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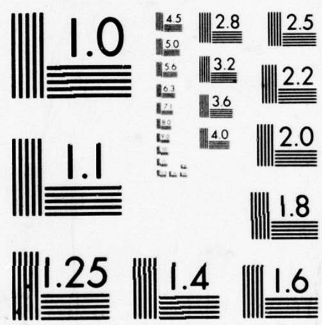

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RADC-TR-78-45
Final Technical Report
February 1978

EFFECTS OF HORIZONTAL GROUND WIRES ON LOW ANGLE RADIATION FROM HF ANTENNAS

Purdue University

ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

Title of Report: Effects of Horizontal Ground Wires on Low Angle Radiation from HF Antennas

This Technical Report has been reviwed and approved for publication.

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Plans Office

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: RADC-TR-78-45	2. GOVT ACCESSION NO. / 3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): Effects of Horizontal Ground Wires on Low Angle Radiation from HF Antennas	5. TYPE OF REPORT & PERIOD COVERED: Final, Dec 1975 - Dec 1977
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): C. L. Chen, W. L. Weeks	8. CONTRACT OR GRANT NUMBER(s): F 19628-76-C-0086
9. PERFORMING ORGANIZATION NAME AND ADDRESS: School of Electrical Engineering, Purdue University, West Lafayette, Indiana 47907	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61102F, 2305J428
11. CONTROLLING OFFICE NAME AND ADDRESS: Deputy for Electronic Technology (RADC), Hanscom AFB, MA 01731, Contract Monitor: C. J. Drane/EEA	12. REPORT DATE: February 1978
	13. NUMBER OF PAGES: 19
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Antenna Ground Systems

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Digital computer programs have been developed to evaluate the effects of horizontal ground wire systems on the low angle radiation from vertically polarized HF antennas. An extensive method of moments program (WF-LLL2A) has been modified for this purpose. An alternative approximate method has also been studied and the results compared. Results indicate the feasibility

of these types of calculations and that a low angle field enhancement of 20 to 25% by design of the ground wire system may be possible at the higher frequencies in the HF band, but that larger ground screens do not necessarily give greater enhancements. The effect of backscreen reflector size was also studied.

This Final Report under Contract F19628-76-C-0086 summarizes the result of a two-year analytical study on the design of ground wire systems optimized so that antenna performance is enhanced by significantly reducing power lost to the ground near the antenna and by achieving higher field intensities at angles near the horizon. Applications are to long-range, OTH communications and surveillance radar antennas.

Emphasis has been placed on cost-effective design features of ground systems, as well as backscreens for linear arrays of vertical monopoles. Parameters considered in this study have included frequency (in HF band), earth conductivity, ground screen wire length and spacing, angle of slope of earth in foreground of the antenna, backscreen height and spacing from antenna elements.

Detailed results of the analysis and computations conducted in this effort are fully described in two Scientific Reports prepared under the contract. A complementary effort directed toward the experimental verification and corroboration of these analytical results is presently being pursued by this contractor under Contract F19628-77-C-0057.

Charles J. Drane

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Contract Monitor
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1. Introduction

The performance of antennas that operate in the frequency bands below about 50MHz suffers unless the typical low earth conductivity found at most sites is enhanced by an arrangement of conducting wires or screens near or just beneath the surface of the earth. The primary reason for the inclusion of such ground wire systems is to reduce the power lost to the ground in the vicinity of the antenna - that is, to make the input resistance more nearly equal to the ideal radiation resistance of the antenna. A secondary reason for such ground screens is to alter the radiation pattern in some desired way.

For radio transmission paths that involve the ionosphere, long-range communications are enhanced by radiation patterns that have high intensities at angles near the horizon. However, because actual earth has finite conductivity, the field strength near the horizon is very low for both polarizations. This problem is more serious for horizontal polarization, so the applications primarily involve vertical polarization, but there is essentially no field strength at the horizon even with vertical polarization. Thus, a desirable radiation pattern feature that a ground system might bring about is an increase of the field strength at angles near the horizon.

Since the cost of ground systems is a significant fraction of the total cost of the antenna installation, the benefits to be gained must be obtained from a ground system of lowest possible cost, and this implies that it should be as small as possible and shaped so that the ground wires are placed in positions where they are effective in accomplishing the desired purposes.

Most of the work done under this contract was directed toward the question of how a wire ground screen might be designed in order to enhance the field strength near the horizon for vertically polarized antennas. All of the results were obtained from digital computer studies, primarily from one or the other of two programs specially adapted for this work. One of these programs is a very extensive one in which the current distributions on all wires are computed from the best available theory incorporated into a method of moments type of computation. This program gives all pertinent information, including input impedance. The other program is a simpler, faster, approximate program which gives only the field patterns and is based on an assumed current distribution.

2. Development of the Programs

The development of the simpler approximate program was a relatively straightforward task. This program, called ERATP, is based on the reciprocity theorem and is described in some detail in report RADC-TR-77-171 issued under this contract. The program calculates the ratio of the field of an antenna with a ground wire system to the same antenna with no ground system at specified angles. The current distribution on the wire is specified in terms of traveling wave components. The variables are the length of the ground wires, the frequency, the electrical parameters of the earth, and the slope angle of the ground wires. The program is set up for automatic plotting of the field patterns as well as the field enhancement ratios if desired.

The more complicated program required considerably more effort, for although the basic formalism for the calculation was available in a program called WF-LLL2B developed at the Lawrence Livermore Laboratories, the code would not converge within the time limits available at the Purdue Digital

Computing Center (and indications were that for certain types of ground wire situations, it would not converge at all). The system of calculation was, therefore, revised and rewritten, and the whole program adapted for more convenient use on our CDC 6500 computer. Some of the details of the problems and their solutions were presented in the report (RADC-TR-77-171) mentioned above and more of the details are given in (RADC-TR-78-65). The revised program we will call WF-LLL2BP.

3. The Results of the Studies

A. Horizontal Ground Wires at the Earth Surface

The object of the work was to study specific wire ground systems in specific earth conditions in order to generalize, eventually, the results and incorporate them into rational engineering design procedures. Consequently, we started with relatively simple antennas and ground wire systems so that the effects brought about by varying certain parameters would be apparent.

In the first studies (reported in detail in the report RADC-TR-77-171) the ground wire system consisted of a small number of parallel wires on the surface of ground extending only in the "forward" direction. The vertically polarized antennas were one or more vertical elements, at most equivalent to a 4-element array. Both programs were utilized and from the more complicated one (WF-LLL2BP), it was determined that a reasonable assumption is that a current wave propagates on the horizontal ground wire system with a propagation constant given by Coleman's formula

$$\gamma_w = \frac{j\beta_o}{\sqrt{2}} \sqrt{\frac{\varepsilon_G'}{\varepsilon_o} + 1 - \frac{j\sigma}{\omega\varepsilon_o}}$$

The radiation patterns of the complete structures over grounds having conductivities of 10^{-3}, 5×10^{-2}, and 10^{-2} mhos per meter at frequencies of 3, 10, and 30MHz were calculated, with particular attention to the enhancement of the field at angles near the horizon brought about by the ground wire systems. It was found that with a pure traveling wave along the ground wires, the field enhancement was decidedly wire length, frequency and conductivity sensitive. In general, the field enhancement at the lower frequency and higher conductivity was very small, just a few per cent at most, increasing very slightly with ground wires of greater length. At 3MHz with the lower conductivity (10^{-3} mhos/meter), the field enhancement reached a broad maximum of about 18% with ground wire lengths in the vicinity of 20 meters. At 10MHz with the lower conductivity, there was a much more pronounced maximum of the field enhancement with a length of about 5.5 meters, reaching a value of about 22%. However, it was found that in this case, greater ground wire length actually resulted in a decreased field at the horizon, with a minimum of about .92 of the field with no ground screen at all, reached with wires about 17 m; the effect seemed to be periodic with length although this was not studied in detail. With the higher conductivity (10^{-2} mhos/m) at 10MHZ, the enhancement was less (about 10% at most) and the enhancement remained nearly constant with wire lengths about 4 meters or longer.

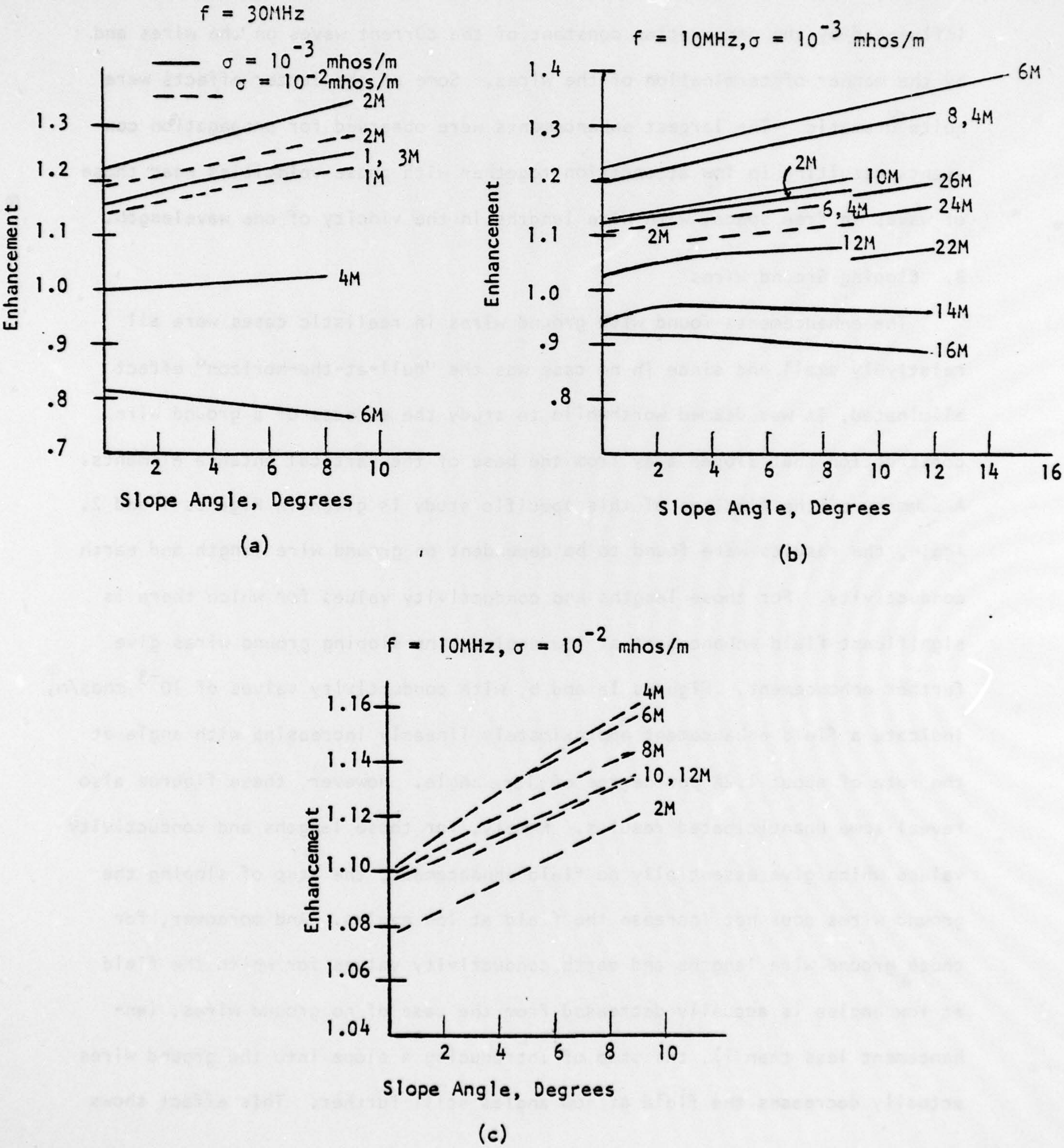
At a frequency of 30MHz, the effects suggested in the previous paragraphs become more evident and pronounced. All three conductivity values showed a maximum in the field enhancement when the wire length was in the vicinity of 2 m, with enhancement in the vicinity of 20%. All three show a minimum with lengths near 5.6 m. And with the lower conductivity (10^{-3} mhos/m) the ground wires of that length actually reduce the field at low angles to .82 of the value with no ground wires at all.

Further studies showed that the type of effect described in the foregoing two paragraphs could nearly always be seen but the specific numbers were influenced by the propagation constant of the current waves on the wires and by the manner of termination of the wires. Some of the latter effects were quite dramatic. The largest enhancements were observed for propagation constants resulting in low attenuation together with phase velocities near those of waves in free space, with wire lengths in the vincity of one wavelength.

B. Sloping Ground Wires

The enhancements found with ground wires in realistic cases were all relatively small and since in no case was the "null-at-the-horizon" effect eliminated, it was deemed worthwhile to study the effects of a ground wire construction that slopes away from the base of the vertical antenna elements. A summary of the findings of this specific study is given in Figures 1 and 2. Again, the results were found to be dependent on ground wire length and earth conductivity. For those lengths and conductivity values for which there is significant field enhancement at low angles, the sloping ground wires give further enhancement. Figures 1a and b, with conductivity values of 10^{-3} mhos/m, indicate a field enhancement approximately linearly increasing with angle at the rate of about 1.2% per degree of slope angle. However, these figures also reveal some unanticipated results. Namely, for those lengths and conductivity values which give essentially no field enhancement, the step of sloping the ground wires does not increase the field at low angles. And moreover, for those ground wire lengths and earth conductivity values for which the field at low angles is actually decreased from the case of no ground wires, (enhancement less than 1), the step of introducing a slope into the ground wires actually decreases the field at low angles still further. This effect shows

Figure 1. Influence of Introducing a Downward Slope into the (Horizontal) Ground Wires



up (Figure 1a) at 30MHz when the length is 6M and the conductivitv is 10^{-3} mhos/m and at 10MHz (Figure 1b) when the length is 16M and the conductivity is 10^{-3} mhos/m. At the higher conductivity and at a frequency of 10MHz (Figure 1c) this effect is not evident but the enhancement with increasing slope angle is much less, namely, about a half of a per cent per degree of slope, with little dependence on length for lengths greater than 10 m.

Another interesting effect is shown in Figure 2, which displays normalized radiation patterns at a frequency of 10MHz in the range of angles between 50 and 89° measured from the zenith and with a conductivity value of 10^{-3} mhos/m. The solid line gives the pattern with no ground wire and the points plotted are for a 6M ground wire having differing slope angles. Note that when the patterns are normalized to their value at the maximum, the patterns are all very similar, especially above 63°. What difference there is in the normalized patterns shows up at the higher elevations (smaller angle θ). In view of this, there is a strong possibility that with the same power input, a system design incorporating a slope in the ground wire might not actually increase the power toward angles near the horizon.

The observations in the preceding two paragraphs suggest that the added expense of artifically introducing a slope into a ground wire system would be difficult to justify in general.

C. Buried Ground Wires

In practice it may be necessary to bury the ground wires to protect them from various activities at the surface. The burial of the ground wires has two effects. One is to alter somewhat the propagation constant of the current waves on the ground wires; this effect is most pronounced on wires having no insulation (or very thin insulation). The second effect is the attenuation

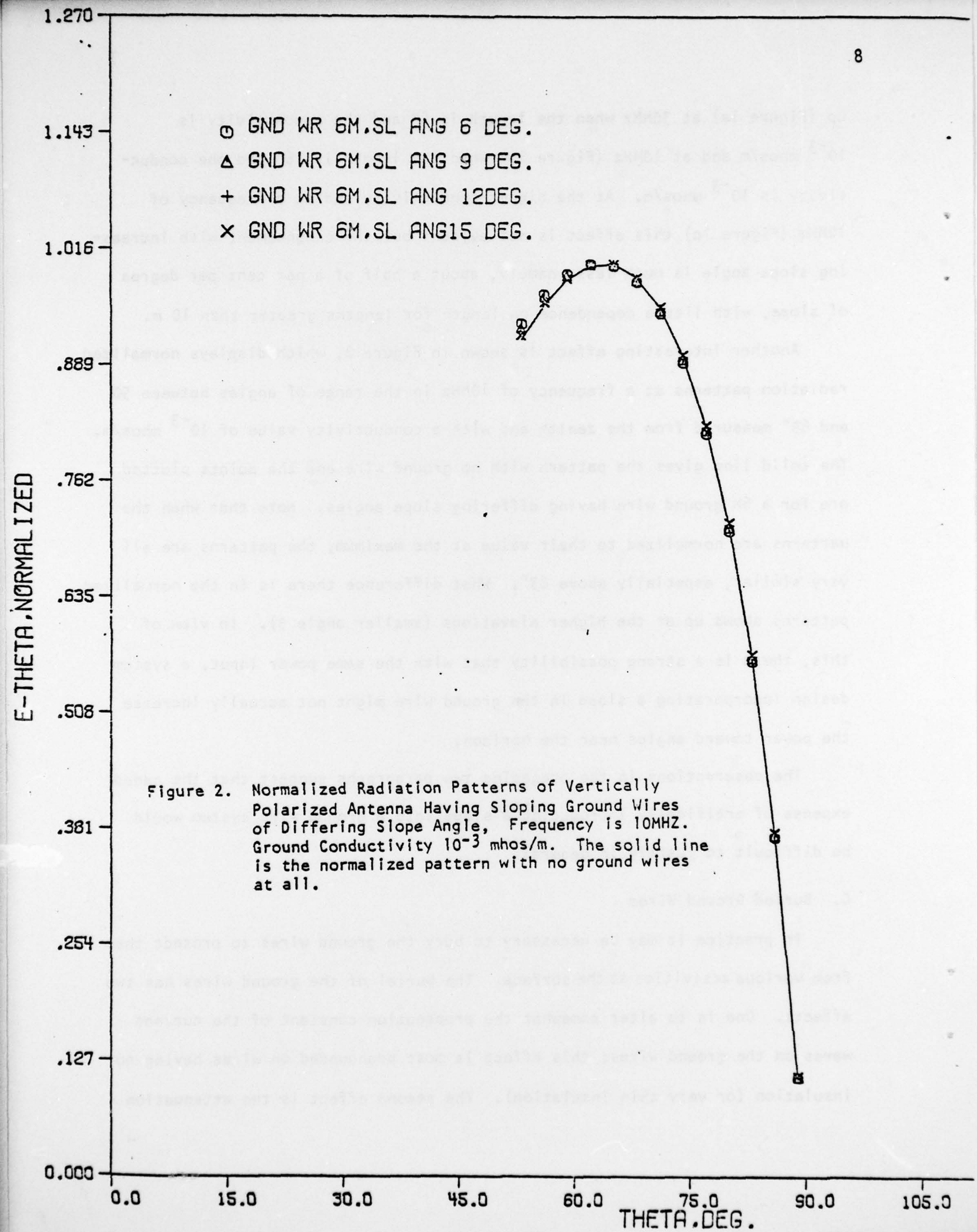


Figure 2. Normalized Radiation Patterns of Vertically Polarized Antenna Having Sloping Ground Wires of Differing Slope Angle, Frequency is 10MHZ. Ground Conductivity 10^{-3} mhos/m. The solid line is the normalized pattern with no ground wires at all.

of the signal that has to pass through the earth a distance equal to the depth of burial. This latter effect is universal but is most serious for the higher values of earth conductivity. Essentially, the field falls to 1/eth of its value in a depth of one skin depth. The attenuation constant is essentially that of plane waves of the specified frequency traveling in a medium having the conductivity and permittivity values of the earth in question. The effect of burial on the propagation constant also tends to reduce the field enhancements from those for wires at the surface since it was mentioned that the field enhancements are greatest with small attenuation of the wave on the ground wires and phase velocities nearly equal to free space phase velocities. The act of burying wires increases attenuation and decreases the phase velocity unless the wire has a very thick, foam insulation.

4. Shape Effects in Ground Wire Systems

The influence of ground screen shape was studied through the use of the larger, more accurate computer program (WF-LLL2BP). Because of the large time involved in carrying out a calculation for a particular configuration having many segments, we could study only relatively simple systems with limited parameter studies. The model selected for detailed study consisted of a short vertical monopole having up to four ground wires arranged into a cross at the base of the antennas or into a fork arrangement extending into one quadrant direction. The full details of this study are given in report RADC-TR-78-65. A brief summary of these results are given here.

A. A 5.62 m monopole was assumed to be base fed at 10MHz against a horizontal ground system consisting of a 3-legged fork having up to five 1.86 m segments in each leg. The vertical plane patterns and low angle field enhancement were studied for varying numbers of segments in the legs. The ground system arrangement having two segments in the outer legs of the fork and five segments on the center leg gave the largest low angle enhancement, with earth having conductivity of 10^{-3} mhos/m and dielectric constant of 9.

B. A 2.74 meter monopole was assumed to be base-fed at 2MHz against a horizontal wire system consisting of four wires forming a right angle cross. Each ground wire might have as many as 13 segments, 9 of which were 3.05 m and the others having shorter lengths (near the feed point) to give a maximum total length of 31.9m. The number of segments (i.e., the length) of each ground wire could be varied independently. These studies indicate that only the wires extending in the "forward" direction are effective in producing radiation enhancement in the forward direction. This observation was reinforced by a variation in geometry in which the angle between the wires was decreased to 60° in the forward direction. It also showed that the longer ground wires do not necessarily give more radiation enhancement.

5. Effects of Varying the Height of Reflecting Screens for Broadside Arrays

A related question written into the contract was a study of the effect of the height of back reflecting screens that might be used with broadside arrays operating over lossy ground in the HF frequency range, with the hope of minimizing and optimizing reflecting screen sizes.

In order to study this question, we modeled the array by an operating unit consisting of a driven vertical element with up to seven vertical masts in a line spaced less than a quarter wavelength behind the driven element. The details of this study are included in report RADC-TR-78-65. In brief, the findings were that greater field strengths are produced by reflecting masts having a height of 3/4 wavelength with a driven monopole about 1/4 wavelength. But if the reflector heights are greater than about 1/4 wavelength but less than 3/4 wavelength, the gain is actually reduced by the added reflector height. However, the field strength with reflectors 3/4 wavelength in height is only about 5 percent greater than the field with reflectors that are 1/4 wavelength in height. And with reflectors having a height of 1/2 wavelength, the field is reduced by about twenty percent from the value produced by reflectors having a height of about 1/4 wavelength.

6. Effect of Scanning

We considered the effect of azimuthal scanning on the low angle field enhancement function of ground wire systems. Although clearly, for uniform performance over the angle of scan the ground wire system should be radial covering the scan angle, in the main we considered only parallel ground wire systems. We studied the effect of waves coming in at angles with respect to this parallel ground wire system. With radial wire systems, effects of the type to be discussed would occur for all directions of propagation within the scan angle since the wires (except one) are not parallel to the direction of propagation for any direction.

The general effect of propagation directions that are not parallel to ground wires is shown by the field enhancement integral of the type that was presented in RADC-TR-77-171, where the field enhancement comes from the term involving the integral, $\int E_{inc} \cdot J_{HGW}\, dv$, where E_{inc} is the electric field vector at the postion of the ground wire and J_{HGW} is the current density on the ground wires. For angles of arrival near the horizon, the only contribution to the integral comes from the component of electric field along the direction of propagation and this in turn means that the enhancement will vary approximately as the cosine of the angle between the propagation direction and the direction of the ground wires. There is, in addition, a phase effect. When the ground wires and the wave propagation direction are both along the same direction, say x, there is a factor in E_{inc} varying as $e^{j\beta_o \sin\theta x}$ and a factor in J_{HGW} varying as $e^{-\gamma_w x}$. Thus, the net result of the integral depends on how the factor $e^{(j\beta_o \sin\theta - \gamma_w)x}$ integrates over the length of the wire. And it will be recalled that the effects were greater at low angles where γ_w was near to $j\beta_o$ in value. But when the wave propagation direction is not along the wire, the phase factor in the incident field has the form $\exp(j\beta_o \sin\theta \cos\phi)$ where ϕ is the angle that the propagation direction makes with the direction of the ground wires. In this case, the maximum effect will occur when γ_w is near $j\beta_o \cos\phi$ in value, rather than near $j\beta_o$, and the lengths for maximum (and minimum) enhancement will be different.

7. Plans for Experimental Work

With the aid of the computer programs ERATP and WF-LLL2BP, many interesting results concerning HF antenna ground systems have been generated. Most significant are those results which indicate that larger ground systems may not always be better in the task of producing long range signals (at low angles). And while the longer program (WF-LLL2BP) utilizes the best available theory, there are enough pitfalls in the execution of the theory on a digital computer that the results should be verified by experiment. We have, therefore, developed a plan for checking the results experimentally.

The most crucial part of the calculation is the determination of the current distributions on the horizontal ground wires. If the current distribution on these wires is known accurately, both in amplitude and in phase, it is relatively an easy matter to compute the radiation pattern, even in the presence of a lossy earth. Consequently, much of the experimental work should be in the careful measurement of the current distributions on ground wires. In view of the expense and inconvenience of working at full scale over actual earth, many of these measurements should be done at a higher frequency in a model facility; on the other hand, because of the difficulty of modeling the actual earth environment, some of the measurements should be done at full scale.

A. Choice of Frequency

In the full scale experiments, a relatively high and relatively low frequency should be used. To avoid interference with other radio services, we suggest the use of the ISM bands at 13.56MHz and at 27.12MHz. It is believed that these frequencies are close enough to the 10MHz and 30MHz employed in the computer studies to exhibit the same effects.

For the model experiments, a much higher frequency is convenient in order to reduce the size of the structure to one that is easier to work with. A scale factor of 30 to 100 seems reasonable since the earth conductivity must be modeled by the same scale factor. Again, we suggest the use of an ISM band to avoid interference and the frequency that suggests itself is, therefore, 915MHz.

B. Full Scale Models

We suggest that the full scale models be constructed over earth with low to moderate conductivity such as is common in the midwest. For the vertical primary radiator it does not seem necessary, at least initially, to have anything more complicated than a quarter wave monopole. As a start, this monopole should be fed against a ground stake system, with no appreciable horizontal ground system, with careful measurement of input impedance and base current. If possible, a vertical plane radiation pattern should also be measured for reference (it is realized, however, that a measurement of the true distant field pattern may not be possible at reasonable cost). Next a single ground wire should be studied, with attachment, in two trials, a) directly to the ground side of the generator with no connection to the ground stake system, and, b) then fed in parallel with the ground stake system. The currents in the two cases should be carefully measured. The ground wire system should be sectioned, with easy snap on, small diameter connectors, into lengths of 1/2, 1, 2, 4, 8, 12, and 16 meters, for flexibility in studying the effect of length. A set of insulated stakes should be driven to hold the wires in a position just above the surface of the ground with enough clearance to allow a current probe to be moved along the wire without interference. The far end of the wires should be insulated (open) except for special tests. Next, two more ground wires should be added, parallel to the first one and the tests repeated at both suggested frequencies. Then more ground wires should be added two at a time in the same way, until up to 15 parallel ground wires extend in one direction from the vertical masts. Input impedance and current distribution measurements should be made on each set. Radiation patterns should be measured, if feasible.

C. Reduced Scale Model Experiments

In order to scale and simulate earth conductivities with reasonable convenience, a tank containing salt water with controlled amount of salt is suggested. Probably the most convenience tank for the work would be a plastic, above ground swimming pool having minimum metal supports. A pool diameter of 10-12 feet should be adequate for the studies. For convenience and protection of the equipment and operations from weather, the swimming pool should be enclosed in an air supported shelter of the type now available commercially.

Experiments of the same type as those described in the outline for full scale experiments (paragraph B above) should be carried out, except that a system should be devised for allowing continuously adjustable length of the ground wires (probably a form of spring-loaded reel at the base with a nylon cord connected to the remote end to draw out the wires to the desired lengths).

Further tests should also be made in the tank facility. Any dependence of the propagation constant as the density of wires is increased should be documented, with a check to see if the tendency to resonate at certain lengths is diminished. Also, the dependence of the wire propagation constants upon insulation thickness should be studied, since the computer studies indicate that wires having current propagation constants near free space values are capable of greater field enhancement.

8. Summary

With the results obtained to date plus those that will be obtained in a proposed follow-on study, data will be available that will aid the Air Force and other interested parties in the economical design of ground systems for HF antennas.

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United States Air Force
Hanscom AFB, Mass. 01731