direct measurement of the electrical properties of the media of interest.

B. The selection and design of suitable directive antennas.

C. The quantitative characterization of the properties of these antennas as circuit elements when embedded in any one of the constituent materials of the earth's crust. This has involved primarily the determination of the distributions of current and charge per unit length since the complete electromagnetic field and the driving-point admittance can be evaluated from them.

D. The theoretical determination of the electromagnetic field at the location of the receiving element due to the currents in the transmitting antenna when both are embedded in the earth near its boundary with air. For purposes of comparison the direct measurement of the electric field of an actual transmitter at distant points in the earth is also of interest.

E. The specification of the voltage across the load of the receiving antenna in the dissipative medium in terms of the electromagnetic field maintained at its location by the distant transmitting antenna. The determination of the over all gain and efficiency of the system as a function of the frequency with the properties of the earth as parameters.

F. An answer to the question: With the most directive transmitting and receiving antenna that can be designed, under what conditions and over what distances is point-to-point subsurface communication practical in the several materials encountered in the earth's crust ? Relevant parameters are the frequency, the depth of the antennas below the surface, the electrical properties of the materials, the required power level and its possible environmental impact.

ACHIEVEMENTS

The accomplishments and present status of the research effort are best summarized in their relation to the six principal problems listed above, the chronological list of actual and projected publications resulting from work initiated under this Contract, and a list of closely related supplementary references.

A. In order to predict and understand the behavior of any antenna embedded in a dissipative medium it is necessary to know the actual values of the electrical constitutive parameters of that medium. For this reason and in order to fill a general need for a simple, direct method for measuring the in situ electrical properties of various parts of the earth's surface, a new procedure has been developed and tested [Smith and King, 6] that makes use of a bare resonant monopole as a probe. From measurements of its length and resistance at resonance when immersed in the medium of interest, the relative permittivity and loss tangent of the medium are obtained. The theory of the new method is based on the earlier work on the bare monopole in a dissipative medium [King and Scott, 27].

B. The selection of an antenna with the special properties required to make it suitable for subsurface communication posed a difficult problem. Its solution required extensive theoretical and experimental studies of the characteristics of a number of possible and quite different elements. These included the bare and insulated dipole, the bare and insulated loop, and the cavity-backed slot. Complete data on the bare dipole were available [King and Scott, 27], as were those of the bare loop antenna [King and Harrison, 31]. New theoretical and experimental studies of the properties of the insulated loop antenna in a general medium were carried out [Smith, 3 and 20]. An investigation of the cavity-backed slot antenna [Long, 32, 33, and 34] in air was made; extension to the slot in a dissipative medium has not been undertaken to date. On the basis of these researches, the work of Baños [35], and the very extensive investigations of the insulated dipole described below, this last named antenna was selected as the most versatile and generally useful element. This does not imply that for special purposes the other types do not have useful applications. A general review of the remarkable properties of the insulated dipole has been completed [King, 15]; its application to the problems of subsurface communication is summarized in the following pages. Of particular interest are its novel, eccentric form and its use as a traveling-wave antenna.

C. At the outset of the researches under this Contract the insulated antenna had been treated only as a coaxial line with a highly conducting outer region, a condition that applied primarily to insulated wires in sea water. The first major contribution under this Contract was the development of a new and much more general theory of the insulated antenna [Wu, King, and Giri, 4] which permitted the outer region to be a dielectric or a conductor so long as its wave number was large compared with that of the insulating layer. The accuracy of this theory and the broad scope of its validity were verified in a comprehensive series of measurements that made use of a newly developed technique [Scott and Smith, 1; Lee and Smith, 13] for providing a dissipative medium that was effectively infinite in extent but had a wide range of readily varied electrical properties. The measurements included distributions of current and charge per unit length of insulated monopoles over a wide range of lengths, thicknesses of the insulation, and electrical properties of the insulator and of the ambient medium [King, Lee, Mishra, and Smith, 5 and 10; Lee and Smith, 13]. An interesting observation was that the attenuation of the current on an insulated antenna in lake water due to radiation exceeded that due to dissipation as heat in sea water. As a consequence an antenna only a wavelength long with an insulation of proper thickness behaved like a traveling-wave antenna without termination. Extensive studies of the driving-point admittance and of the associated junction problems were also made [King, Lee, Mishra, and Smith, 11]. Very good agreement between measured and theoretical quantities was obtained and the new theory with its simple transmission-line form was shown to be quantitatively reliable under all conditions.

A generalization of the theory to include ambient media with wave numbers that need not be large compared with that of the insulator is almost complete, [Lee, 24]. It consists of a numerical approach with a program that evaluates the relevant properties of the antenna and of a simple formula that is an adequate approximation under most conditions. The theory has also been extended to include insulated antennas terminated in bare, quarter-wave monopoles, [Lee, 16]. These provide effectively longer antennas with unidirectional currents.

A second major contribution was the invention and analysis of the eccentrically insulated antenna. A complete theoretical treatment of this novel structure has been given [Wu, Shen, and King, 9] together with an experimental verification of its circuit properties [Mishra and King, 12]. This antenna has special significance as an element in directional arrays of insulated antennas and as a traveling-wave antenna for lateral-wave transmission.

A third major contribution (which has an important bearing on over-the-surface and over-the-horizon transmission) is the extension of the generalized theory of the eccentrically insulated antenna to the horizontal-wire antenna over the earth [King, Wu, and Shen, 7] and to the Beverage wave antenna [Sorbello, 18]. This is the only available theory of these antennas that correctly includes the effect of the properties of the earth on the attenuation and phase constants of the current on the antenna. It also specifies the restrictions on the applicability of the transmission-line form which characterizes the properties of the Beverage antenna.

The use of insulated antennas in directional arrays requires an analysis of coupled insulated antennas in a dissipative medium. This is quite different from conventional coupled antenna theory. This is apparent in the theory of a circular array of insulated antennas [King, Shen, and Wu, 14] which shows that each phase sequence has a different wave number for the current. A comparison with measurements has been carried out with good agreement [King, Mishra, and Shen, 25]. An extension of the theory to linear and planar arrays is anticipated.

Another very important contribution which evolved from the general theory of the insulated antenna [Wu, King, and Giri, 4] is in the field of plasma diagnostics. At frequencies not too far from the plasma frequency, the distributions of current and charge per unit length along an antenna immersed in a finite plasma contained in a glass tube can be determined from the generalized theory of the insulated antenna in a manner that takes full account of the finite radius of the plasma column and of the thickness and dielectric constant of the glass container, [King and Ward, 8]. This is the first and only available analysis of an antenna in a finite rather than an infinite plasma. It is quantitatively accurate for cold plasmas.

D. The electromagnetic fields of insulated antennas in infinite dissipative media are well known [King and Harrison, 31]. They involve only direct transmission through the medium and do not include the effects of the earth-air boundary. The fields of infinitesimal electric and magnetic dipoles near such a boundary have been analyzed [Baños, 35]. They depend on lateral-wave as well as direct transmission. Their evaluation depends on complicated complex integrals (Sommerfeld integrals) which can be simplified for certain restricted ranges of the parameters to yield approximate formulas for the near field, the intermediate field and the far field [Baños, 35]. Unfortunately, these formulas do not overlap but are separated by wide regions for which the general integrals must be evaluated. This has been done numerically [Siegel and King, 28] for infinitesimal dipoles in sea water and extended to resonant antennas of finite length and terminated, traveling-wave antennas [Siegel and King, 29]. The numerical results were compared with the approximate formulas of Baños [35] where these are valid and also with direct measurements on antennas in the ocean [Siegel and King, 2 and 29] with good agreement.

The numerical evaluation of the Sommerfeld integrals for media other than sea water presented great difficulties. These have now been overcome and complete sets of data on the electromagnetic fields of infinitesimal dipoles have been computed not only for sea water but also for lake water and dry earth. For these the transmitting and receiving dipoles were at fixed depths below the surface. Fields have been calculated at radial distances from the transmitter of 1 m to 50 km at frequencies from 1 Hz to 10^8 Hz. Graphs showing the radial, transverse, and vertical components of the electric field of infinitesimal horizontal dipoles as functions of the distance and the frequency have been prepared. Where appropriate these results have been compared with those obtained from Baños' special formulas for limited ranges with excellent agreement. A paper describing the new and often unexpected results is in preparation [King and Sandler, 17]. The extension of the calculations to a wider range of materials, to resonant antennas of finite length, and to traveling-wave antennas with rotationally symmetric and eccentric insulation with the distributions of current obtained under C remains to be done. The procedure is that already described for such antennas in sea water [Siegel and King, 29, 2]. A single set of measurements of the electromagnetic field of a traveling-wave antenna in lake water has been completed* and a comparison with the numerically determined theoretical results is in progress, [Shen, King, and Sorbello, 22]. Extensive measurements of the fields of scale models of various insulated antennas in dissipative media has been carried out in a specially designed anechoic tank. Their interpretation and relation to far-field measurements is the subject of a forthcoming paper [Smith, 21].

In order to determine the actual magnitude of the electric field in a practical dissipative medium, direct field intensity measurements must be made. However, the use of a bare dipole or monopole embedded in the medium as a probe for the field-intensity meter is inadequate since the response of a bare antenna depends on the permittivity and conductivity of the medium as well as on the incident field. A new method that makes use of electrically short insulated dipoles or monopoles has been developed to overcome this difficulty. It permits the direct reading of the electric field strength in a manner that is substantially independent of the electrical properties of the medium over a wide range [Smith and King, 23; Smith, 21]. (This work on field probes was presented at the International Symposium on Electromagnetic Compatibility at Montreux, Switzerland, in May 1975 where it won the first prize as the best paper of the Symposium). The new method is of particular value

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*The extensive program for measuring the fields of insulated antennas in lake water using the field site in Camden, Maine, which had been planned for the summer of 1974 had to be abandoned because the Contract was not renewed in time.

in measuring fields in biological materials especially in conjunction with radiation hazards [Smith, 19].

E. The directional properties of receiving antennas as displayed in the magnitude of the voltage across the load can be determined from the properties of the same antenna when used for transmission by application of the reciprocal theorem. For subsurface communication both transmitting and receiving antennas should be as directive as possible so that both may be alike. A quantitative study of the gain and efficiency of a complete transmitting-receiving system comprising directional arrays of resonant or traveling-wave eccentrically insulated antennas has not yet been undertaken. A detailed study of the relative magnitudes of the components of the electric field maintained by a subsurface transmitting antenna as a function of the distance, frequency, and electrical properties of the medium must first be completed. Antennas and arrays to receive the radial component E_ρ of the electric field which predominates in lateral-wave transmission are necessarily quite different from those designed to receive the transverse component E_ϕ which characterizes direct transmission [Sivaprasad and King, 30; King and Harrison, 31]. This means, for example, that antennas designed for use in sea water cannot be the same as those designed for lake water at high frequencies or dry sand. Note that over a frequency range from 10 to 10^8 Hz many parts of the earth's crust change from effectively good conductors to good dielectrics with corresponding changes in the relative magnitudes of the components of the electric field. Numerical data for infinitesimal dipoles indicate that even at a fixed frequency the ratio E_ρ/E_ϕ may change from substantially greater than one to much less than one as the radial distance from the transmitter is increased. This suggests the possible need to design antennas and arrays to receive both components of the electric field.

If there is interest in the current in the receiving antennas at points other than the load or the scattered electromagnetic field, a separate analysis of the receiving antenna is required since these quantities are not easily obtained from an application of the reciprocal theorem. An analysis of the insulated parasitic antenna in a dissipative medium has been made for several terminations [King, 26]. Its behavior is quite different from that of the bare dipole.

F. While all major steps leading to an answer to the question about the practicality of subsurface communication have been taken, a final conclusion is not yet available. This depends primarily on whether sufficient over all gain can be achieved in directive arrays to compensate for the very rapid decay with distance of even the largest component of the transmitted electromagnetic field. Specifically, the calculation of the fields of antennas of finite length and the combination of these into the fields of directive arrays remains to be done over a wide range of frequencies and radial distances for all relevant materials.

Chronological List of Publications and Papers in Preparation

1. L.D. Scott and G.S. Smith, Measurement techniques for antennas in dissipative media, IEEE Trans. on Antennas and Propagation, vol. AP-21, pp.499-507, July 1973.
2. M. Siegel and R.W.P. King, Electromagnetic propagation between antennas submerged in the ocean, IEEE Trans. on Antennas and Propagation, vol. AP-21, pp. 507-513, July 1973.
3. G.S. Smith, A theoretical and experimental study of the insulated loop antenna in a dissipative medium, Radio Science, vol. 8, pp. 711-725, July 1973.
4. T.T. Wu, R.W.P. King and D.V. Giri, The insulated dipole antenna in a relatively dense medium, Radio Science, vol. 8, pp. 699-709, July 1973.
5. R.W.P. King, K.-M. Lee, S.R. Mishra, and G.S. Smith, Insulated linear antenna: theory and experiment, Journal of Applied Physics, vol. 45, pp 1688-1697, April 1974.
6. G.S. Smith and R.W.P. King, The resonant linear antenna as a probe for measuring the in situ electrical properties of geological media, Journal of Geophysical Research, vol. 79, pp. 2623-2628, June 1974.
7. R.W.P. King, T.T. Wu and L.C. Shen, The horizontal wire antenna over a conducting or dielectric half space: current and admittance, Radio Science, vol. 9, pp. 701-709, July 1974.
8. R.W.P. King and M.A.V. Ward, Current and charge distributions along an antenna in a cylinder of cold plasma, IEEE Trans. on Plasma Science, vol. PS-2, pp. 234-232, December 1974.
9. T.T. Wu, L.C. Shen and R.W.P. King, The dipole antenna with eccentric coating in a relatively dense medium, IEEE Trans. on Antennas and Propagation, vol. AP-23, pp. 57-62, January 1975.
10. R.W.P. King, K.-M. Lee, S.R. Mishra and G.S. Smith, Insulated linear antenna: theory and experiment, II, Journal of Applied Physics, vol. 46, pp. 1091-1098, March 1975.

11. R.W.P. King, K.-M. Lee, S.R. Mishra and G.S. Smith, The insulated monopole: admittance and junction effects, IEEE Trans. on Antennas and Propagation, vol. AP-23, pp. 172-177, March 1975.

12. S.R. Mishra and R.W.P. King, An experimental study of the circuit properties of the eccentrically insulated antenna, IEEE Trans. on Antennas and Propagation, vol. AP-23, pp. 579-584, July 1975.

13. K.-M. Lee and G.S. Smith, Measured properties of bare and insulated antennas in sand, IEEE Trans. on Antennas and Propagation , vol. AP-23, pp. 664-670, September 1975.

14. R.W.P. King, L.C. Shen and T.T. Wu, Coupled insulated antennas in a relatively dense medium, Radio Science (accepted for publication); also accepted for presentation at USNC/URSI Meeting, Boulder, Col., October 20-23, 1975.

15. R.W.P. King, The many faces of the insulated antenna, Proc. IEEE (accepted for publication in February 1976); also presented as invited paper at IEEE/URSI Symposium, University of Illinois, Champaign-Urbana, June 1975.

16. K.-M. Lee, The terminated insulated antenna, accepted for presentation at USNC/URSI Meeting, Boulder, Col., October 20-23, 1975.

17. R.W.P. King and B. Sandler, Subsurface communication between dipoles in general media: description and interpretation of results, accepted for presentation at USNC/URSI Meeting, Boulder, Col., October 20-23, 1975.

18. R. Sorbello, Properties of the horizontal wire antenna over an imperfect conductor with special application to the Beverage wave antenna, accepted for presentation at USNC/URSI Meeting, Boulder, Col., October 20-23, 1975.

19. G.S. Smith, A comparison of electrically short bare and insulated probes for measuring the local radio-frequency electric field in biological systems, IEEE Trans. on Biomedical Engr. (accepted for publication in November 1975).

20. G.S. Smith, A comparison of measured field patterns of bare and insulated circular loop antennas, (submitted for publication in Radio Science).

21. G.S. Smith, Measured fields of linear insulated antennas in dissipative media, (to be submitted for publication).

22. L.C. Shen, R.W.P. King and R.M. Sorbello, Measurements on a directional antenna submerged in a lake, (to be submitted for publication).

23. G.S. Smith and R.W.P. King, Electric field probes in material media and their application to EMC, IEEE Trans. on Electromagnetic Compatibility, (accepted for publication in November 1975); also presented at International Symposium on EMC at Montreux, Switzerland, May 1975 where it was awarded first prize as the best paper of the symposium.

24. K.-M. Lee, The insulated antenna in general media (in preparation).

25. R.W.P. King, S.R. Mishra and L.C. Shen, Coupled insulated antennas: theory and experiment, (in preparation).

26. R.W.P. King, The insulated conductor as a scattering antenna in a relativvely dense medium, (submitted for publication to Trans. IEEE).

Supplementary References

27. R.W.P. King and L.D. Scott, The cylindrical antenna as a probe for studying the electrical properties of media, IEEE Trans. on Antennas and Propagation, vol. AP-19, pp. 406-416, May 1971.

28. M.Siegel and R.W.P. King, Electromagnetic fields in a dissipative half space, a numerical approach, Journal of Applied Physics, vol. 41, pp. 2415-2423, May 1970.

29. M. Siegel and R.W.P. King, Radiation from linear antennas in a dissipative half space, IEEE Trans. on Antennas and Propagation, Vol. AP-19, pp. 477-485, July 1971.

30. K. Sivaprasad and R.W.P. King, A study of arrays of dipoles in a semi-infinite dissipative medium, IEEE Trans. on Antennas and Propagation, Vol. AP-11, pp. 240-256, May 1963.

31. R.W.P. King and C.W. Harrison, Jr., ANTENNAS AND WAVES, A MODERN APPROACH, The M.I.T. Press, Cambridge, Mass. 1969.

32. S.A. Long, A mathematical model for the impedance of cavity-backed slot antennas, Scientific Report No. 1, Contract F19628-74-C-0060, Gordon McKay Laboratory, Harvard University, October 1973.

33. S. A. Long, An experimental study of the impedance of cavity-backed slot antennas, IEEE Trans.on Antennas and Propagation, vol. AP-23, pp. 1-7, Jan.1975.

34. S.A. Long, A theoretical and experimental investigation of combinations of slot and linear antennas, Scientific Report No. 2, Contract F19628-74-C-0060, Gordon McKay Laboratory, Harvard University, February 1974.

35. A. Baños, Jr., DIPOLE RADIATION IN THE PRESENCE OF A CONDUCTING HALF-SPACE, Pergamon Press, Inc., New York, 1966.

Professional Personnel

Professor T. T. Wu and

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Dr. Glenn S. Smith

Mr. Kuan-Min Lee

Mr. S.R. Mishra (TERMINATED June 30, 1974)

Dr. L. C. Shen May-June, 1975.

Dissertations

The Insulated Antenna: Theory and Experiment by Kuan-Min Lee; February 1976.

Coupling

Conferences with Messrs. Drane and McIlvenna of AFCRL on applications of the theory of insulated and horizontal wire antennas to the Beverage antenna and its possible extension to coupled Beverage antennas.

Conference with Dr. Simon of Lincoln Laboratory on applications of the theory of cavity-backed slot antennas.

Discussions with Dr. J.T. de Bettencourt of the Raytheon Company on the subject of Beverage antennas and their possible application to over-the-horizon radar.

Solution of the problem of scattering from an insulated wire in the sea at the request of Mr. P.F. Sforza of the Raytheon Company.

Correspondence replying to questions by Dr. James Wait on questions relating to insulated antennas and horizontal-wire antennas.

Papers presented at the Williamsburg meeting in 1972, the Boulder meeting in 1974 and the Urbana meeting in 1975 evoked many questions and considerable discussion.

Patentable Inventions

It is believed that the eccentrically insulated antenna is a patentable invention. Extensive measurements to reduce the theoretical analysis to practice were planned for the summer of 1974. These had to be abandoned because the Contract was not renewed until August. Plans to carry out the measurements in the summer of 1975 could not be implemented since the Contract terminated on June 30, 1975.

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Researches directed toward understanding and improving communication between antennas below the surface of the earth are reviewed. They have included: A) The development of a new method for the in situ measurement of the electrical properties of a dissipative medium, B) the selection of the insulated dipole as the most versatile for the purpose, C) the theoretical and experimental determination of currents, charge, and admittances of rotationally symmetric and eccentrically insulated antennas in various media and of arrays of such elements, D) the determination of the electromagnetic field (CONTINUED ON BACK)

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of dipoles in sea and lake water and dry earth near the air interface by numerical methods. The need to extend the results to antennas of finite length including traveling-wave insulated antennas is pointed out. Reference is made to a new method for measuring the electric field in a medium in a manner independent of its electrical properties, E) the properties of the receiving antenna are obtained with the reciprocal theorem or by direct analysis if quantities other than the voltage across the load are required, F) the information still needed to answer the following question is summarized: With the most directive transmitting and receiving antenna that can be designed, under what conditions and over what distances is subsurface communication practical in the earth's crust?