***Is it more efficient to collect return currents from vertical antennas as displacement currents rather than as conduction currents? K8CFU says yes and tells us why he thinks so based on his studies of radials.***

# Improving Vertical Antenna Efficiency

## A Study of Radial Wire Ground Systems

**BY ARCH DOTY*, K8CFU**

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Approximately 50,000 miles of bare wire has been buried in the United States as radials under commerical and amateur radio station antennas in an effort to provide the most efficient artificial ground systems possible.

A recently concluded research program indicates that buried bare-wire radials do NOT provide optimum performance. Rather, the investigation indicates that wires comprising an artificial ground system should be elevated for maximum efficiency, and if it is necessary to bury these wires for practical or esthetic reasons, **insulated** wire should be used.

### Theoretical Considerations

The vertical antenna is versatile. It can be constructed in a wide range of heights; it can consist of a thin wire or a thick tower; it can be top loaded, bottom loaded, capacitively loaded, or inductively loaded; its feed impedance can be varied to a convenient value by a number of methods.

The main problem with verticals is that to work efficiently they must be used with a good (electrical) ground system. This ground must meet three basic requirements which can be described, in somewhat simplified form, as:

**(1) The ground must efficiently collect the "return currents" from the antenna.** When r.f. energy is fed to a vertical antenna, displacement currents flow from the antenna through surrounding space and toward the earth below. To complete the circuit, and allow these currents to flow, they must be collected from or near the earth and returned to the feed point at the base of the antenna.

Considerable losses will be incurred if these currents must pass through the earth, as the earth presents a high resistance to r.f. current flow. Even sea water, which has quite high conductivity (low resistance), cannot compare with a "perfect," or metallic, ground.

One special type of antenna, the so-called "ground plane," operates independently from the ground. This antenna uses two or more ¼-wavelength radial wires or rods located at the base of a vertical radiator. However, in this arrangement the radials are, in effect, a portion of the radiating element rather than an artificial ground system.

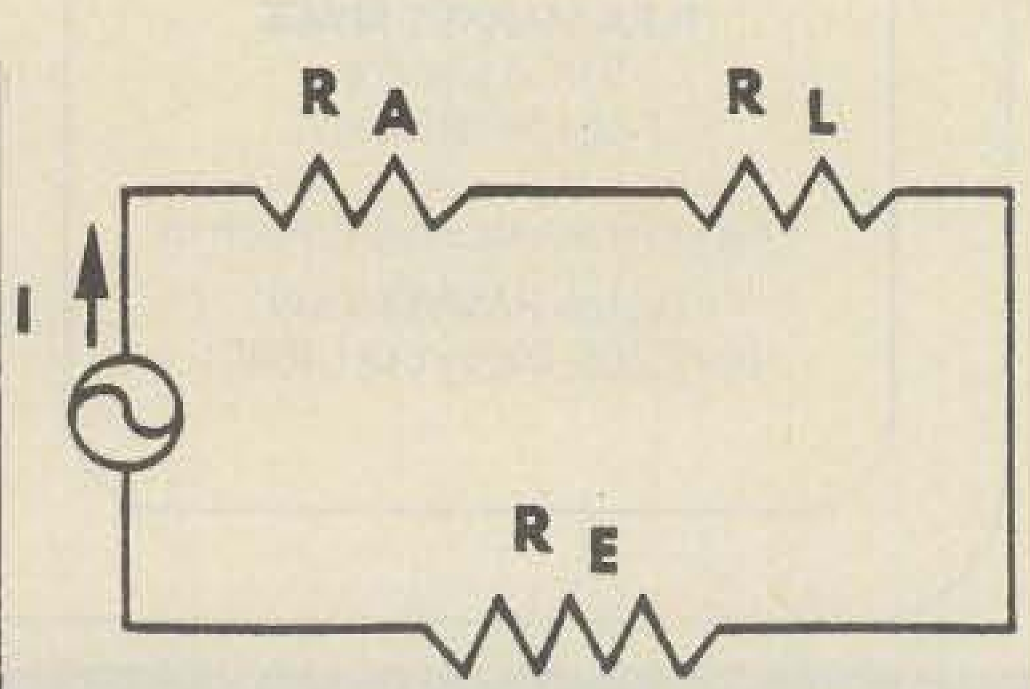


*Fig. 1– Equivalent circuit representing current flow.*

Other antenna systems utilizing vertical radiators must include some method for collecting and returning currents from the antenna. The method that has been most commonly used is to allow the return currents to enter the earth, and then to collect them with an array of buried "radial" wires. In past years there has also been occasional use of elevated arrays of radials under vertical antennas (counterpoise and ground screens) designed to intercept return currents before they enter the earth or to collect them after they have entered the earth through the capacitive relationship between the radials and the ground.

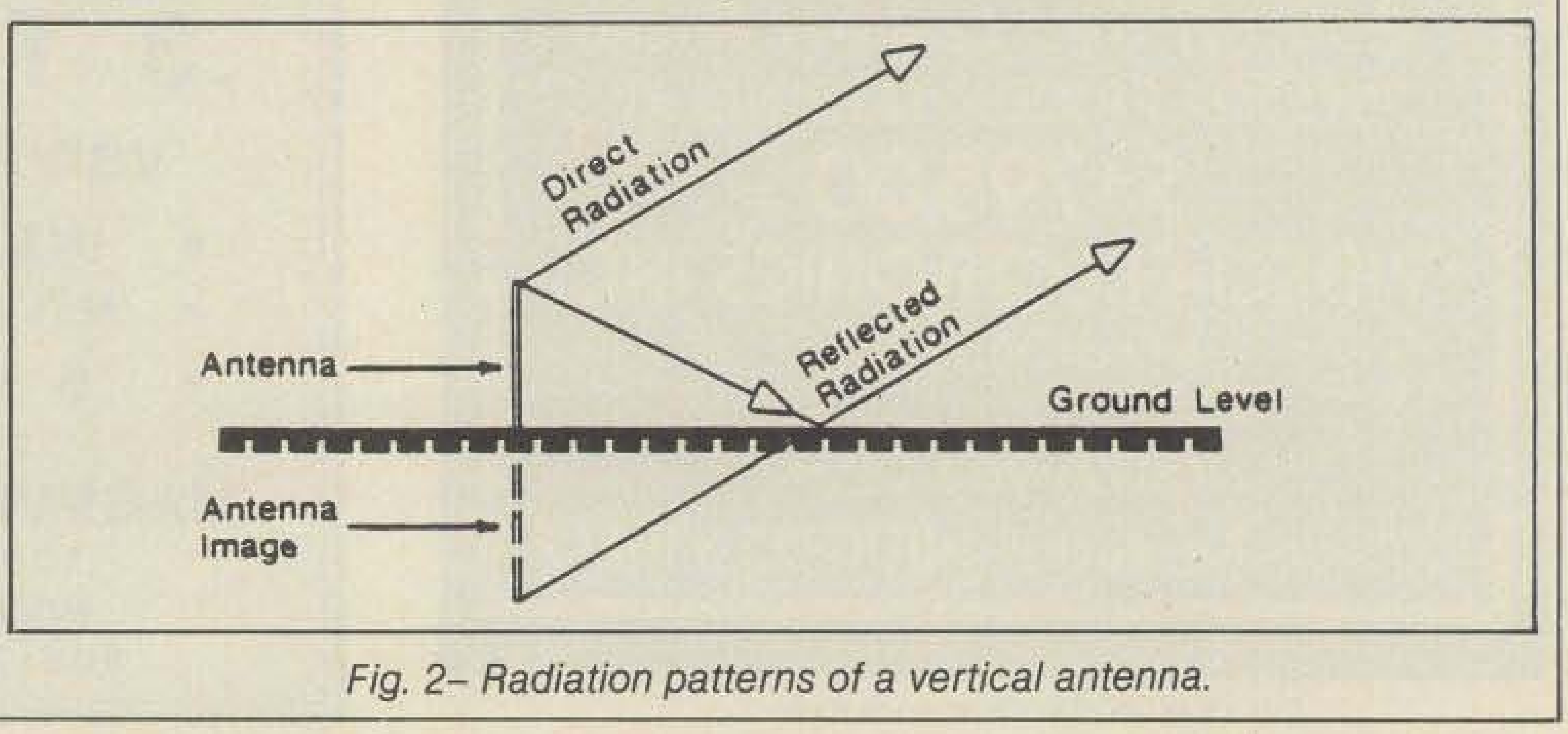


*Fig. 2– Radiation patterns of a vertical antenna.*

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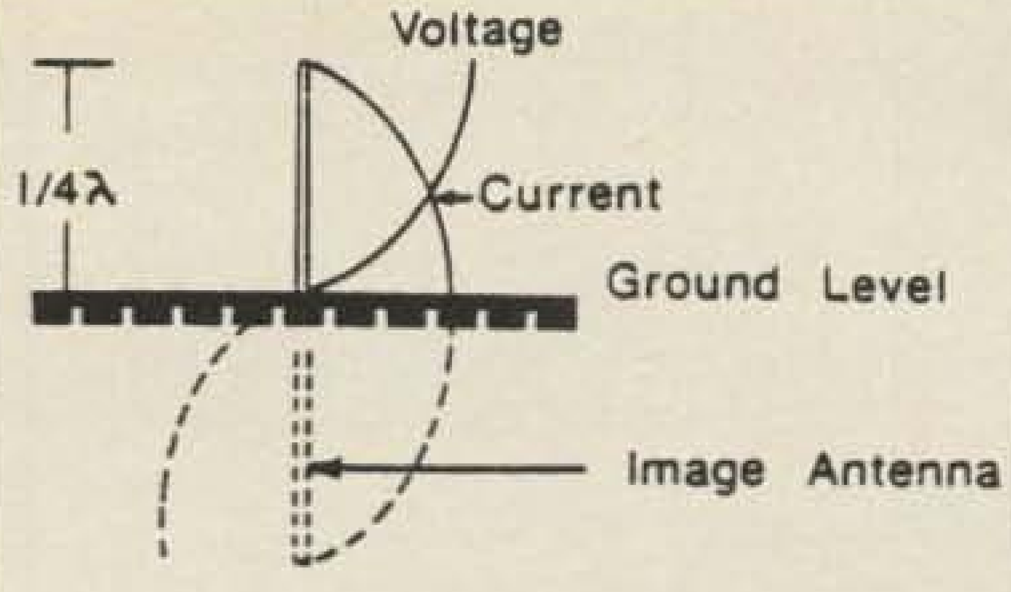


*Fig. 3– The image antenna component of a vertical antenna.*

**(2) The antenna's return currents must be conducted through the ground system to the base of the vertical radiator with minimum losses.** Once the return currents have been collected, they must be returned to the base of the antenna. The complete circuit through which these currents flow can be considered as shown in fig. 1, where:

Ra = radiation resistance
R1 = conductor resistance
Re = ground resistance

(It should be noted that Re relates only to those return currents that enter the earth, and are then collected by buried wires as conduction currents.)

**(3) The ground must provide a distinct (electrically) reflecting surface under the vertical antenna.** Some of the radiation from a vertical antenna is directed below the horizon, and will thus impinge on the surface of the earth. This radiation will be reflected from the earth's surface, and may combine with the direct radiation from the vertical to assist in establishing the radiation pattern of the antenna array as shown in fig. 2. In calculating and comprehending the radiation pattern from a vertical antenna it is convenient to consider that a portion of this radiation is coming from an "image antenna," as indicated.

Fig. 3 shows that the image antenna is an exact reproduction of the vertical antenna as it would look if the earth's surface were a perfect "electrical mirror." Unfortunately, the surface of the earth is far from being a good electrical conductor, as noted earlier. A good artificial ground system should assist in correcting this situation by presenting a good reflecting surface.

## Past and Current Practice

At the present time there are approximately 5,000 a.m. broadcasting stations in the United States. Calculation shows that if each of these stations has followed FCC recommendations and installed a minimum of 120 radial wires (each at least ¼ wavelength long) under its vertical transmitting antenna, there are more than 137,000,000′, or 26,000 miles, of such wires buried in this country.

In addition, many of this country's 400,000 amateur radio operators have buried systems of radial wires under their antennas. These range from modest arrays to the 25,000′ of wire "planted" in the California dessert by an ambitious experimenter there.

Assuming that the efforts of amateurs over the past 60 years have equalled those of the commercial station owners, it can be estimated that more than 50,000 miles of bare wire has been buried in this country under vertical transmitting antennas in the belief that it will provide the most efficient "artificial ground" system possible.

The mole-like endeavors of the radio station owners have not been without good justification. Rather, they have been based on the results of a landmark research effort undertaken almost 50 years ago.

Throughout history one finds examples of "classic" works that dwarf contemporary efforts in the same field of endeavor. In antenna technology the paper on ground systems for vertical antennas by Dr. George Brown and his compatriots[1] is acknowledged to be a true "classic" in its field. Dr. Brown's work stands apart, and even recent tests utilizing instrumentation far more sensitive than anything available in the 30's can find no fault with it. The stature of this work, however, had two unfortunate, although probably unavoidable, results:

1. The overpowering completeness and excellence of the study had the effect of discouraging further research in the particular area that it covered.

2. The Federal Communications Com-

mission was so impressed by the work that it used it as the basis for requirements on the number of "ground system" radial wires that each Standard Broadcast Station is required to have.

The only problem with these events is that the research on which they are based considered only one of the several possible configurations of artificial ground systems—the one using buried wires.

## The Recent Research Program

For more than 60 years there have been several alternatives to the buried-wire type of ground system. These have included the elevated "ground" systems of the counterpoise and ground screen types.

Little early data was published on the characteristics of these systems, and apparently no research was conducted on them after publication of Dr. Brown's paper until the extensive tests conducted at Fletcher, North Carolina, in 1981 and 1982.[71,72] Although the Fletcher tests were comprehensive and involved over 16,000 measurements, they, as Brown's work, covered only certain variations of the several possible artificial ground systems—in this case elevated counterpoise and ground screen arrays. These tests clearly showed that these elevated ground system were unusually efficient—perhaps more so than equivalent buried-wire systems.

The Fletcher tests, however, did not compare the relative performance of buried bare-wire radials vs. elevated insulated-wire radials. And, an extensive review of the literature showed no record of such a comparison in the past. Thus, in order to obtain data on the relative performance of the different types of radial ground systems, a test program was carried out in late 1982 using the instrumentation and techniques developed in the earlier Fletcher counterpoise/ground screen tests. In this program several thousand measurements were made of the magnitude and distribution of return currents carried by:

- Elevated/insulated radial wires.
- Insulated wires lying on the surface of the ground.
- Buried bare-wire radials.

In the tests the radial wires terminated at the base of a 90-degree vertical antenna and were the sole means of collecting the return currents. The tests wre made at 1805 kHz. The following combinations of radial wires were tested:

**Single Wires**

Elevated Wires: 180', 135', 90' & 45' long
Wires on the Ground: 180', 135', 90' & 45' long
Buried Wires: 180', 135', 90' & 45' long

**Multiple Wires**

180' buried wire below 180', 135', 90' & 45' elevated wires
180' elevated wire above 180', 135', 90' & 45' buried wires
180' wire on the ground over 180', 135', 90' & 45' buried wires
180' buried wire below 180', 135', 90' & 45' wires lying on the ground

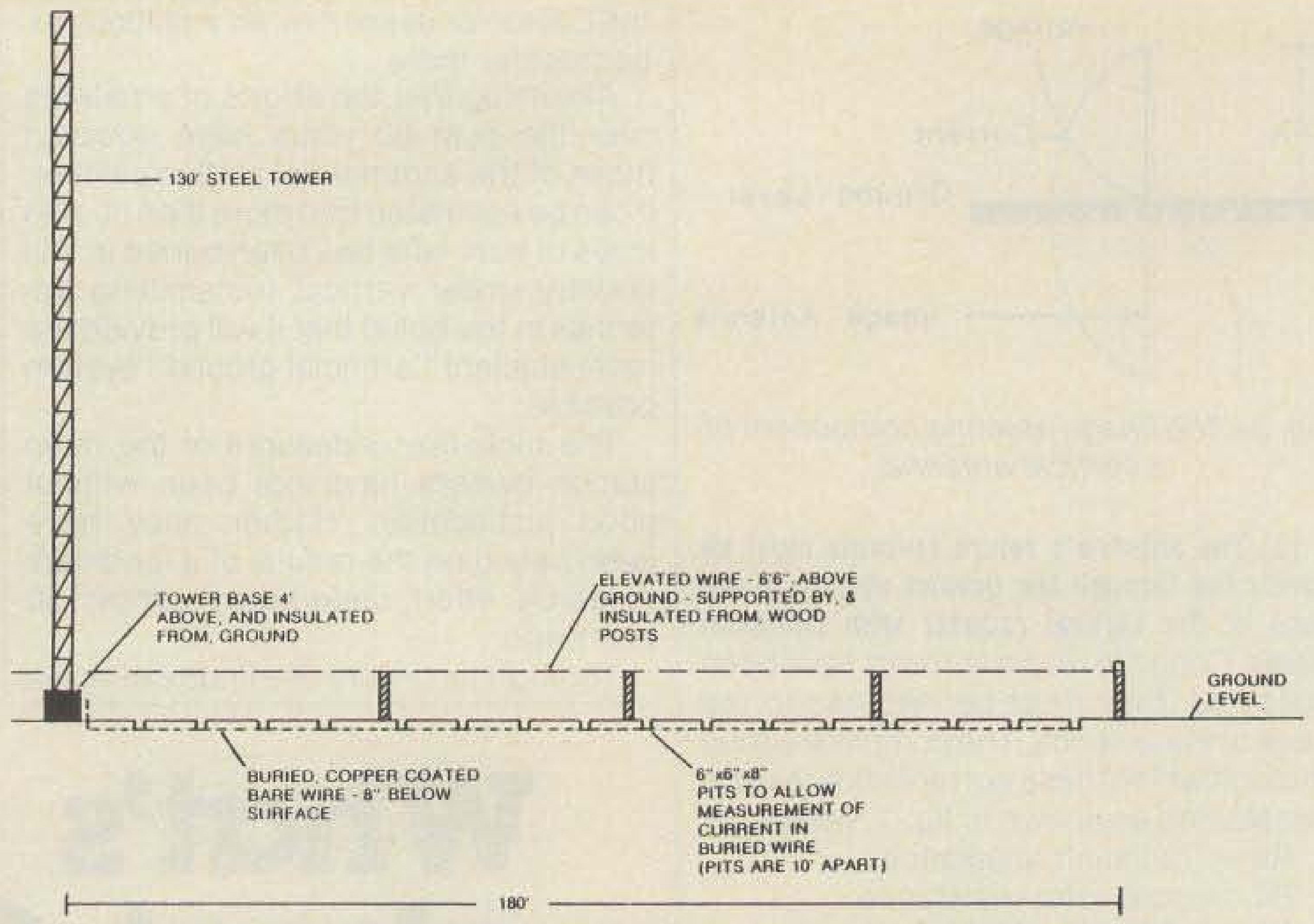


*Fig. 4– Test setup for radial current measurements of above ground, on the ground, and buried wires.*

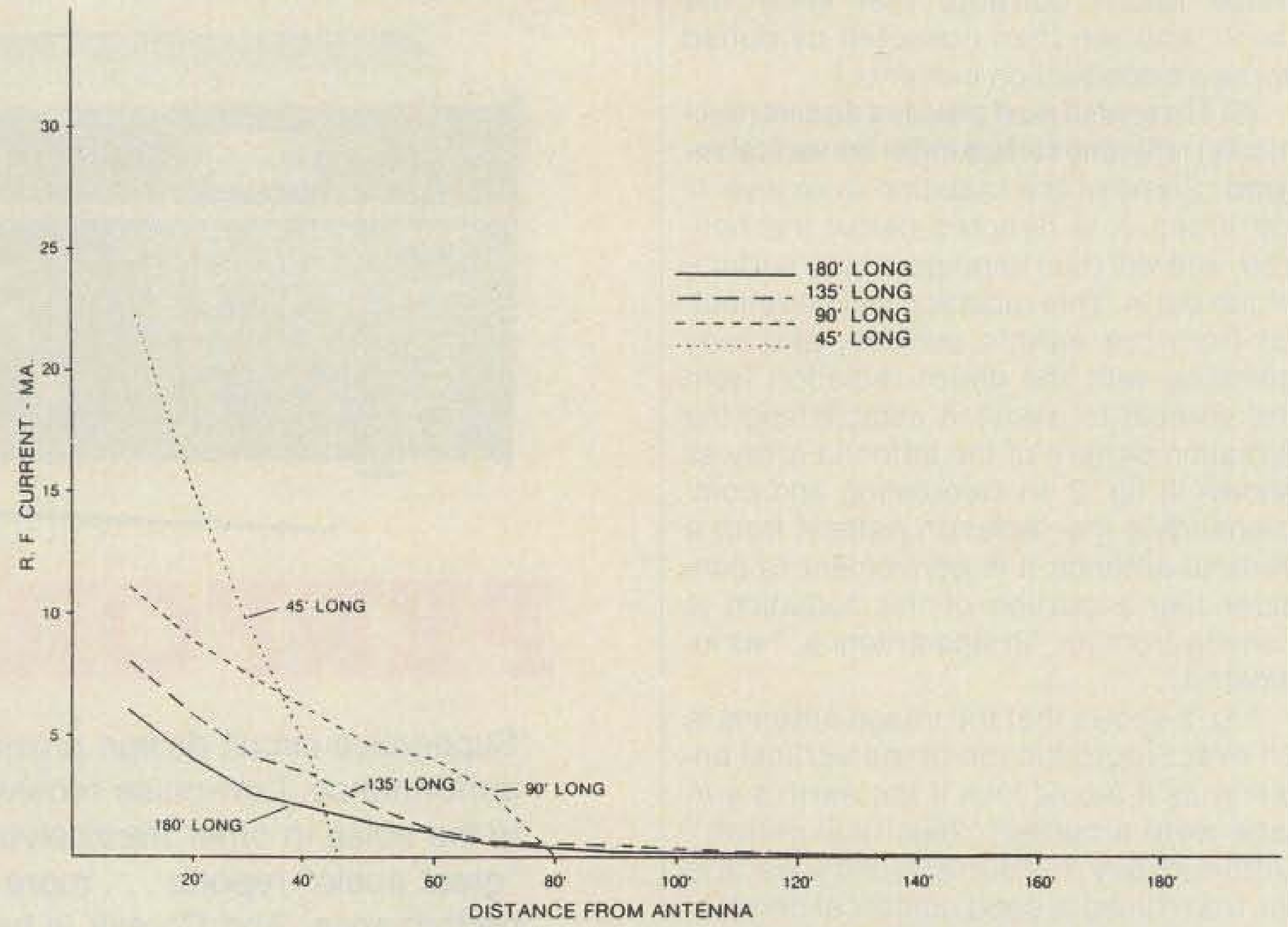


*Fig. 5– Measurement of current return in a single radial wire buried at 8".*

Radial current measurements were made every 10' on each of the various wire lengths listed above.

In the tests the "elevated" wires were 6'6" above ground level, the "on the ground" wires were lying loosely on the earth, and the "buried" radials were 8" below the earth's surface, as shown in fig. 4.

Location of the "elevated" and "on the ground" wires was directly above the "buried" wire.

The results of this series of tests were compared and supplemented by data from the 1981–1982 tests. This was possible since the earlier tests were conducted on the same site, and the same instrumentation and testing techniques were employed. The following observations are based on these studies:

**I:** The currents in buried, non-insulated, radial wires are concentrated near the base of the antenna and decrease at a generally constant rate as the distance from the antenna increases. This is shown in fig. 5 and confirms what has been described in the literature for several decades.

**II:** As shown in fig. 6, the distribution of return currents in elevated or insulated radial wires having lengths less than approximately 0.20 wavelength is the same as that found in buried wires.

**III:** Fig. 7 shows that the distribution of return currents collected by elevated wires *can* be distinctly different from that found in buried "radial" wires. Extensive testing showed that this phenomena exists as long as the elevated wire is more than approximately 0.20 wavelength long.

In these elevated wires the current level is at a moderate level near the antenna, rises very slightly, remains at an almost constant level for a considerable distance, and then gradually decreases to zero.

This same current distribution pattern was consistently found in similar elevated radials tested in the very comprehensive previous Fletcher test program. It has also been observed in the counterpoise radials of another research antenna extensively tested this year at a different location.

**Note:** The current distribution pattern of these elevated radial wires results in lower losses (R1 in fig. 1) than those caused by the high level of currents adjacent to the antenna when buried radials are used. In practice, the high level of current found near the base of the antenna with buried radials has resulted in heating (I squared R) losses so high as to set grass afire near the base of a vertical antenna!

**IV:** Fig. 7 also illustrates that currents found in insulated radial wires lying on the ground are similar to those found in elevated wires. Again, tests showed that this effect occurs so long as the radial is longer than approximately 0.20 wavelength.

**Note:** Thus, this type of radial provides the same advantages over buried bare-wire radials as discussed above for elevated wires.

**V:** Elevated ground systems—counterpoise or ground screen—are extremely efficient in intercepting return currents directly from the antenna before they can reach the ground. As shown in fig. 8, there are very small currents in the ground under elevated wires connected to collect such currents. Those currents that *do* exist in the ground are conducted to the elevated wires as displacement currents.

The new test program has indicated that a properly dimensioned elevated ground system, or a radial system using insulated wire, operates more efficiently (with less losses) in collecting return currents from a vertical antenna than does a buried bare-wire ground system.

One of the reasons for the low efficiency of buried bare wires is that the return currents that they collect must pass through the ground for a greater or lesser distance before they reach the location of a radial wire. There are relatively high ohmic losses in this process, as the earth through which the currents must flow has finite resistance. This situation becomes serious near the antenna, where the return currents in buried radials are concentrated, and (I squared R) losses become high.

In contrast, elevated and/or insulated radial wires collect the majority of the currents that they carry directly from the antenna, and the balance as displacement currents from the earth below the wires. The losses incurred in the passage of these return (displacement) currents to the elevated wires in each case involves only the relatively low losses involved in their transference through the dielectric between the wire and the antenna or the ground—air.

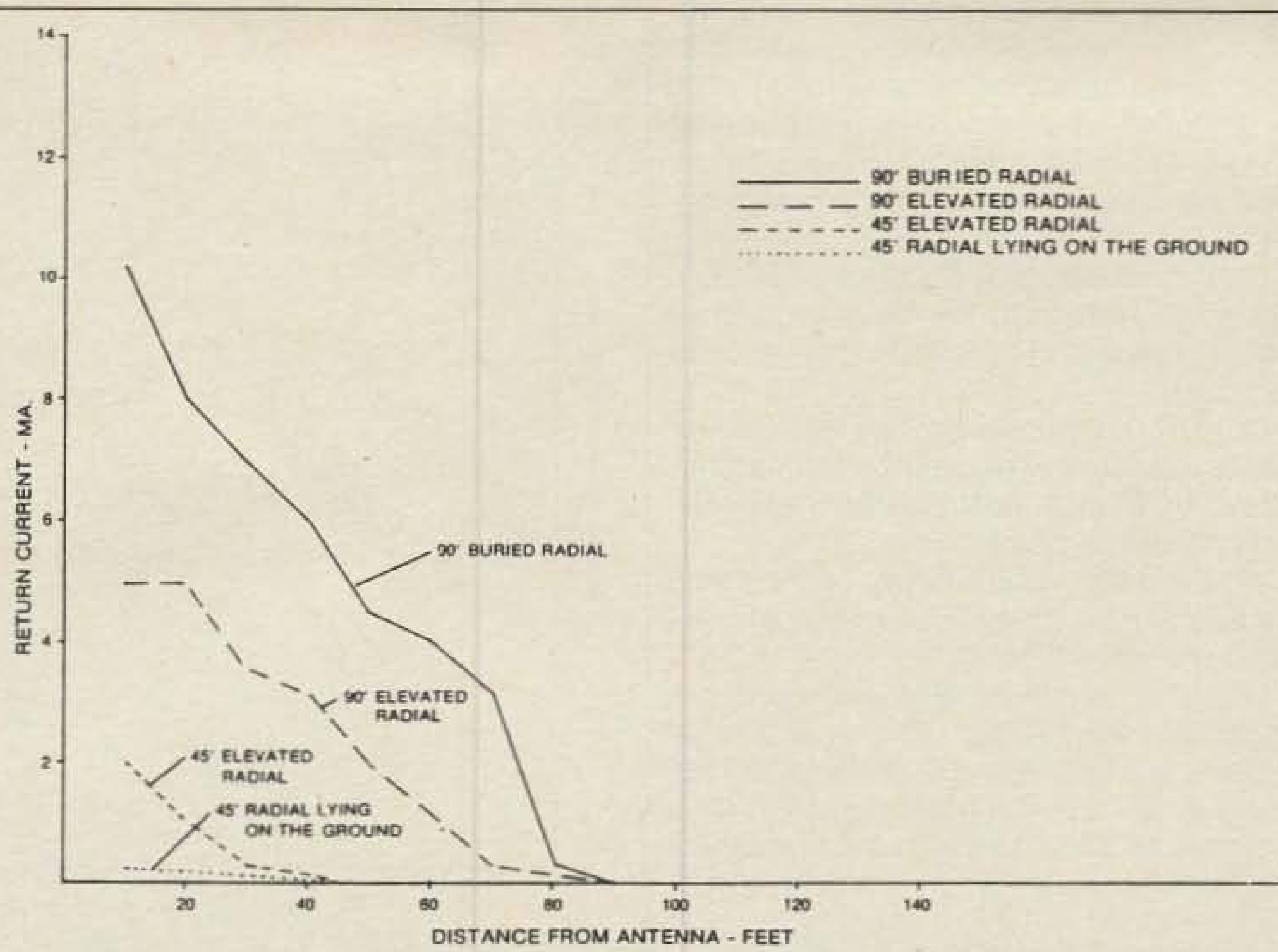


*Fig. 6– Return current distribution in short radials.*

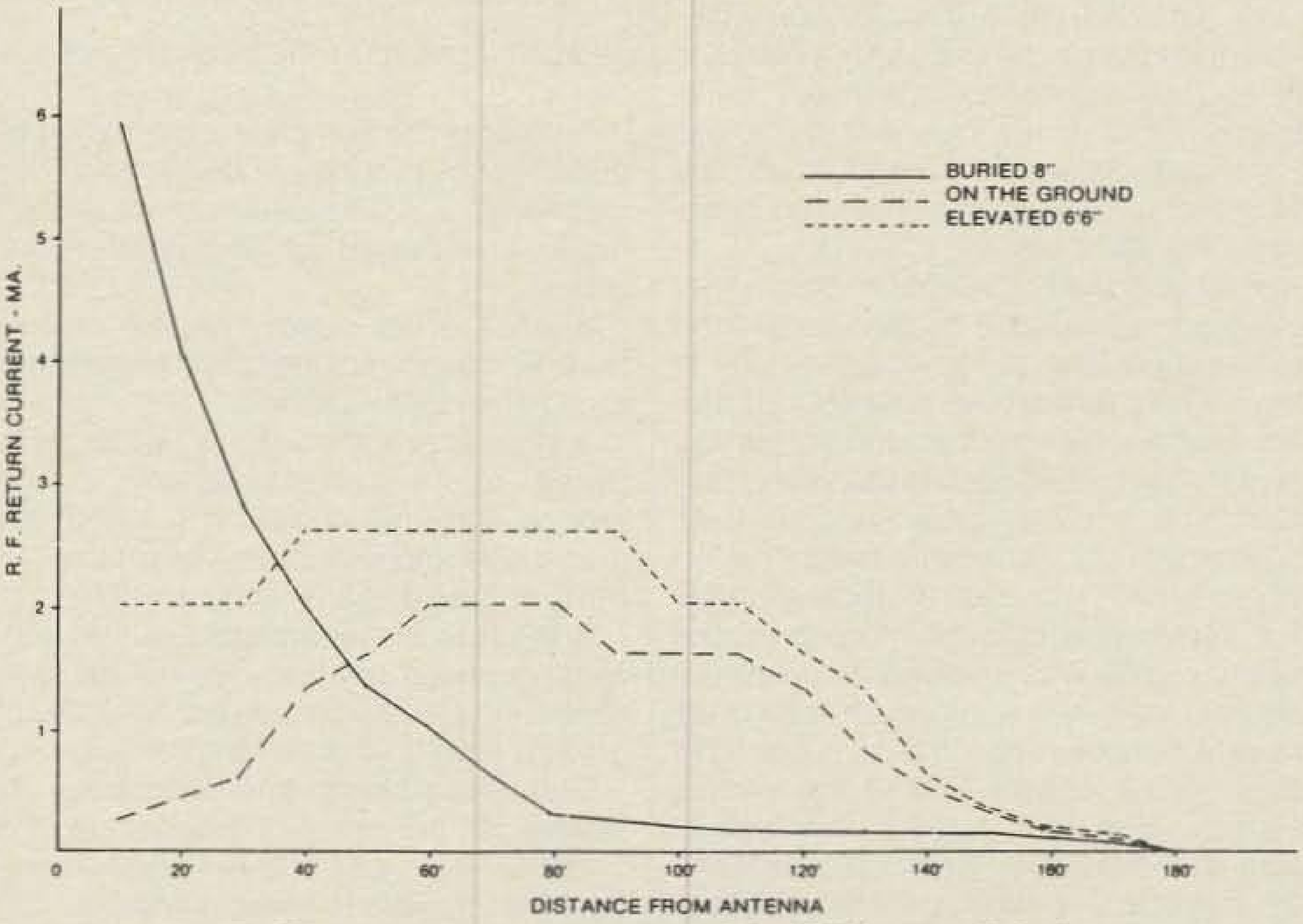


*Fig. 7– The return current measured in 180' long radial wires.*

## Conclusions

From the results of the most recent test program it can be concluded that elevated, or buried but insulated, radial wire arrays fulfill the theoretical requirements of artificial ground systems better than the buried (bare) wire arrays that have been most commonly used in the past. The primary reason for this high efficiency can be best expressed: *It is more efficient to collect return currents from vertical antennas as displacement currents rather than as conduction currents.*

## Recommendations

From the above new data some specific recommendations can be derived concerning radial wires used as the ground system for a vertical antenna. The results of the newer test program have also prompted further analysis of the earlier, and far more extensive, series of tests. Several additional recommendations have resulted from this analysis. The combined recommendations resulting from the several Fletcher research programs can simply be summarized thus:

1. Radial wires should not be buried if they are to collect return currents from a vertical antenna with maximum efficiency.

2. If possible, elevated radials should be used. These can be insulated (i.e., a counterpoise) or grounded (a ground screen).

3. If it is not possible to use elevated radials, insulated wire lying on the ground, or buried as close to the surface as possible, should be used.

4. Elevated radial wires, or insulated radials at ground level, should be at least 0.20 wavelength long.

5. If the above recommendations are followed, 50 radials utilizing insulated wire should provide the same effectiveness as an artificial ground system for a vertical antenna as 120 buried radials of non-insulated wire.

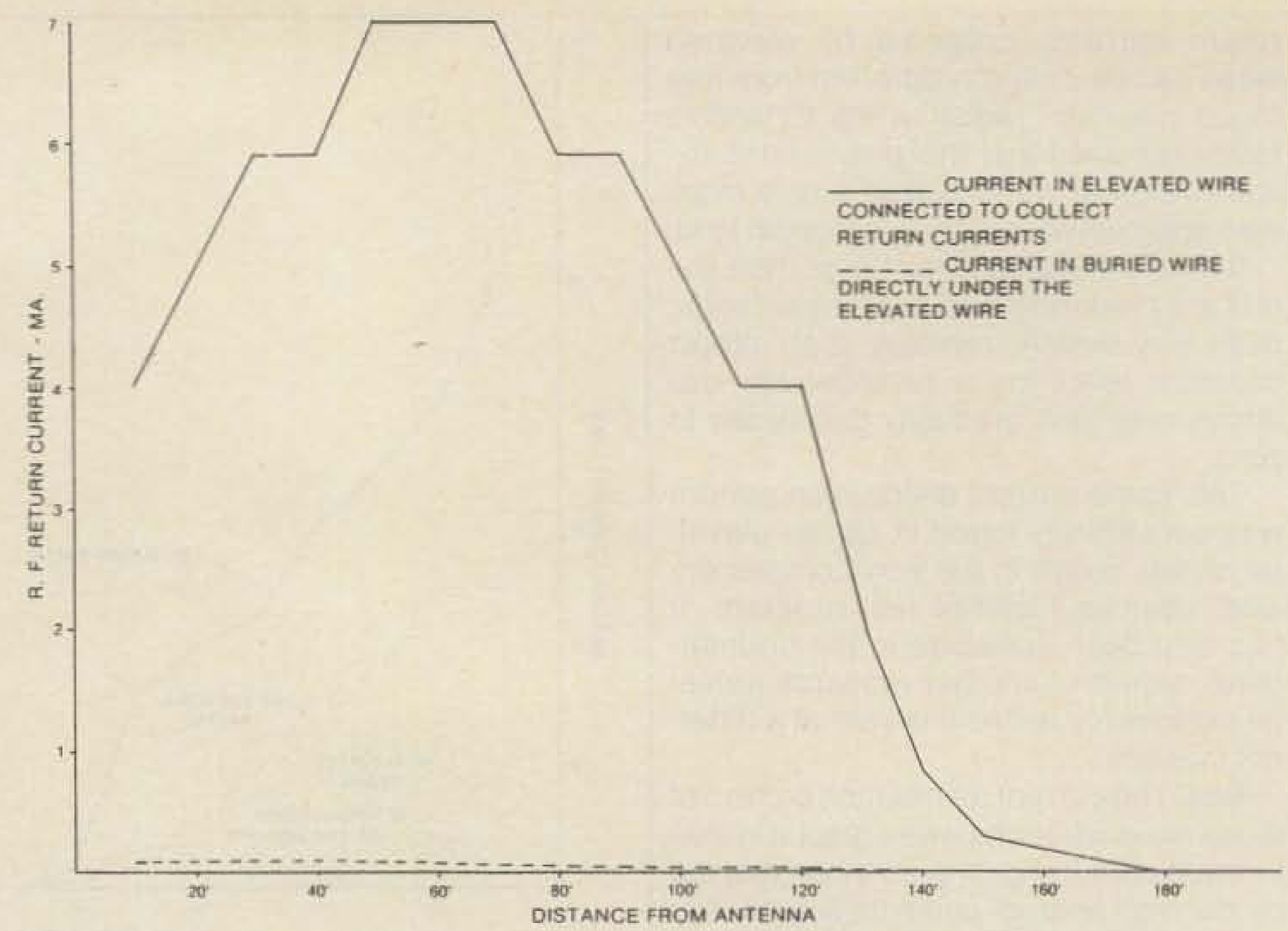


*Fig. 8– Return currents in elevated and buried wires.*

## Unresolved Questions

Any test program—and even ones that have included more than 20,000 measurements, as in the case of the Fletcher tests—leaves some questions unresolved or raises new considerations. The Fletcher tests are no exception, as they have left a number of unresolved questions. For example:

• What is the full scientific reason why elevated or insulated radial-wire ground systems perform as well as they do? In this regard, it must be remembered that the counterpoise and ground screen arrays that provided such outstanding performance in the original Fletcher tests used a total of 7500′ of wire radials covering an area 200′ x 300′, or approximately 1.4 acres. This sounds impressive, but what actually was involved, to present it another way, was a miniscule total of 31 square feet of wire surface suspended over 60,000 square feet of the earth's surface. How is it that this thin web of wire can have the "capture area" and other properties that allow it to be so successful in filling the theoretical considerations described at the beginning of this paper?

• What is the complete explanation of the effect of ground conductivity on the magnitude and distribution of return currents in elevated or insulated radial wires?

• What is the density pattern of currents in the ground under and beyond the artificial ground system?

• What correlation, if any, is there between return current density in the ground, ground conductivity, and the magnitude and distribution of return currents in the adjacent radial wires?

• What is the complete analysis—including phase relationship—of the currents in elevated/insulated radials of greater than 0.20 wavelength?

The researchers who have been involved in the various phases of the Fletcher tests can't give truly comprehensive answers to these questions, and several years of study of the available literature—which spans 60 years—has not been much help. It is hoped that publication of this data will encourage others to search for the answers to these questions and will help in enlarging the knowledge of artificial ground systems.

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This paper is dedicated to the late Edmund A. Laport. Without his encouragement, friendship, support, and an occasional prod, this research would not have been completed.

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