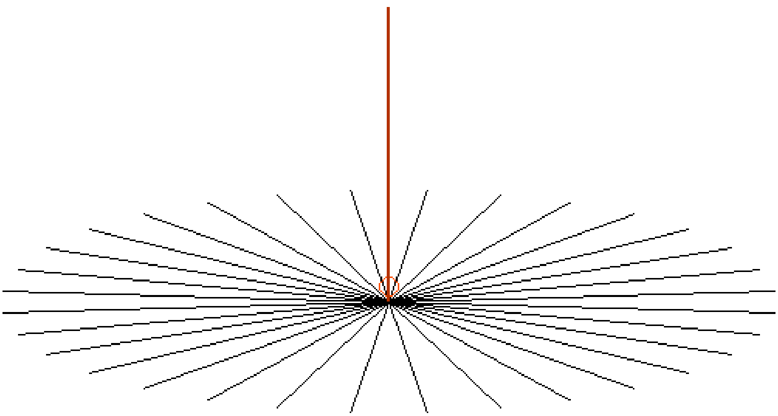
Ground-Plane Notes



L. B. Cebik, W4RNL

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Dedication

This volume of studies of ground-plane antennas is dedicated to the memory of Jean, who was my wife, my friend, my supporter, and my colleague. Her patience, understanding, and assistance gave me the confidence to retire early from academic life to undertake full-time the continuing development of my personal web site (http://www.cebik.com). The site is devoted to providing, as best I can, information of use to radio amateurs and others–both beginning and experienced–on various antenna and related topics. This volume grew out of that work–and hence, shows Jean's help at every step.

1. Some Ground Grounding

Despite the fact that the idea of the ground plane is one of the fundamentals of antenna work, the subject still eludes many folks, especially in the amateur community. Over the years, I have had occasion to model many aspects of ground-plane operation. However, the available collection of notes at my web site (http://www.cebik.com) reflects the varied circumstances of each small study. Hence, visitors have difficulties drawing together the threads of the pieces into a more complete whole cloth. So, with considerable trepidation, I decided to start over, hoping to weave a more coherent tapestry.

The notes collected here rest on a completely new set of models. Since lower HF (and MF) antennas raise the most questions, I have created a series of models for 160, 80, and 40 meters. The test frequencies are 1.85, 3.6, and 7.15 MHz, but the results generally apply to the entire bands in question. Before we close the book on ground planes, we shall also have occasion to sample some upper HF and VHF ground-plane antennas. However, they will present us with different questions than the lower HF antennas and their associated ground planes. Indeed, seeing how the various spectrum regions are related will become part of our general goal.

We shall examine a number of questions for which modeling data (NEC-4, specifically GNEC) is relevant. Chapters 1 through 4 form a body of background information, helpful in understanding the concepts and models of antennas intimately involved with the ground. Of course, the most fundamental of those antennas is the ground-plane monopole with radials at or below the surface of the earth. Those with a practical turn of mind may wish to start their reading with Chapter 5. In that section, the models serve to provide answers to frequently asked questions that I regularly receive. How many radials? How long? How deep? What material? Insulated or bare? How fat a monopole? How tall? Do not stop with Chapter 5, but return here to add the necessary background to aid you in understanding the data that provides the answer to the frequently asked questions.

Virtually all of the questions that we shall tackle in this volume will involve the development of adequate models, especially for ground-plane radial systems using buried wires or wires close to the ground. In Chapter 2, we shall examine various ways to formulate models, using the full set of geometry commands offered by NEC-4. In the process, we shall become accustomed to using NEC's GM, GR, and GX commands. These are not idle exercises in modeling, since later chapters will use them as integral parts of data gathering tasks. The symmetry commands can shorten the work of gathering data over a wide span of variations on a basic model. As well, we shall at least briefly examine the relationship of the models to reality.

Most lower-HF antennas that use ground-plane radial systems are monopoles, and these antennas are fundamentally confusing. The confusion arises as a function of classical monopole theory and its basis in optically related concepts, such as the image. There are alternative perspectives on monopoles, and we shall explore at least one major strain of them. In Chapter 3, we shall look at the idea of a monopole top hat load and gradually convert that idea into a set of ground-plane radials. Then we shall lower the monopole and its radial set (actually, sets ranging from 4 to 64 radials) until the radials bury themselves in the ground. The modeling ground, of course, will be the Sommerfeld-Norton ground calculation system that is a part of NEC-4. It may offer some insights and surprises that just might alter the way we look at the ground.

In Chapter 3, we shall only have space to look at one test frequency and a few selected samples of soil quality. These samples will leave us with numerous questions about the effects of ground or soil quality on the performance of lower HF monopoles. We generally define a soil quality by reference to 2 independent properties: conductivity and relative permittivity (or dielectric constant). Because the NEC program combines these values into a single complex permittivity value that we shall examine later in this chapter, we often fail to appreciate the role played by each value in ground-plane monopole performance. Chapter 4 will provide a detailed dissection of the properties through actual data gathering, that is, by combining the values into a systematic series of combinations. Because the effects of ground have a frequency-dependent component, we shall use 3 separate frequencies of keen amateur interest: 1.85 MHz, 3.6 MHz, and 7.15 MHz.

Chapter 5, on frequently asked questions tries to capitalize on the background developed in preceding chapters to provide some sensible answers to common inquiries. Eventually, we shall have to compare buried radials with elevated radial systems, and we shall approach this matter in Chapter 6. Al Christman (ex-KB8I, now K3LC) has perhaps done the most work in this arena, especially as it relates to slight elevations in the upper MF and lower HF ranges, so little in our presentation will show anything new. However, as we move upward in frequency and gather some freedom to place our upper-HF verticals on rooftops, we shall discover a second region of concern over elevated ground-plane antennas: getting them too high. By the time we reach the VHF range, however, we shall discover still a third sense of elevation in which nothing is too high.

In Chapter 7, we address 2 questions about modeling. The first question applies to a growing number of radio amateurs who are expanding their simple lower-HF monopoles into multiple monopole arrays. These systems require multiple–often intersecting–radial systems. The analytical question that we shall tackle is how best to model them efficiently, that is, in models that run accurately and rapidly. While we are at it, we might as well look at what modeling has to say about the use of radials below vertical dipoles and other arrays that in principle do not require radials. For that exercise, we shall examine some interesting antennas, collectively known as self-contained vertical arrays (SCVs), such as half squares and bobtail curtains. The discussion will eventually return us to some of the topics that appear in this very first chapter.

Another facet of the monopole and its ground plane revolves around the monopole length. For better or worse, there is a mystique surrounding the 5/8-λ monopole that we should explore. We shall examine and compare monopoles of various lengths from 160 m through 432 m. In the course of our meanderings, we shall look at some of the monopole shapes and raise a perennial question: when is a monopole not a monopole, but only a dipole in disguise? We may even succumb to the temptation of formulating an answer to an even tougher question: when does a dipole become a doublet? Although these questions may seem foreign to the matter of 5/8-λ monopoles, we shall discover that they are perfectly germane and even crucial to understanding the "monopole scene."

Our main vehicle of investigation will be the judicious use of NEC-4 modeling software to develop large data collections that we could not begin to assemble using physical antennas. The process begins with the development of models that pass all adequacy tests. We shall be alert to the patterns and trends in the data that reveal something about what may be important (and unimportant) to the behavior of ground-plane antennas. But as many good models as we may develop and as many indicative trends and patterns that we may uncover, the effort will remain incomplete.

Everything that we shall explore falls in the middle of the antenna studies. In one direction, there abounds a rich literature of basic theory about monopoles, ground, and radial systems. In the other direction lies an equally rich literature devoted to practical applications, ranging from regulations affecting the engineering of high-power broadcast stations to using easily obtained materials for modest amateur installations. Our modeling data compendium lies in between these extremes. My premise is simply the belief that the data trends and patterns can increase our understanding of antenna operation and performance and improve the expectations that we carry to antennas. However, an old song tells us, "Don't mess with Mr. In-Between," at least in the wisdom of Johnny Mercer. Whether that line applies to this work is for you to decide.

Because our topic is the ground plane, we shall begin our foray by looking at the very fuzzy idea of ground. The goal is to sort out some aspects of this much over-used term so that we begin to get a sense of what we mean by it in various contexts. Let's dig in.

One Ground or Many?

A ground is a ground is a ground. Or is it? In the earliest days of radio, the notion of a ground referred to an earth ground. The need for safety, especially with the rise of the AC power supply for vacuum-tube equipment, brought the earth ground up to the chassis. Indeed, anything ultimately connected or connectable to an earth ground was a ground. That practice led to a certain careless way of using the term "ground." Eventually, most radio amateurs lost their ability to distinguish among the fine shades of functional difference among the references to ground.

In some ways, all uses of the term "ground" have a connection. However, the following notes are more interested in sorting out some of the functional differences. Because we are referring to functional differences, we shall find no sharp dividing lines between categories. Indeed, in many cases, we can satisfy the grounding needs of many categories with a single set of actions. Nevertheless, we may find it useful in the present context to keep the functional differentiations in mind.

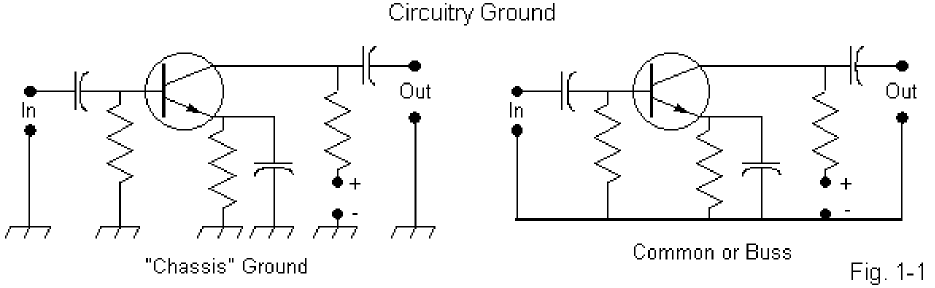


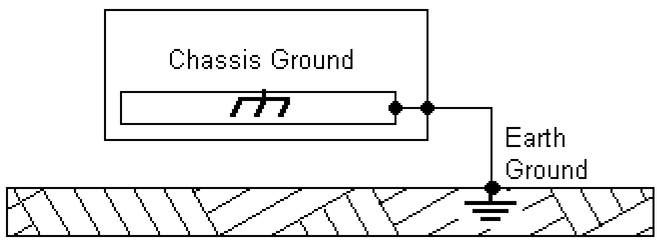
Fig. 1-1

1. The circuitry common buss or ground: **Fig. 1-1** shows a simple circuit. On the left, the circuit diagram shows separate chassis ground symbols. The chassis-ground symbol arose only in the second half of the 20th century to differentiate the circuitry common buss from an earth ground proper. Indeed, many circuits use no connection to an earth ground, in some cases intentionally and preferably. For a self-contained circuit (or collection of circuits forming an electronic instrument), a connection to an earth ground might be the occasion for potential trouble, perhaps by opening a path for surge voltages into components not designed to withstand more than a few tens of volts. When a short-term spike may reach several hundred volts, its presence on the negative or common side of the circuit or its presence on the positive side makes little difference to the damage that results.

On the right, we find an alternative way to represent the circuit buss or common, one that does not involve a ground symbol. Nevertheless, we continue to refer to the circuit common as a ground. The use of this type of diagram makes clearer the option that we have of whether to connect the common or chassis ground to earth. **Fig. 1-2** shows both chassis and earth ground symbols and their correct application.

Where once we had only the earth ground symbol for all applications of ground, we now have multiple ways to represent the situation. Technically, we should only use the earth ground symbol when we truly intend some form of earth ground mechanism. However, I continue to see the chassis ground symbol used as an earth ground symbol, perhaps because it is easier to draw. I am often guilty myself. And, of course, some old timers, recognized by their references to condensers rather than capacitors, continue to use the earth-ground symbol for all ground references. Yet, even if we carefully honor the difference between the two symbols, we may discover that not all earth grounds are alike.

Chassis vs. Earth Ground Fig. 1-2



2. DC and static discharge grounds: Perhaps the simplest earth ground serves to provide a safe path to ground for discharging static charges that accumulate on antennas, equipment cases, and similar metallic objects. In this case, a simple measure ensures safe discharge: a low-loss path to a single ground rod. The same technique also serves to provide a ground for DC short circuits, ensuring that the short blows out a fuse (or the power source, if a fuse is wanting). Modern house-wiring codes also call for a central ground of the same sort for the low-frequency AC system that forms our main power source at home. In many cases, we connect the copper plumbing pipes to the same ground rod at some point along the way.

Modern materials can thwart the intentions of such a system, especially under the axe of remodeling. In many localities, both water supply lines and waste lines may use non-conductive materials. New construction may take this into account, but remodeling often inserts non-conductive pipe runs between conductive sections. As a result, the cable company's static discharge wire clamped to an outdoor water faucet may prove totally ineffective in bleeding surges and static charges from the cable shielding.

The key evidence of a need to differentiate this form of grounding from others that we shall note lies in our efforts to separate RF energy from static charges to be bled off through the ground rod. Some antenna makers install an RF choke in the static discharge line to ensure that the RF signal energy goes to the equipment, while the line remains at 0-volts DC potential. Not only can we differentiate RF from DC and low-frequency AC ground lines, we can also note differences in the needs for each kind of grounding.

3. Lightning ground: Household and electronic equipment damage due to lightning makes it a major category for insurance companies. The required grounding system for adequate lightning protection is quite complex where communications systems are involved, and there are entire books devoted to the subject. For a station that must remain available or on the air during an electrical storm, the system involves shunting any lightning strike to ground by a series of conductors having the lowest possible resistance. As well, such systems require long ground rods (8' to 10' is standard in the U.S.), spaced apart only by about the length of each rod. Most systems also include lightning rods and similar devices to form a peak height to which the system brings the ground and to catch lightning discharges instead of the station equipment and antennas. Indoors, such stations have an array of devices to divert lightning surges before they can adversely affect the operating equipment.

Of course, lightning does not need to directly strike an antenna to damage equipment. Distant strikes on power lines and even distant strikes to the ground can provide a surge path through the very low-resistance lines we use to connect to an earth ground. For the radio amateur who does not absolutely need to be on the air during an electrical storm, the best safety measure for the station equipment may be the "total disconnect." A total disconnect means the removal of all connections between the equipment and the external world, including antenna connections, AC power connections, and ground connections. The work involved in setting up such a system for quick use may save both the equipment and even one's home. Of course, disconnected antennas should find a new connection to a good lightning ground rod. As well, although equipment disconnection may save it, the radio amateur needs to determine whether his home requires professional treatment in its own right.

4. RF ground: An effective RF ground also requires attention to many details. Deep rods, while useful, may be less effective as RF grounds than we previously thought, and the U.S. Army developed a system of perimeter straps and a sequence of shorter rods to effect a satisfactory overall station RF ground, as sketched (with many missing elements) in **Fig. 1-3**. The goal is to have among all of the elements of the station very low loss connections everywhere that requires an RF ground. A ground rod at the house and a ground rod at the base of an antenna 200' away may not be sufficient. RF paths to and from ground via transmission lines, circuitry-to-case connections, common mode paths, and numerous other sources are receiving increased attention both by those who build equipment and by those who assemble operating stations.

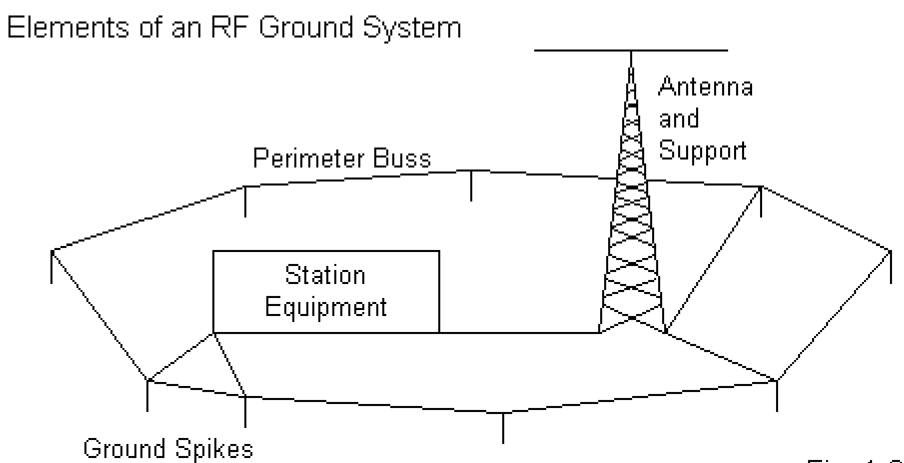


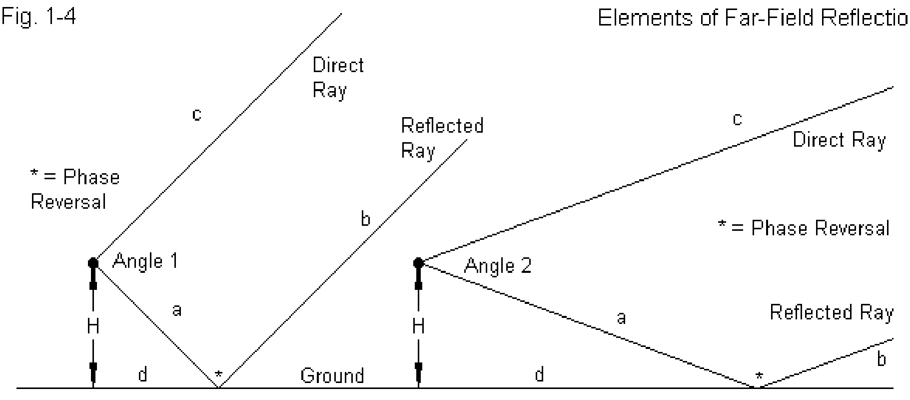
Fig. 1-3

There are many elements of a good RF ground system that are compatible with the elements of a good lightning-protection ground system. The use of long rods and a perimeter buss might serve both purposes. However, we should not assume without adequate planning that one system is doing the work of two.

In the course of our travels through many types of antennas, we shall find a few cases where many folks mistake an RF ground situation for an antenna-related grounding situation. In a subset of such cases, we may discover that we have a combination of the two, a condition that can make diagnosing operating troubles more than a little difficult.

We might extend this list–not to mention subdivide it. But let's turn to a couple of new categories created out of one old one. Both have to do with antennas. We tend to think of the ground relative to an antenna as a single ground. Hence, we tend to lump together the ground from which signals reflect to contribute to antenna far field patterns and the ground directly under a monopole antenna. The "only" difference is their relative distance from the antenna itself. However, let's see where separating the two ideas leads.

Fig. 1-4 Elements of Far-Field Reflections



5. Far-field reflection ground: An antenna's far field (or Fraunhofer zone) begins at a point about twice the square of the antenna's maximum dimension divided by a wavelength at the operating frequency. The near-field region (or Fresnel zone) lies closer to the antenna than the specified limit. However, our interest on the far field hinges less upon where it begins than on where it ends.

Generally, we consider any point in the far field as lying so far away from the antenna that the antenna shrinks to a near infinitesimal compared to the distance. At such distances, the energy reaching any point of concern is a function of 2 parallel rays, one emerging directly from the antenna, and the other a product of reflection from the earth's surface. As shown in **Fig. 1-4**, the two paths have different lengths, and the reflected ray undergoes a phase reversal in the reflection process.

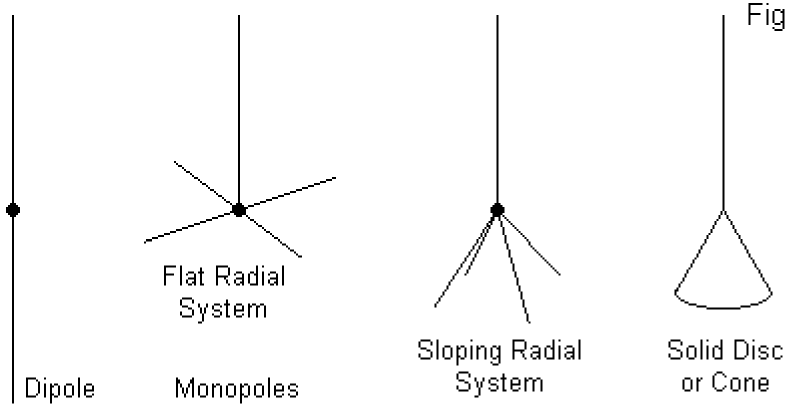
At the distant point, the combination of the direct and reflected rays may be in phase, creating a lobe in the overall elevation pattern. At the other extreme, they may be out of phase, creating a null. Since the reflected path varies in length according to the angle that we investigate, an elevation pattern may undergo many transitions from lobe to null and back again. Note that at a very low angle, the direct and reflected ray paths are very nearly identical, resulting in nearly complete signal cancellation. NEC software does not provide any usable far-field pattern gain or signal strength values for the horizon, although one can specify an elevation angle that is nearly zero (perhaps 0.1°).

The strength of the lobes and nulls depends on many factors in addition to the angle of investigation. Some of these factors are built into antenna modeling software. For example, as we shall see shortly in more detail, the modeler can select the quality of the ground in terms of applicable values of conductivity and permittivity (or relative dielectric constant). However, other ground conditions lie outside most antenna modeling software packages. Rough or sloping terrain and variable soil qualities both defy NEC-based modeling, which assumes a flat horizon and uniform soil quality.

In virtually all cases, the reflection zone for the far field lies outside the range over which the antenna installer has any control. Far-field reflections are at the mercy of the environment surrounding the antenna from distance from 2 to many wavelengths away. Stated briefly, ground-plane radial systems installed around a vertical monopole antenna may increase the ratio of radiated energy to energy lost to ground resistance, and thereby enhance overall gain. However, they have no effect on the ratio of direct to reflected energy in the far field.

6. Antenna-completion "ground": Before we look at monopoles in their traditional garb of having an image antenna in the ground, let's take a different slant on the matter. **Fig. 1-5** presents a vertical monopole along with three different but intimately related monopoles.

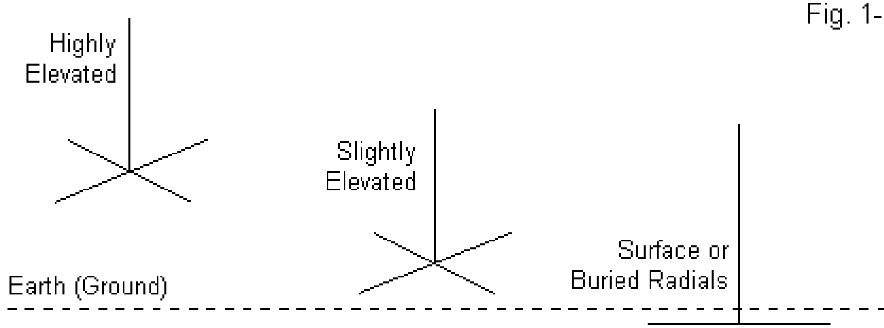
Fig. 1-5



Antennas with Non-Radiating or Reduced Radiation Completions

The flat-radial system is the most traditional portrayal of a ¼-λ monopole. At lower HF frequencies, we often see the radials sketched as lying on the ground or in the ground. However, we also know that the antenna works at VHF, and we persist in calling the radials the "ground plane." Essentially the radials for an elevated monopole constitute the missing part of the dipole. We arrange enough radials so that the fields from the remaining legs cancel the radiation field from each leg. Hence, we develop no horizontally polarized radiation component to the total field, and we have a vertically polarized antenna. The remaining versions of the antenna show two different types of sloping-radial systems, the last one being a solid cone. Each of these sloping systems carries a vertical and a horizontal component. However, the balance among the horizontal components yields overall self-cancellation. The vertical component becomes part of the overall vertically polarized radiation field.

Fig. 1-6



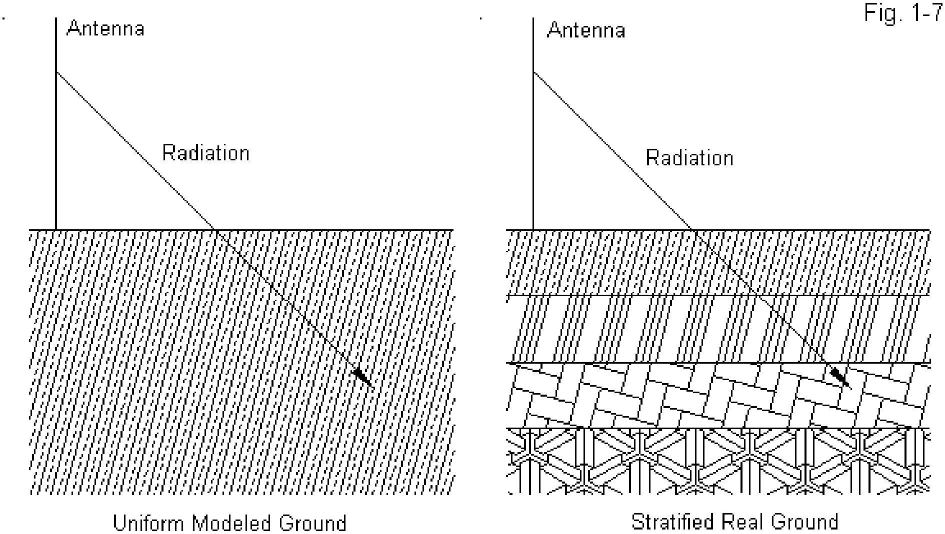
Typical Ground-Plane Positions Relative to Earth Ground

We call these radial systems ground planes, although in many cases, they have nothing to do with the earth ground. As shown in **Fig. 1-6**, the relationship of the radials to the ground varies according to the position of the antenna. At many wavelengths above ground–typical for a VHF installation, the ground has almost no interaction with the ground plane, although the far-field reflection ground considerations that we previously noted play a strong role in overall antenna performance properties. As we bring the antenna closer to the ground, interactions are stronger, as witnessed by required changes in element lengths to maintain resonance. In the amateur MF and low-HF regions, the radials may actually lie upon the ground or be buried beneath the ground. Although some of our work will involve elevated ground-plane radials systems, we shall primarily focus on buried radials and their models.

Ground Qualities and Their Models

For ground-plane monopoles that use buried radials or radials only slightly elevated, the quality of the ground plays a key role in several different performance categories. NEC-2 and NEC-4 can accurately model ground performance within the model developed by Norton and given extended mathematical formulation by Sommerfeld. Relative to reality, NEC has an important limitation, suggested by the crude sketch in **Fig. 1-7**. In effect, NEC calculates on the basis of a uniform and homogenous ground beneath the antenna.

Fig. 1-7



Modeled vs. Actual Ground Conditions

The actual ground may be stratified or layered such that each layer may have distinct values of conductivity and permittivity. Hence, NEC's ability to model actual ground is limited, although it remains very useful. We have already noted in passing that NEC also presumes a flat surface to the horizon. Hence, it is further limited relative to reality wherever reality includes sloping, undulating, or rough terrain. One of the better-detailed accounts of how antennas interact with the ground is in chapter 3 of *The ARRL Antenna Book*, 20th Ed., developed in large part by Rudy Severns, N6LF. I recommend this chapter as perhaps required reading by anyone contemplating the installation of a ground-mounted vertical antenna array, whatever the simplicity or complexity.

We ordinarily characterize the ground quality for any antenna site in terms of its conductivity and its relative permittivity. We measure conductivity (σ) in terms of Siemens/meter. Relative permittivity (or relative dielectric constant) (ε_r) has no unit of measure because its value is simply a comparative with the permittivity of free space (ε_0). References give the value of ε_0 as

$$\varepsilon_0 = 8.854 \cdot 10^{-12}\ F/m$$

Note the unit of measure in Farads per meter. By definition, the relative permittivity of a vacuum is 1.0, and this value is also applicable to dry air. Since the atmosphere is so variable and almost impossible to measure on a real-time basis, we ordinarily apply the base value of relative permittivity to the entire region from the ground into space. NEC follows this presumption in setting the relative permittivity of the entire region above a specified ground at the basic value.

Except for salt water, the conductivity of all grades of earth falls into the category of a semiconductor. Conductivity values range from 0.0001 S/m to 0.0303 S/m in most tables. If we translate these values into equivalent values for resistivity, we obtain a range from 33.0 Ω/m up to 10,000 Ω/m. In contrast, the conductivity of copper wire is about 5.8e7 S/m or, for resistivity, 1.7e-8 Ω/m.

For reference, I shall present two tables of values for the ground constants applicable to various types of ground. The first or traditional table has received the widest distribution, but the data is approximately 65 years old as I write these notes. The second table comes from the table of preset values available in the GNEC program and rests on an accumulation of values from several sources, both older and newer. It includes the original general categories, especially as they have acquired names, such as "very good," "good," "average," "poor," and "very poor." However, it also includes a large number of categories applicable to specific types of materials that form the ground beneath antennas for many applications.

In the tables, note the values for very good, average, and very poor soil, especially. They form a wide range of sample values often used to compare antenna performance over various soil qualities. We shall have extensive use for these ground quality categories as we progress through these notes.

Conductivity and Permittivity of Common Ground Conditions

A. Standard Table. The following soil descriptions are commonly used in antenna modeling. Always substitute more precise values wherever known. The table represents an adaptation of values found in *The ARRL Antenna Book* (20th Ed., p. 3-13), which are themselves an adaptation of the table presented by Terman in *Radio Engineer's Handbook* (p. 709), taken from "Standards of Good Engineering Practice Concerning Standard Broadcast Stations," *Federal Register* (July 8, 1939), p. 2862. Terman's value for the conductivity of the worst soil listed is an order of magnitude lower than the value shown here.

Soil Description	**Conductivity in S/m σ**	**Permittivity (Dielectric Constant) ε**	**Relative Quality**
-Fresh water	0.001	80	
-Salt water	5.0	81	
-Pastoral, low hills, rich soil, typical from Dallas, TX, to Lincoln, NE	0.0303	20	Very Good
-Pastoral, low hills, rich soil, typical of OH and IL	0.01	14	Good
-Flat country, marshy, densely wooded, typical of LA near the Mississippi River	0.0075	12	
-Pastoral, medium hills, and forestation, typical of MD, PA, NY (exclusive of mountains and coastline)	0.006	13	
-Pastoral, medium hills, and forestation, heavy clay soils, typical of central VA	0.005	13	Average
-Rocky soil, steep hills, typically mountainous	0.002	12 - 14	Poor
-Sandy, dry, flat, coastal	0.002	10	
-Cities, industrial areas	0.001	5	Very Poor
-Cities, heavy industrial areas, high buildings	0.001	3	Extremely Poor

B. The Table Used in NEC-Win Pro and GNEC. The following list of conductivity and permittivity values is drawn from many recent sources and is used as a set of user-selectable entries for ground conditions in GN and GD entries in NSI programs. Users may also enter custom values wherever information on the actual soil conditions is available.

Soil Description	**Conductivity in S/m σ**	**Permittivity (Dielectric Constant) ε**
Poor	0.001	4.5
Moderate	0.003	4
Average	0.005	13
Good	0.01	4
Dry, sandy, coastal	0.001	10
Pastoral hills, rich soil	0.007	17
Pastoral medium hills and forestation	0.004	13
Fertile land	0.002	10
Rich agricultural land, low hills	0.01	15
Rocky, steep hills	0.002	15
Marshy land, densely wooded	0.0075	12
Marshy, forested, flat	0.008	12
Mountainous, hilly (up to about 1000 m)	0.002	5
Highly moist ground	0.005	30
City industrial of average attenuation	0.001	5
City industrial of maximal attenuation	0.0004	3
City industrial area	0.0001	3
Fresh water	0.001	80
Fresh water @ 10° C and 100 MHz	0.001	84
Fresh water @ 20° C and 100 MHz	0.005	80
Sea water	5.0	81
Sea water @ 10° C up to 1 GHz	4.0	80
Sea water @ 20° C up to 1 GHz	4.0	73
Sea ice	0.001	4
Polar ice	0.0003	3
Polar ice cap	0.0001	1
Arctic land	0.0005	3

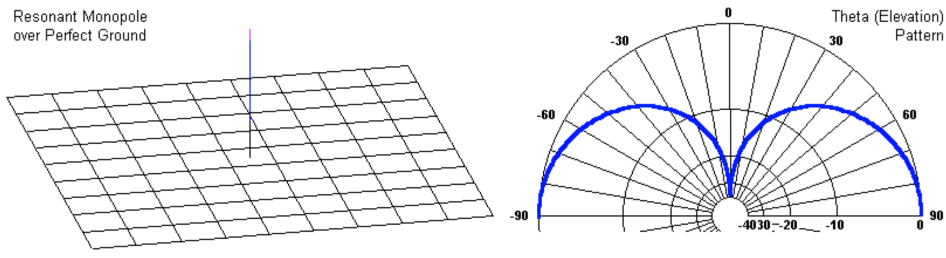
In a future chapter, we shall look in more detail at how the changes in the values of soil conductivity and relative permittivity affect antenna performance. For these introductory notes, let's focus on another factor in the calculation of soil effects that many radio amateurs overlook: the effect of frequency. An adequate demonstration must have a baseline. For this purpose, we may choose resonant monopoles over a perfect ground, using our key frequencies of 1.85, 3.6, and 7.15 MHz. So that all things except frequency will be equal, the monopoles for each frequency are exact scalings of each other to about 4 significant figures. The following models use perfect conductors so that skin effect changes with frequency will not affect the outcome.

```
GW 1 11 0 0 0 0 0 38.9076 .04826
GE 1 -1 0
GN 1
EX 0 1 1 0 1 0
FR 0 1 0 0 1.85 1
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN

GW 1 11 0 0 0 0 0 19.9942 .0248
GE 1 -1 0
GN 1
EX 0 1 1 0 1 0
FR 0 1 0 0 3.6 1
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN

GW 1 11 0 0 0 0 0 10.067 .0125
GE 1 -1 0
GN 1
EX 0 1 1 0 1 0
FR 0 1 0 0 7.15 1
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

The models differ from each other only in the monopole length and radius and in the test frequency. If you replicate the test using the models included with this volume, you will obtain a maximum gain of 5.14 dBi and a source impedance of 36.08 + j0.07 Ω. See **Fig. 1-8** for the model sketch and the elevation (theta) pattern.



Demonstration 1.85, 3.6, and 7.15 MHz Monopoles with Perfect Ground

Fig. 1-8

Lossless models over lossless ground, when perfectly scaled, yield identical results, regardless of frequency. That fact is our baseline for the following experiment. We shall retain the 3 monopoles, using the same length, segmentation, and radius as in the original models. However, we shall add 64 radials as a ground plane that we shall place above the ground by 0.001 λ. The actual dimensions in meters, of course, will vary from one frequency to the next in accord with scaling principles. The radial systems will be perfectly symmetrical using 4-mm diameter wire–a common European value–at 7.15 MHz. We shall, of course, scale the wire diameter upward as we decrease the frequency.

Having access to the full command set, we can create abbreviated models, since we do not require separate entries for each radial in the system. We create the first radial and then replicate it with the GM command 63 more times at an angular separation of 5.625°.

The ground for this demonstration will be "average," with a conductivity of 0.005 S/m and a relative permittivity of 13. We might have selected almost any set of ground values from the lists in the tables, but average ground will do the job of demonstrating the dependence of antenna system performance on frequency, relative to the effects of ground.

Despite our addition of 64 wire radials and a Sommerfeld-Norton (SN) ground to replace the perfect ground, the resulting models are still very compact.

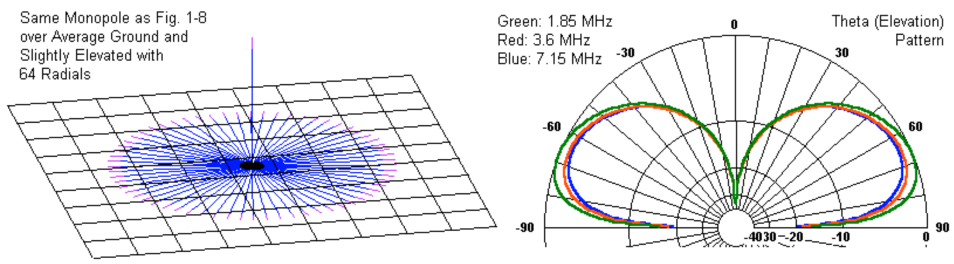
```
GW 1 11 0 0 .1623 0 0 39.0699 .04826
GW 2 11 0 0 .1623 40.5125 0 .1623 .00773
GM 1 63 0 0 5.625 0 0 0 2 1 2 11
GE -1 -1 0
GN 2 0 0 0 13.0000 0.0050
EX 0 1 1 0 1 0
FR 0 1 0 0 1.85 1
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN

GW 1 11 0 0 .0834 0 0 20.0776 .0248
GW 2 11 0 0 .0834 20.8189 0 .0834 .003972
GM 1 63 0 0 5.625 0 0 0 2 1 2 11
GE -1 -1 0
GN 2 0 0 0 13.0000 0.0050
EX 0 1 1 0 1 0
FR 0 1 0 0 3.6 1
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN

GW 1 11 0 0 .042 0 0 10.109 .0125
GW 2 11 0 0 .042 10.48225 0 .042 .002
GM 1 63 0 0 5.625 0 0 0 2 1 2 11
GE -1 -1 0
GN 2 0 0 0 13.0000 0.0050
EX 0 1 1 0 1 0
FR 0 1 0 0 7.15 1
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

If we tabulate the results of the modeling we arrive at the following data. The TO angle (or angle of maximum gain) uses the theta convention (counting from the zenith downward) followed in parentheses by the corresponding elevation angle (from the horizon upward).

Frequency MHz	Maximum Gain dBi	TO Angle degrees	Impedance R +/- jX Ω
1.85	+0.97	67 (23)	36.20 - j3.99
3.6	+0.21	65 (25)	35.56 - j5.45
7.15	-0.09	64 (26)	33.89 - j6.39



Demonstration 1.85, 3.6, and 7.15 MHz Monopoles 0.001-WL above Average Ground Fig. 1-9

Fig. 1-9 outlines the antenna model and shows an overlay of all three patterns. The 160-m monopole has over a full-dB advantage relative to the 40-m version, with a slightly lower TO angle. These value differences result from the manner in which NEC calculates ground effects. Essentially, the program combines the listed values for conductivity and permittivity into a complex relative permittivity (ε_g):

$$\varepsilon_g = \varepsilon_r - j\sigma / (2\pi f \varepsilon_0)$$

The terms of the equation have the same meanings as used earlier, and f is the frequency in Hz. As f changes, so too does the value of ε_g.

Increasing ground losses with rising frequency are not the only factors affecting monopole performance. The more familiar skin effect will also increase losses as we increase the frequency, at least up to element diameters that are so large as to reduce losses to nearly zero. You may modify the attached models to include a loss (for the monopole only) related to material conductivity (the LD5 command). This loss factor will show up in all of the models, including those using a perfect ground.

For reference, the following table lists the bulk conductivity values and resistivity values for some common materials used in antenna construction. Conductivity, of course, is simply the reciprocal of resistivity. The NEC core uses conductivity values within its LD 5 command that assigns material losses to the element or elements of an antenna. NEC-4 also allows the entry of a permeability value to account for affects resulting from the magnetic properties of the element material.

Material	Resistivity Ohms/meter	Conductivity Siemens/meter	Permeability
Pure Silver	1.62E-08	6.17E07	1.0
Copper	1.72E-08	5.80E07	1.0
Gold	2.19E-08	4.57E07	1.0
Chromium	2.6E-08	3.85E07	1.0
Pure Aluminum	2.62E-08	3.82E07	1.0
6063-T832 Aluminum alloy	3.25E-08	3.08E07	1.0
6061-T6 Aluminum alloy	4.10E-08	2.50E07	1.0
Zinc	6.0E-08	1.67E07	1.0
Brass ("yellow," 35% Zn)	6.4E-08	1.56E07	1.0
Brass (66% Cu, 34% Zn)	3.9E-08	2.56E07	1.0
Beryllium Copper	8.0E-08	1.25E07	1.0
Iron	9.71E-08	1.03E07	150
Phosphor Bronze (4% Sn, 0.5% P, rest Cu)	9.4E-08	1.06E07	1.0
Phosphor Bronze (5% Tin)	1.1E-07	9.09E06	1.0
Tin	1.14E-07	8.77E06	1.0
Steel (0.4-0.5% C, rest Fe)	1.3E-07 - 2.2E-07	7.69E06 - 4.54E06	200
Lead	2.19E-07	4.57E06	1.0
Stainless Steel (type 302)	7.20E-07	1.39E06	1.00008

Most of the materials are familiar. However, a few may require some thinking to discover why I have included them. For example, the values for tin and lead are sometimes used to simulate galvanized steel towers used in some vertical antenna installation.

As a simple exercise, let's assign to each of the 3 near-ground vertical arrays a conductivity of 1.4E06. This value is the lowest conductivity among materials on the list and will make any differences among the 3 antennas more vivid. To each model we may introduce a single LD 5 entry covering all parts of the structure. We can place the line anywhere between the GE entry and the RP entry.

```
LD 5 0 0 0 1.4e6 1
```

To see to what extent skin effect has a frequency dependency, we may compare the results of the 3 stainless steel assemblies with the 3 ground-plane verticals that use lossless wire elements. Remember that the antenna assemblies are physically perfect scalings of each other for the test frequencies.

Version	Frequency MHz		Maximum Gain dBi	TO Angle degrees	Impedance R +/- jX Ω
0-loss	1.85		+0.97	67 (23)	36.20 - j3.99
St-St			+0.94	67 (23)	36.40 - j3.82
		Δ	-0.03	–-	+0.20 + j0.17
0-loss	3.6		+0.21	65 (25)	35.56 - j5.45
St-St			+0.18	65 (25)	35.84 - j5.22
		Δ	-0.03	–-	+0.28 + j0.23
0-loss	7.15		-0.09	64 (26)	33.89 - j6.39
St-St			-0.14	64 (26)	34.27 - j6.06
		Δ	-0.05	–-	+0.38 + j0.33

For the simple arrays that we used as our samples, the changes are small, even though we used a relatively lossy material. Nevertheless, the progressions are clear. In general, material losses do not affect the take-off angle for far-field radiation from an antenna. However, we notice a small decrease in the maximum gain. The gain loss increases as we increase frequency. As well, the resistive component of the source impedance grows larger to reflect the resistive loss in the material. As well, the impedance becomes slightly more inductively reactive.

The additional losses due to skin effect clearly depend on frequency. They also vary with the diameter of the elements. The vertical element in each case is fairly large, reducing the skin effect losses relative to elements that might be ½ or ¼ the diameters used in the sample models. Indeed with fat enough elements (as a fraction of a wavelength), the losses even of stainless steel become completely insignificant relative to a truly (and practically impossible) lossless material. Hence, stainless steel has many applications in VHF and UHF ground-plane verticals, where even a material thin to the eyes is fat relative to a wavelength at the operating frequency.

Demonstrations such as these require the use of perfect scaling as we change frequency. Otherwise, we introduce too many variables into the performance outcome to assure ourselves that we have isolated the influencing factor in which we have an interest. Although we shall have other occasions on which to use perfect scalings, we may also purposely design antennas using standard size materials. In later chapters, we shall adopt a radius of 0.01-m (10-mm) as a standard monopole size for 160-m through 40m models. With a diameter just over ¾", this monopole provides a mid-range radiator between the 3-legged towers used by some and the wire verticals used by others. For radials, we shall adopt wire with a radius of 0.001-m (1-mm). The wire size is common in Europe and other metric regions of the world. In the U.S., it falls between the two most common wires sizes: AWG #14 (0.0641" diameter) and AWG #12 (0.0808" diameter). As we encounter upper-HF antennas and ground planes monopoles for VHF and UHF, we shall try to give them wire sizes that are representative of actual practice.

Except in answer to specific questions, we shall generally let the monopole and radial wires be lossless. Since our main focus is upon the effects of ground (along with related effects of physical size and frequency), using lossless wire will reduce by 1 the number of variables attached to our data.

The Next Steps

In this introduction, I have laid out a bit of background on the ground, especially as it applies to creating models that will provide us with useful information on ground-plane antennas. All of the types of ground that we have distinguished are equally important from our perspective–and in many ways not fully separable. However, the sorting process has allowed us to focus on some specific issues regarding the requirements for good and adequate grounds, whether we are concerned with safety or effective equipment and antenna operation. We shall have many occasions throughout this volume to call attention to one or more of the categories that we created for grounds.

Most of the information developed in succeeding chapters will have the form of data trends. Modeling care is critical to gathering the information. However, the modeling enterprise need not be arduous, nor need the models be excessively long or long running, even when we approach 120 radials or so. There are techniques that can shorten both the workload and the work time. When we add the necessary care required to remain within NEC guidelines for adequate and accurate models, we can obtain a considerable body of data to enlighten our expectations of antennas employing ground planes. The next chapter, then, focuses on model making and model limitations.

2. Modeling Ground-Plane Antennas

At first sight, ground-plane antennas seem to be simple matters. Monopoles consist of a single vertical radiator–about ¼-λ long–with anywhere between 4 and 128 radials symmetrically arranged at the base. In models, we normally place the source on the lowest segment of the vertical radiator.

Of course, we have already made an error. We tend to call the vertical portion of the antenna the radiator, silently implying that the radials do not radiate. Of course, they do individually radiate, but the symmetrical arrangement tends to cancel out the radiation. A field of opposite polarity counters the field from a radial wire pointed in any direction. So each radial does radiate, but the net radiation from the ground plane is close to zero.

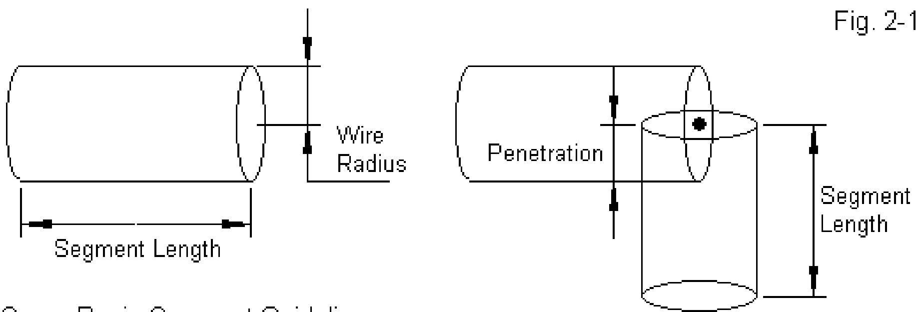
Most of the data in this volume arises from models of ground-plane antennas. All of the models in this volume use NEC-4, specifically, the NSI program GNEC. NEC-4 provides the ability to model buried or underground wires, necessary for a full evaluation of lower HF ground mounted monopoles and vertical arrays. The advanced program gives access to the full command set for the core. Indeed, anyone who wishes to model ground-planes or other buried-wire systems should use NEC-4 rather than the somewhat misleading NEC-2 work-arounds.

This chapter, then, has 3 goals. First, it will show you techniques for modeling ground-plane antennas. We shall not cover all possible techniques here, but enough to prepare us for the basic data acquisition and for more complex models later on in the study. Second, the chapter will focus your awareness of the limitations of NEC-4 relative to producing adequate and accurate models of ground-plane antennas. We have already covered a few limitations, for example NEC's use of a uniform and homogenous ground beneath a level horizon. The program has no means of capturing the tilted, rough, and stratified nature of the ground radio amateurs must often use for their antenna installations.

Third, the chapter will show the essential make-up of the types of models actually used to gather data. Very often, brief articles only mention the use of NEC models, but do not make the specific models available in the course of presenting data. In this volume, I shall reveal every model used for ease of replication or even improvement. This chapter will orient you to the significance of many of the line entries that compose the model.

The place to begin our modeling is with a few of the basic NEC guidelines for all models. **Fig. 2-1** calls attention to a pair of guidelines that are critical to the effective modeling of ground-plane antennas.

Fig. 2-1



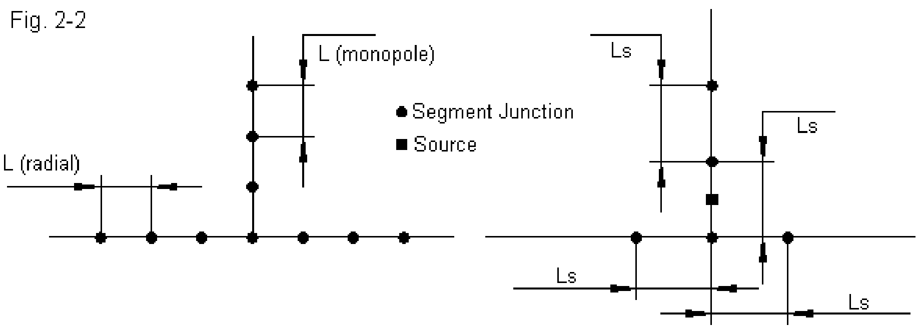
Some Basic Segment Guidelines

On the left is a reminder that segments in a NEC model should never be more than about 0.1-λ long. As the geometry grows more complex, segment lengths between 0.025-λ to 0.05-λ may yield more accurate results. Remember that the junction of the vertical element and the radials in a ground-plane monopole assembly represents a considerable level of geometry complexity.

At the same time, the ratio of the segment length to the wire radius should be as great as possible. Ratios greater than 8:1 are desirable for good accuracy, although in some cases, we may have to work with smaller ratios. Whenever working with a ratio of less than 4:1 or so, check the model for convergence, adequacy, and sensibleness. Convergence testing generally means changing the number of segments per unit of length and seeing whether the results are the same or significantly different. Adequacy testing generally includes the average gain test (AGT). However, both convergence and AGT tests are necessary but not sufficient conditions of model adequacy, and some model problems will not show themselves in these tests. Hence, we require the final test: examining the results and posing the question of whether they are sensible for the antenna under study.

On the right in **Fig. 2-1** is a consideration often overlooked by modelers: the degree to which one wire penetrates another at an angular junction. In general, the surface of one wire should not extend into the middle third to half of the other wire to avoid errors in the currents on the second wire. Since ground-plane monopoles often consist of a fat vertical wire surrounded by many thin wires that join at the base, it is easy to penetrate too far along the first segment of each radial. The penetration does not have to reach the level at which NEC-4 provides a warning flag before introducing significant errors into the model output reports.

Fig. 2-2



Some Segment-Length Recommendations

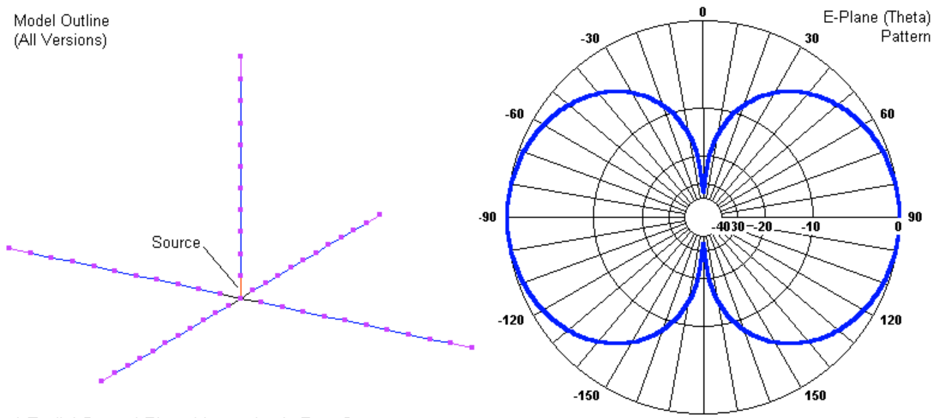
As suggested by **Fig.2-2**, we should strive–within the limits of feasibility–to use the same segment length in both the vertical and horizontal elements of a ground plane monopole or similar array. Very often, we use radials that are exactly ¼-λ long, but shorten the vertical element until it is resonant for a given environment. In some cases, the vertical element may require 1 segment less than the radials, since the element will usually be less than ¼-λ.

The right side of **Fig. 2-2** shows an area of major concern: the source or feedpoint region of the model. The virtual source appears as the center of a wire segment, although the entire segment is the actual source. The length of the source segment and of the segments adjacent to the source should be as close to identical in length as possible. Indeed, in many cases, it pays to develop special techniques to ensure the equality. The goal is to have equal current magnitudes on each side of the source segment for maximum accuracy of current distribution along the wire.

With these basic guidelines, we can begin to model a few sample ground-plane antennas. All models will be in meters to give us the simplest models possible. To convert meters to feet, divide by 0.3048. For this chapter, all models will use a frequency of 7.15 MHz, since the principles of model formation do not change with frequency. Again, for simplicity, I shall omit all wire loss entries and use perfect or lossless wire for both the vertical and horizontal elements. All of the models will use a horizontal radial system, that is, radials that are 90° from the orientation of the vertical element.

The Many Ways to Make a Ground Plane

We can begin with a very simple situation: a monopole in free space using 4 radials. We do not need many radials in free space for perfectly adequate performance, so we do not need to clutter up the model with too many lines or with high numbers. We shall examine 4 methods of constructing the very same model. **Fig. 2-3** shows the model in outline form, although conventional modeling software does not reveal the fact that the vertical element is many times thicker than the radials at its base. In fact, with one exception, all vertical radiators will have a radius of 0.0125 m (close to ½"), while the radials have a radius of 0.002 m (close to 0.08"). The fundamental terms of NEC software refer to wire radius, so the diameters are about 1" for the vertical radiator and about AWG #6 wire for the radials. (For reference, the AWG wire-gauge scale doubles in diameter for a change of 6 gauges downward and halves in diameter for a change of 6 gauges upward.) All vertical element lengths derive from the perfect-ground example in the preceding chapter, and all radials are exactly ¼-λ long. Since the lengths do not differ by much, all elements use 11 segments.



4-Radial Ground-Plane Monopoles in Free Space

Fig. 2-3

The most direct way to model the monopole shown in the figure is to enter a wire for each of the 5 elements. Many entry-level NEC programs are limited to this form of entry, even if there are means for generating radial systems based on the first radial introduced.

```
GW 1 11 0 0 0 0 0 10.067 .0125
GW 2 11 0 0 0 10.48225 0 0 .002
GW 3 11 0 0 0 0 10.48225 0 .002
GW 4 11 0 0 0 -10.48225 0 0 .002
GW 3 11 0 0 0 0 -10.48225 0 .002
GE 0 -1 0
EX 0 1 1 0 1 0
FR 0 1 0 0 7.15 1
RP 0 361 1 1000 -90 0 1.00000 1.00000
EN
```

We may omit the portion of the model from the Geometry end (GE) command onward in the alternative model formulations, since those lines remain constant. The EX or excitation line provides a 1-v (peak) source for the antenna, while the FR line specifies the frequency. The RP command requests the E-plane or theta pattern shown on the right. A theta pattern is simply an elevation pattern that counts its angles from the zenith downward rather than from the horizon upward.

Within NEC, we need not enter a new wire for each of the radials past the first one. 4 radials make a simple model to create and to present, but a field of 120 radials would make a long model indeed. Instead, we may replicate the first radial at 90° increments to produce the remaining 3 (or 119) radials.

```
GW 1 11 0 0 0 0 0 10.067 .0125
GW 2 11 0 0 0 10.48225 0 0 .002
GM 1 3 0 0 90 0 0 0 2 1 2 11
```

GW1 is the vertical element, and GW2 is the first radial extending along the X-axis. The GM entry requests 3 new replicas spaced at 90° angles. Note that to avoid replicating and overlaying the vertical element 3 extra times, the command specifies that it applies to Wire (or tag) 2, segment 1, through wire (or tag) 2, segment 11. (The format of the corresponding command in NEC-2 differs, and we shall sample that difference later in the chapter.)

We have a third alternative: the use of the GR or rotational symmetry command. The next model shows one way to use the command.

```
GW 2 11 0 0 0 10.48225 0 0 .002
GR 1 4
GW 1 11 0 0 0 0 0 10.067 .0125
```

Here we may note a potential for NEC models when we directly enter them. We do not have to enter the wire or tag numbers in sequential order. The rotational symmetry command applies to all preceding parts of the structure. To avoid replicating the vertical element, we begin with the initial radial, but do not need to change its number. The GR command is very simple. The first number indicates that each new radial will receive its own tag number 1 above the preceding entry. The second number reports that we shall have a total of 4 wires, including the initial wire. (Note that the GM command requested that we enter the number of new wires (3), while the GR command requests that we enter the total number of wires.) Finally, we have the vertical element.

If we run this model, we shall discover that the program will not make use of the timesaving symmetry function. (Of course, the timesaving is trivial in these simple models.) However, it will produce the 4 radials as 4 wires. The key lies in the NEC output report, a document that too few modelers examine in detail.

```
TOTAL SEGMENTS USED= 55  NO. SEG. IN A SYMMETRIC CELL= 55  SYMMETRY FLAG= 0
```

When the symmetry flag = 0, the program does not employ the symmetry function, but calculates in the same way it does for the first two alternative ways of setting up the ground-plane monopole. The following GW command defeats the symmetry request.

We have a fourth alternative. Although this technique is not especially useful for the simple monopole, it comes in handy when radial systems are very large and we wish to use numerous different vertical elements with the same radial system. For example, suppose that we had a field of 120 radials and wished to check the pattern of monopoles ranging from 0.05- through 0.625-λ. The trick is to separately model the radial field and then add the dipole to its results. We may do this by creating a numerical Green's file for the radial system. It will calculate and store the results of the matrix calculations for use with other elements that complete the model. For our simple radial system, we can create the file with the following model.

```
GW 2 11 0 0 0 10.48225 0 0 .002
GR 1 4
GE 0 -1 0
FR 0 1 0 0 7.15 1
WG r4-40.ngf
EN
```

As in all of the sample models, I have omitted the CM/CE comment lines. The GW entry specifies the first radial and the GR entry gives us rotational symmetry. With no following GW entry, symmetry is in effect. Note the output file line.

```
TOTAL SEGMENTS USED= 44  NO. SEG. IN A SYMMETRIC CELL= 11  SYMMETRY FLAG=-1
 STRUCTURE HAS 4 FOLD ROTATIONAL SYMMETRY
```

When the symmetry flag equals -1, symmetry is at work. The core creates the stored matrix data file, which is not normally readable by the user, under the specified filename and extension. Different cores may limit the range of available extensions for a Green's file. GNEC allows a wide range, but the extension should not be the same as used by other output products of the program.

Certain commands governing the overall model (including the main file yet to be seen) must go into the model that produces the Green's file. The frequency and the ground environment are 2 such elements. If we provide either a material load (or wire conductivity) for the elements or even a spot R-L-C load that applies to each radial, then such loads go into the Green's-file model. But the last command (before EN or model end) is the instruction to write the Green's file under the assigned file name and extension (WG). The file name must begin with a letter to avoid having NEC read an initial number as a mistaken command value.

The companion file will include the vertical element, the source or excitation, and the pattern request. Note that it omits the commands already within the Green's-file model, and any load or LD commands will apply only to the element or elements introduced in this new model. Of course, the first entry in the model list recalls the stored data in the Green's file itself (not the model that created the Green's file).

```
GF 0 r4-40.ngf
GW 1 11 0 0 0 0 0 10.067 .0125
GE 0 -1 0
EX 0 1 1 0 1 0
RP 0 361 1 1000 -90 0 1.00000 1.00000
EN
```

All 4 of these alternative formulations of our simple free-space ground-plane monopole produce identical output reports. The gain is 1.47 dBi, with a 98° beamwidth. The source or feedpoint impedance is 20.54 - j18.51 Ω, a value that should give us pause. The 36-Ω impedance of a resonant monopole over a perfect ground does not translate into a 36-Ω monopole when we place the same vertical element atop radials in free space. We still have half of a dipole, but not simply half the impedance. This fact will acquire considerable significance in a later chapter.

The average gain test (AGT) score is 0.98047 for a free-space test at 5° intervals. A perfect score would be 1.00, indicating that all supplied power to a lossless structure appeared as radiated power. Because we have a smooth and regular pattern, the 5° increment is satisfactory. In fact, using a 1° increment (and a good bit more run time), the resulting value was 0.98077, an insignificant difference.

When the source impedance is close to resonant, that is, has a low reactance, we may correct the resistive portion of the impedance by multiplying the reported resistance times the AGT score. We can also convert the AGT value into dB by taking 10 times the log of the score. The resulting value (in this case, -0.086) tells us that the reported gain is low by the indicated amount. We subtract the value from the reported value (in this case, giving us a slightly higher value, namely, 1.56 dBi). In this sequence of models, the AGT score is so close to perfect that the adjustment is trivial, but in some exercises, it may prove both useful and necessary.

The only differences among the models involve their run times. The following numbers come from a slow (400 MHz) machine. The "NGF" entry is the sum of the run times for the Green's file model and for the main or companion file.

Version	Run Time
All GW	0.33 sec.
GM	0.27 sec.
GR	0.33 sec.
NGF	0.06 + 0.27 = 0.33 sec.

The times are not significantly different and mostly composed of "overhead," that is, writing the output reports and generating the current and radiation pattern tables. However, they do form a baseline against which to measure run times with more complex radial systems.

Before we leave our simple model, let's place it above ground by the amount used in Chapter 1, that is, 0.001 λ. The actual distance above ground will be 0.042 m. Again, we have multiple ways to accomplish this feat. One is to create a model that meets the conditions in the wire lines.

```
GW 2 11 0 0 .042 10.48225 0 .042 .002
GR 1 4
GW 1 11 0 0 .042 0 0 10.109 .0125
GE -1 -1 0
GN 2 0 0 0 13.0000 0.0050
EX 0 1 1 0 1 0
FR 0 1 0 0 7.15 1
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

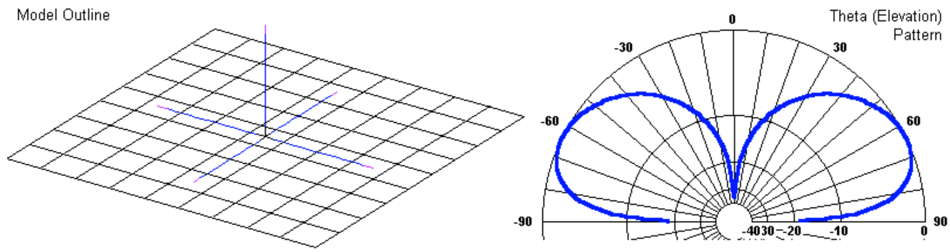
The version used employs the GR command with symmetry defeated. The ground is average (C = 0.005 S/m, P = 13). Note that we have built the height above ground into the GW entries. We have an alternative route to the same goal.

```
GW 2 11 0 0 0 10.48225 0 0 .002
GR 1 4
GW 1 11 0 0 0 0 0 10.067 .0125
GM 0 0 0 0 0 0 0 0.042
```

The alternative model begins with the free-space set-up and uses the GM command to elevate it the required amount. This formulation is very useful when gathering data about a fixed ground-plane antenna design at various heights above ground. Simply changing the last number on the GM command will revise the model as needed.

The model, in either form, reports a gain of -0.89 dBi at a take off (TO) angle (of maximum gain) of 64° theta (26° elevation). The reported source impedance is 41.76 + j25.11 Ω. The AGT test score for this model is identical to the free space models. Since the AGT test removes all loss sources and places the antenna structure in free space, of course the score cannot differ from the earlier models.

Fig. 2-4 shows the model outline and a reference theta pattern.



4-Radial Ground-Plane Monopole 0.001-WL Above Average Ground

Fig. 2-4

Some 64-Radial Models

We may reproduce the same set of models using 64 radials, omitting the all-GW version so that we do not need to show 65 wire entries. The free-space versions of the remaining 3 ways of forming ground-plane models will look almost exactly like the models using 4 radials. For example, if we specify 64 radials using the GM command, we obtain a model like this one.

```
GW 1 11 0 0 0 0 0 10.067 .0125
GW 2 11 0 0 0 10.48225 0 0 .002
GM 1 63 0 0 5.625 0 0 0 2 1 2 11
GE 0 -1 0
EX 0 1 1 0 1 0
FR 0 1 0 0 7.15 1
RP 0 361 1 1000 -90 0 1.00000 1.00000
EN
```

The only difference between this model and the corresponding 4-radial version is in the GM line. We specify 63 replications of the first radial (GW2) and set the angular separation at 5.625°. This and all of the other 64-radial free-space models show a gain of 1.36 dBi with a beamwidth of 101°. Relative to the 4-radial model, the new version has slightly less gain spread on a broader front. The source impedance is 21.28 - j7.14 Ω. Due to the compression of many wires at the junction with the vertical element, the AGT score becomes 0.97762, a 0.003 drop. **Fig. 2-5** shows the model outline and the E-plane or theta pattern. Note that the vertical and radial elements use equal-length segments.

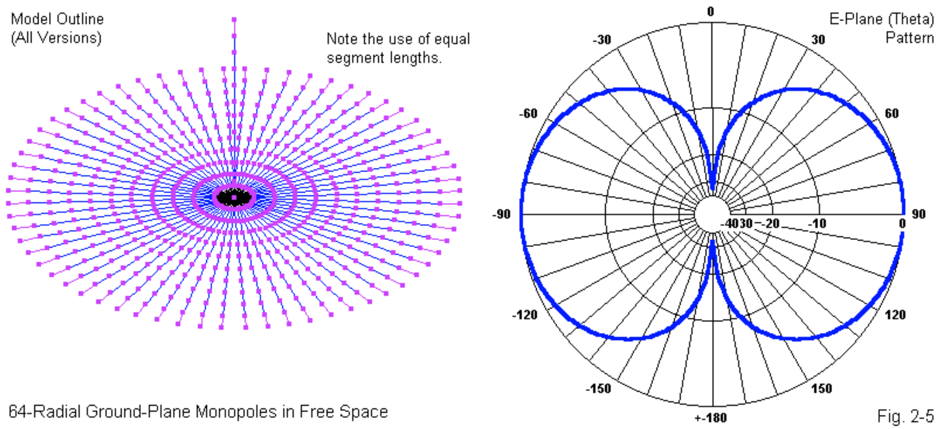


Fig. 2-5

The version of the antenna using the GR command with symmetry defeated also has a familiar appearance. The GR command simply replaces "4" with "64." Only the wire entries appear here.

```
GW 2 11 0 0 0 10.48225 0 0 .002
GR 1 64
GW 1 11 0 0 0 0 0 10.067 .0125
```

We may also use a Green's file for the radials in order to implement the symmetry function. The model forming the Green's file looks like this set of lines. Again, the only difference between the 4- and 64-radial models is in the GR line, plus the assignment of a unique Green's file name.

```
GW 2 11 0 0 0 10.48225 0 0 .002
GR 1 64
GE 0 -1 0
FR 0 1 0 0 7.15 1
WG r64-40.ngf
EN
```

The companion file containing the vertical element appears next. It differs from the 4-radial model only in the GF line that request access to the correct

Green's file. Of course, the CM/CE (comment lines) will differ, but I have omitted these non-calculation lines to save space.

```
GF 0 r64-40.ngf
GW 1 11 0 0 0 0 0 10.067 .0125
GE 0 -1 0
EX 0 1 1 0 1 0
RP 0 361 1 1000 -90 0 1.00000 1.00000
EN
```

For reference, let's record the run times for the 64-radial models and compare them to the run times for the 4-radial models.

Version	4-Radial Run Time	64-Radial Run Time
All GW	0.33 sec.	——
GM	0.27 sec.	13.62 sec.
GR	0.33 sec.	13.57 sec.
NGF	0.06 + 0.27 = 0.33 sec.	1.54 + 7.58 = 9.12 sec.

Although the numbers are still trivial in terms of the actual time used, their comparative values are significant. The 64-radial model took about 41 times longer to run than the 4-radial models for both the GM and GR versions. In contrast, the total run time for the Green's-file version required only 27 times the run time. Despite the fact that much of the run time involves the same overhead, we begin to see a significant difference between the values. Note that the actual run times are also a function of computer speed. As well run times will vary from one run to the next, but generally vary for these smaller models by no more than 0.1 second.

Let's move the 64-radial models over average ground at a height of 0.001-λ. We may reduce the number of non-Green's-file version to one, in this case, the GM version of the model. Except for the GM line, it will have the same appearance as the 4-radial model, although we used the GR version for that test. However, since we know that both models–GM and GR–produce the same output reports when all other model entries are the same, the two versions are interchangeable.

```
GW 1 11 0 0 .042 0 0 10.109 .0125
GW 2 11 0 0 .042 10.48225 0 .042 .002
GM 1 63 0 0 5.625 0 0 0 2 1 2 11
GE -1 -1 0
GN 2 0 0 0 13.0000 0.0050
EX 0 1 1 0 1 0
FR 0 1 0 0 7.15 1
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

The gain reported for the model is -0.09 dBi at a TO angle of 64° theta (26° elevation), with a vertical beamwidth of 44°. The reported source impedance is 33.87 - 6.39 Ω. Of course, the AGT score is identical to the value reported for the free-space model. **Fig. 2-6** shows the model outline and the theta pattern.

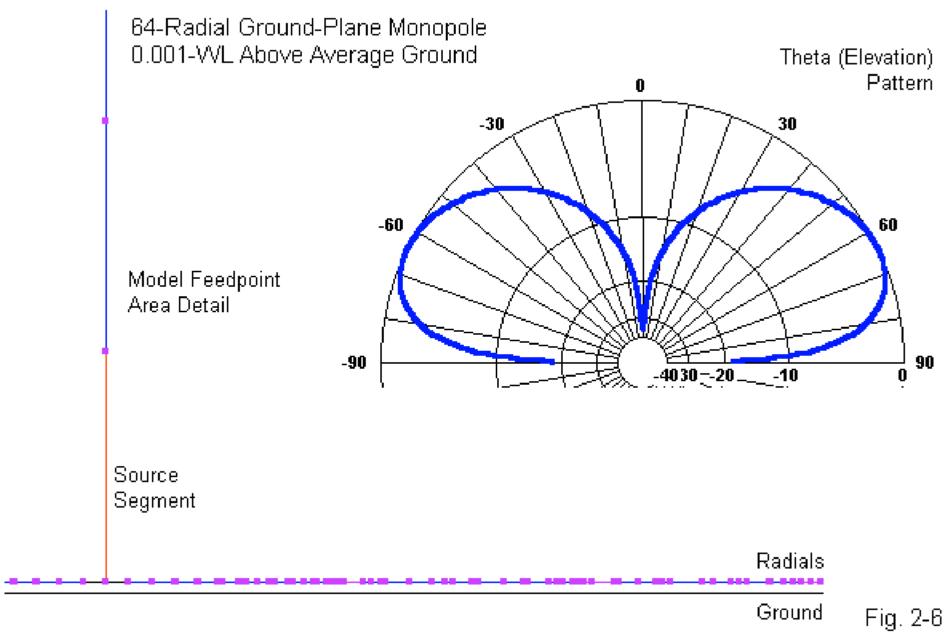


Fig. 2-6

Looking ahead to some models with buried radials, I have zoomed in on the source or feedpoint area of the model. The large number of segment dots on the radial lines results from the overlay of many radials in this perspective. The segment lengths are actually almost identical to those on the vertical element.

The Green's-file version of the same antenna begins with the model that writes the .NGF file. The key elements are the specification of 64 radials and the assignment of a set of ground quality values.

```
GW 2 11 0 0 0.042 10.48225 0 0.042 .002
GR 1 64
GE -1 -1 0
GN 2 0 0 0 13.0000 0.0050
FR 0 1 0 0 7.15 1
WG r64-40-ave.ngf
EN
```

Next, we supply a companion file with the vertical element, and excitation or source, and a pattern data request. From this file, we obtain the same output data as the GM version of the model. Whereas the GM version of the model required a run time of 47.18 seconds, the Green's-file version took 2.97 + 14.50 seconds or a total run time of 17.47 seconds. The runtime ratio is now up to 2.7:1.

```
GF 0 r64-40-ave.ngf
GW 1 11 0 0 0.042 0 0 10.109 .0125
GE 0 -1 0
EX 0 1 1 0 1 0
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

All of the files that we have explored in our look at how to create compact and speedy ground-plane models will run on both NEC-4 and NEC-2, with the exception of those involving a GM command that designates the start and stop points for replicating GW structures. NEC-4 allows places to specify the start and stop tag numbers and segment numbers, the last 4 entries on the following top line. The second line records the NEC-2 version of the same command. Since NEC-2 appeared when Fortran allowed only a limited number of floating decimal places, the programmers used a short cut. The last decimal entry is actually the start and stop tag numbers, stored together. Note that NEC-2 does not allow specification of the start and stop segment numbers and hence can replicate only entire wires. For many cases of replicating entire structures, the appearance of the commands in the two programs will be identical.

```
NEC-4: GM 1 63 0 0 5.625 0 0 0 2 1 2 11
NEC-2: GM 1 63 0 0 5.625 0 0 0 002.002
```

The NEC-2 core calculations are not perfectly identical to those emerging from NEC-4. Hence, the NEC-2 model reports a gain of -0.01 dBi, although the TO angle and beamwidth are the same for both cores. The source impedance for the NEC-2 model is 33.27 - 6.73 Ω. The value differs from the NEC-4 report, but by only about a half-Ohm in each component. Also expect slightly different AGT scores between cores. NEC-2 reported an AGT value of 0.99158.

NEC has a facility that will prove handy in some applications involving ground-plane models. The GC or wire continuation command allows the modeler to length-taper or radius-taper a wire just created. Let's compare a standard GM-based model with its length-tapered counterpart.

```
GW 1 11 0 0 .042 0 0 10.109 .0125
GW 2 11 0 0 .042 10.48225 0 .042 .002
GM 1 63 0 0 5.625 0 0 0 2 1 2 11

GW 1 11 0 0 .042 0 0 10.109 0
GC 1 0 0 .0125 .0125 .042
GW 2 11 0 0 .042 10.48225 0 .042 0
GC 1 0 0 .002 .002 .042
GM 1 63 0 0 5.625 0 0 0 2 1 2 11
```

For our exercise, the smallest segments appear at the hub of the antenna and are 0.001-λ or 0.042-m long. Note that to use the GC command, we set the wire radius at 0 in the GW line. We record the radius as start and stop values in the GC line. For length tapering, we have several options. The simplest specifies the starting segment length. This option retains the total number of segments specified in the GW line and the program calculates the length of each segment needed to produce a smooth curve of rising segment lengths within those limits. For the problem at hand, the GC lines for the radial and for the vertical element produce the following sequence of segment lengths (which are included in the NEC output report). The radial segment lengths grow longer faster because the radial is slightly longer than the vertical element.

Vertical Element		Radial	
Segment #	Length (m)	Segment #	Length (m)
1	0.042	1	0.042
2	0.066	2	0.066
3	0.103	3	0.104
4	0.160	4	0.163
5	0.251	5	0.256
6	0.392	6	0.401
7	0.612	7	0.630
8	0.957	8	0.990
9	1.495	9	1.555
10	2.337	10	2.442
11	3.653	11	3.835

The length-tapered version of the model yields a gain of +0.09 dBi at the same TO angle and beamwidth as the non-tapered version of the model in NEC-4. The difference is only 0.18 dB. The impedance report also varies slightly, with a value of 31.80 - j8.36 Ω. Both components are about 2 Ω more negative than the values in the model using uniform segment lengths. Whether these differences make an operationally significant difference depends on the task at hand. However, the technique will prove necessary in order to model some situations.

Fig. 2-7 shows the effects on the segments in the source region of the model, using the same scale as the uniform-length model in **Fig. 2-6**. The segment length tapering is clearest on the vertical element. As always, the figure includes a reference theta pattern, which shows no detectable differences between the 2 plots.

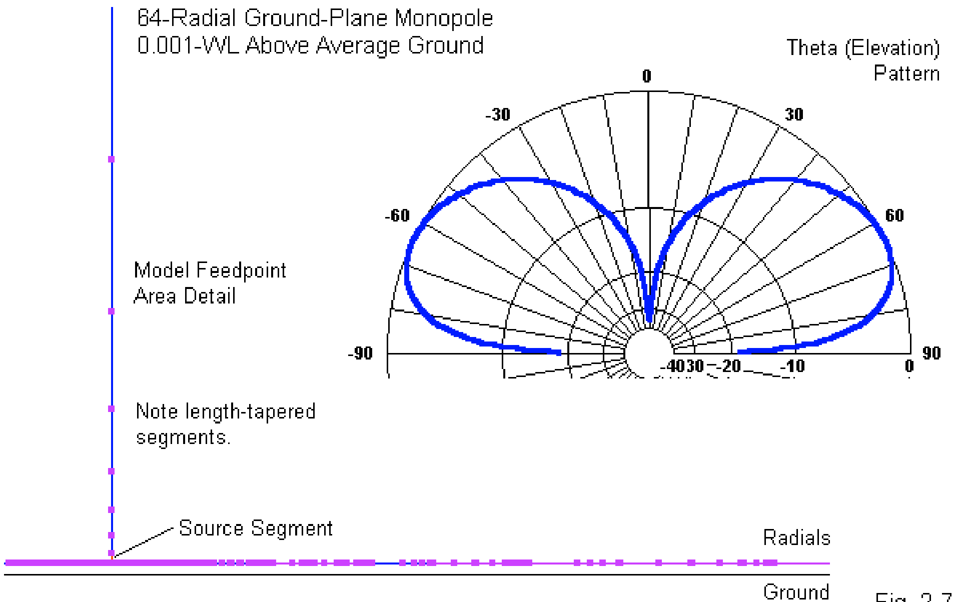


Fig. 2-7

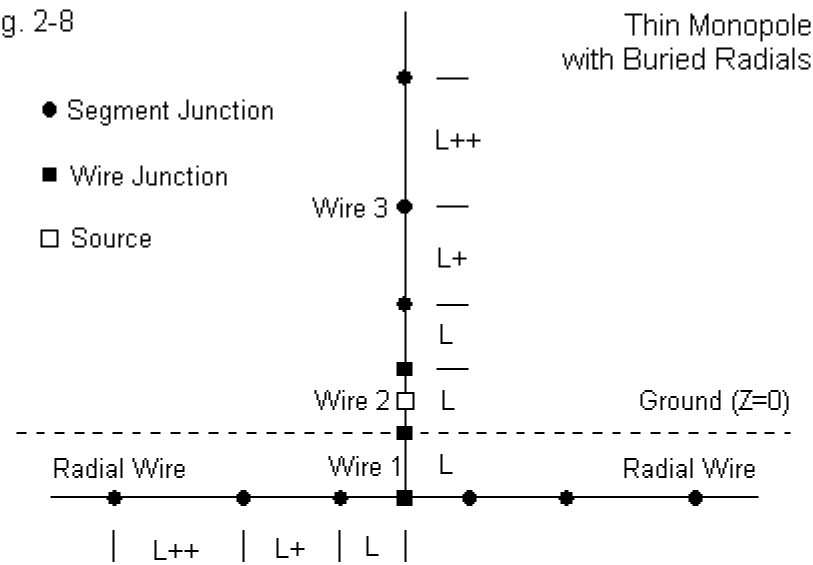
Buried Radials

Creating models of buried radial systems requires the use of NEC-4, since NEC-2 does not support wires below ground level. We shall look more closely at the relationship between buried radial models and their work-arounds (for example, placing radials just above ground and using the MININEC ground system) in a later chapter. For now, our goal is to build adequate and accurate models of vertical antennas with radials below the surface level. As with every other technique that we have surveyed, there is more than one way to accomplish the task, and each technique has its own range of preferred applications.

The first method of creating buried radials is especially applicable to ground-plane arrays with relatively thin vertical radiators. A thin radiator is one in which the radius of the vertical element is at least 8 (or so) times the distance of the radials below ground level. There is no precise dividing point at which a vertical element goes from being thin to being fat, but the 8:1 ratio of burial depth to element radius is a useful rule of thumb.

To create a model, we can combine the use of the GC command with the basic rules governing the junction of wires with the ground (Z=0). A wire may contact ground only at a wire or segment junction. Normally, we place the source for a base-fed vertical element on the first segment above ground level. At the same time, the segments on either side of the source segment should be the same length as the source segment. The result is a structure resembling the sketch in **Fig. 2-8**.

Fig. 2-8



Note that we use a separate wire for the connection between the radial hub and the source wire. We also keep the source wire separate but the same length as the vertical wire below ground. (Actually, we may also use a 2-segment wire to combine Wires 1 and 2 in the sketch.) Each radial wire and the vertical element use length-tapering via the GC command, with the initial segment the same length as wires 1 and 2. One way to create the total structure is to use the GM command to form all but the first radial. The following lines show just the wire structure, since the remaining commands are the same as in previous model samples. Note that the tag numbers do not appear in the same order as the numbered wires in the sketch. GW1 is the top tapered portion of the vertical element. GW2 is the source segment touching the ground at one end. GW3 connects the radial hub to the source wire. GW 4 is the prime radial that the GM command then replicates 63 times. The radials are 0.001-λ or 0.042-m below ground, and that distance determines the length of GW2 and GW3, as well as the length of the first segments in both the radials and the vertical element.

```
GW 1 11 0 0 .042 0 0 10.067 0
GC 1 0 0 .0125 .0125 .042
GW 2 1 0 0 0 0 0 .042 .0125
GW 3 1 0 0 -.042 0 0 0 .0125
GW 4 11 0 0 -.042 10.48225 0 -.042 0
GC 1 0 0 .002 .002 .042
GM 1 63 0 0 5.625 0 0 0 4 1 4 11
```

An alternative method of creating the model is to develop a Green's file holding only the radials in their position below ground. Note that the GC command is permissible within the geometric structure that forms the radials.

```
GW 1 11 0 0 -0.042 10.48225 0 -0.042 0
GC 1 0 0 .002 .002 .042
GR 1 64
GE -1 -1 0
GN 2 0 0 0 13.0000 0.0050
FR 0 1 0 0 7.15 1
WG r64-40-ave-b.ngf
```

The companion file then uses the Green's file in conjunction with the set of vertical wires. This wire set is otherwise identical to the wires in the GM version of the model, with one exception. Because this part of the model may be used with a large number of different Green's files, each with a different number of radials, the vertical wires use tag numbers starting at 201, a value higher than the largest tag number that would be assigned to anticipated large radial systems. Unlike entry-level programs, which insist on automatically assigning tag numbers in order, NEC itself allows the user to assign any tag number to any wire. We shall discover that the combination of the 2 files requires only 18.84 seconds (on the test computer), whereas the GM version of the model needed 56.51 seconds, or 3 times the run time.

```
GF 0 r64-40-ave-b.ngf
GW 201 11 0 0 .042 0 0 10.109 0
GC 1 0 0 .0125 .0125 .042
GW 202 1 0 0 0 0 0 .042 .0125
GW 203 1 0 0 -.042 0 0 0 .0125
```

If we run either version of the model, we obtain a gain of -1.72 dBi at a TO angle of 64° (theta) with a beamwidth of 45°. The reported source impedance is 55.43 - j21.00 Ω, and the reported AGT score is 1.01046. (The application of the AGT test to the companion file of the Green's-file model version is invalid, because the test cannot reach back into the Green's file to place the radials in free space. Once calculated, the Green's file values are fixed and include the modification created by the specification of ground constants.)

If we compare the reported impedance value with those that we obtained from previous models, we find a 20-Ω increase in the resistive component. Initially, we may not know whether the increase is the sum of ground losses or whether we have an inadequate model. The AGT test gives a very good score, but–as earlier noted–the average gain test is not a sufficient condition of model adequacy. The core tests did not report any violations of the guidelines that it scans.

However, the ratio of the shortest segment length (0.042 m) to the vertical-element diameter (0.0125 m) is only 3.36:1. Hence, the diameter may be too fat for this technique. To test this theory, we need only create a pair of new models using a thinner vertical element. We might try a radius of 0.002 m to correspond to the radius of the radials. As the following lines from the GM version of the model show, nothing changes except the radius of the vertical element wires.

```
GW 1 11 0 0 .042 0 0 10.109 0
GC 1 0 0 .002 .002 .042
GW 2 1 0 0 0 0 0 .042 .002
GW 3 1 0 0 -.042 0 0 0 .002
GW 4 11 0 0 -.042 10.48225 0 -.042 0
GC 1 0 0 .002 .002 .042
GM 1 63 0 0 5.625 0 0 0 4 1 4 11
```

The Green's file version of the model may use the existing .NGF file. So the only changes will occur in the companion file.

```
GF 0 r64-40-ave-b.ngf
GW 201 11 0 0 .042 0 0 10.109 0
GC 1 0 0 .002 .002 .042
GW 202 1 0 0 0 0 0 .042 .002
GW 203 1 0 0 -.042 0 0 0 .002
```

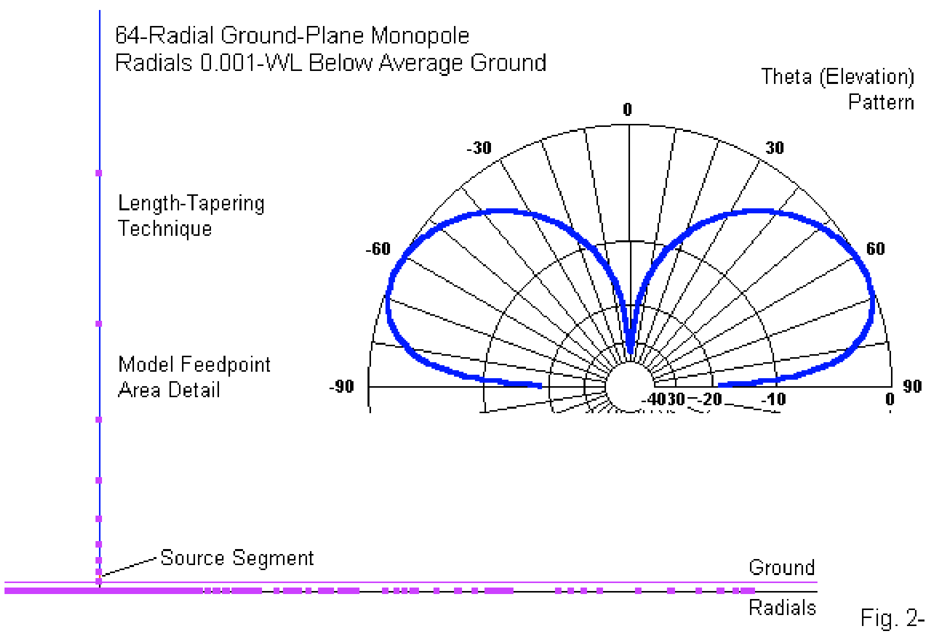


Fig. 2-9

Fig. 2-9 shows the structure of the thin-monopole model, regardless of the vertical element radius. Changing the element diameter does not change the tapering of the element lengths. Also, the general elevation or theta pattern retains its general outlines. However, the changes do result in interesting new output values. The gain is 0.16 dBi at a 64° TO angle with a 45° vertical beamwidth. The source impedance is 35.13 - j5.02 Ω, with an AGT score of 1.00827. These values correlate well with the results of earlier models and suggest that the initial model used a vertical element that is too fat for the modeling technique.

An alternative model-formulation technique can accommodate fat elements and requires no segment length tapering. **Fig. 2-10** shows the general outlines of the method.

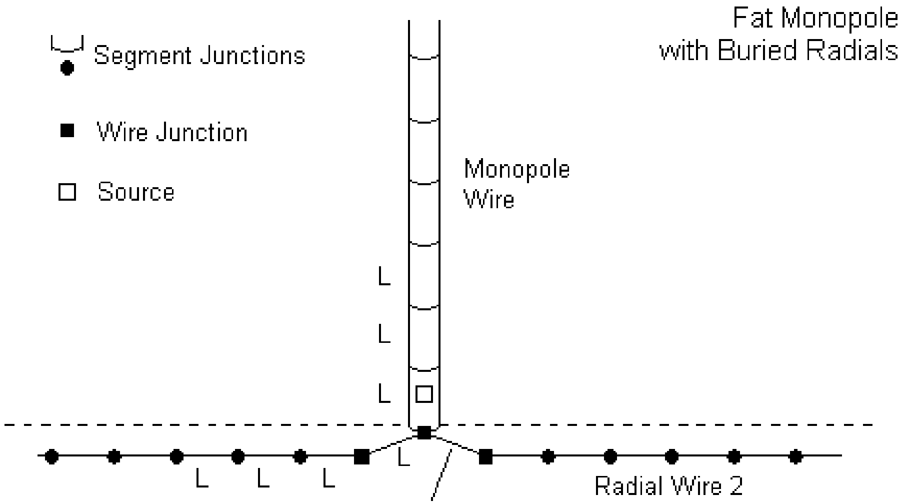


Fig. 2-10

The segment lengths are constant throughout and as equal among all of the elements as may be feasible. The vertical element extends from the ground

(Z=0) to the specified height. We add a bit of complexity to the radial system by breaking the radials into 2 parts. The 1-segment long inner wire should be as long as any segment in any other wire in the system. The wire extends downward at an angle so that one end connects to the vertical element base at Z=0 and the other end just reaches the desired depth of the radial system as a whole. Since the slope of the inner radial wire is so shallow, we usually use an X-coordinate that is just under the normal segment length so that the hypotenuse just about reaches parity with the length of the segments in the main radial wire. We subtract one segment from the main radials and lay them flat at the desired burial level. As a result, the segment lengths remain relatively uniform.

We can create sloping-radial ground-plane vertical antennas using either the GM or the Green's file versions. (Of course, in a single-file model, we can replace the GM command with a GR command, understanding that the presence of the vertical wire following the rotational command will defeat the symmetry function.)

```
GW 1 1 0 0 0 .952 0 -0.042 .002
GW 2 10 .952 0 -0.042 10.48225 0 -0.042 .002
GM 1 63 0 0 5.625 0 0 0 1 1 2 10
GW 201 11 0 0 0 0 0 10.067 .0125
```

GW1 is the master sloping wire for the radial, and GW2 is the flat remainder. Note that the GM command specifies a start at tag 1 and an end at tag 2. As I did earlier, I tagged the vertical wire as 201 so that I could easily modify the GM command for as many radials as I might ever use. The vertical element is a single wire that uses our original 0.0125-m radius.

```
GW 1 1 0 0 0 .952 0 -0.042 .002
GW 1 10 .952 0 -0.042 10.48225 0 -0.042 .002
GR 1 64
GE -1 -1 0
GN 2 0 0 0 13.0000 0.0050
FR 0 1 0 0 7.15 1
WG r64-40-ave-b-sl.ngf
```

The three wire lines above form the heart of the Green's-file model for the radials using the GR command. Since the GR command rotationally replicates all of the preceding structure, we need no start and stop specifications.

```
GF 0 r64-40-ave-b-sl.ngf
GW 201 11 0 0 0 0 0 10.067 .0125
GE -1 -1 0
```

The companion file, after calling up the Green's file data, requires only a single wire to specify the vertical that runs from the ground to the top height. **Fig. 2-11** shows a close-up of the model source region, along with the theta pattern that emerges from both versions of the antenna assembly.

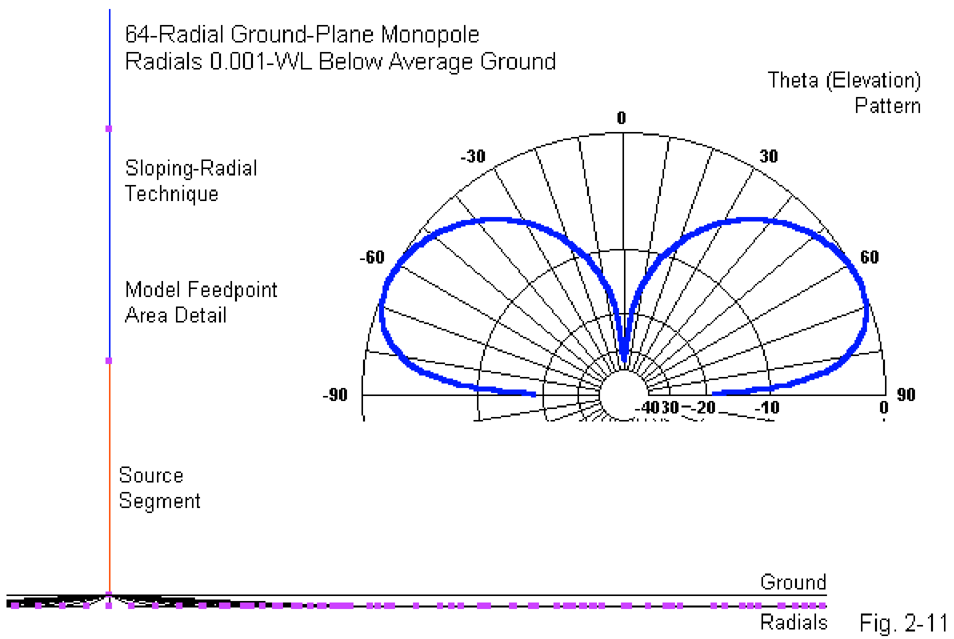


Fig. 2-11

In all of these models, the geometry end (GE) command requires a value of -1 as the first entry. (The second and third entries activate or deactivate core-testing functions.) A first-place entry of 0 indicates a free-space environment that has no ground plane. A positive 1 indicates a ground plane with current modification, and this value is not for use when wires are below the ground surface. -1 indicates a ground plane with no current modification and is suitable for use with buried wires.

The two buried-radial models report a maximum gain of 0.26 dBi at a TO angle of 64° (theta) with a 45° vertical beamwidth. The reported source impedance is 35.14 - 0.37 Ω, a value much more reasonable than the thin-monopole model produced using the fat vertical element. The AGT score from the GM version of the model was 0.97915.

More Complex Radial Systems

There are numerous occasions when accurate modeling requires multiple buried radial systems. Besides yielding very segment-intensive models, these requirements often set up conflicts within a model. Let's briefly survey a few situations to see what we can do to eliminate the conflicts.

Let's start with a hypothetical case, using 2 quarter-wavelength monopoles fed in phase. Suppose, for the sake of the example, that we wish to have each monopole equipped with a separate, non-touching radial system. However, the radials must be exactly ¼ λ, and the exact spacing between the monopoles must be ½ λ. If we construct a conventional radial system using an even number of radials, we shall have one radial from each system with a common junction. Of course, we can "cheat" by separating the monopoles by just a smidgen over ½ λ or we may slight the joining radials by shortening them by an equal smidgen. Both techniques would likely work without creating any significant error, but that would end our exploration of options.

We can use other methods to preserve the exactitude of the model as specified by hypothesis. For example, there are no special rules requiring us to use any of the traditional numbers of radials. Some investigative modelers use progressions of 4, 8, 16, 32, 64, and 128 radials to form orderly progressions. The AM BC industry tends to use 120 radials, which we can divide into 60, 30, or 15 with equal arithmetic ease. In their classic 1937 study of radial systems, Brown, Lewis, and Epstein used 15, 45, and 113 radials, with no reason given for the last number. With all of this variation in the literature, there is no reason not to use an odd number of radials in a buried ground plane.

Suppose that we plan on using 32 radials in the actual system. We may just as well use 31 in the model, so long as we keep the system symmetrical. There is no significant performance difference between 31 and 32 radials, when all other physical factors are the same. As well, using the odd number of radials presents us with some easy ways of meeting the dimensional requirements and still preventing the radial systems from touching.

```
GW 1 11 0 0 10.067 0 0 0 .125
GW 2 1 0 0 0 0 .95 -.042 .002
GW 2 10 0 .95 -.042 0 10.48225 -.042 .002
GM 0 30 0 0 11.612903 0 0 0 2 1 2 11
GM 0 0 0 0 0 10.482255 0 0
GM 2 1 0 0 0 0 -20.96451 0
GE -1 -1 0
```

The lines from our model of a dual in-phase fed monopole system for 7.15 MHz show one way to achieve the goal and still have a very compact model file. GW1 sets up the monopole. The 2 GW2 lines create the first radial, using the sloping technique presented earlier. The first GM line creates 30 copies of the radial, spread evenly around the monopole. Thus far, we have a copy of models that we have already reviewed.

The second GM line creates a difference. It moves entire assembly ¼ λ at the operating frequency in a positive direction along the X-axis. Since we wish to have a second copy of the system a full quarter-wavelength away, the next GM line creates a single replica and moves it exactly ½ λ in the negative X-axis direction. Note that the line also increments the tag numbers by 2, resulting in the new monopole wearing tag 3 and the new radials displaying tag 4. In the part of the model not shown, we have 2 excitation points, one at the base of each monopole. The ground is average.

For our purposes, the most important aspect of the model is what happens to the two radial systems. **Fig. 2-12**, on the left, reveals that we have no contact between the radial systems, although circles drawn on the radial outer ends would touch in the middle.

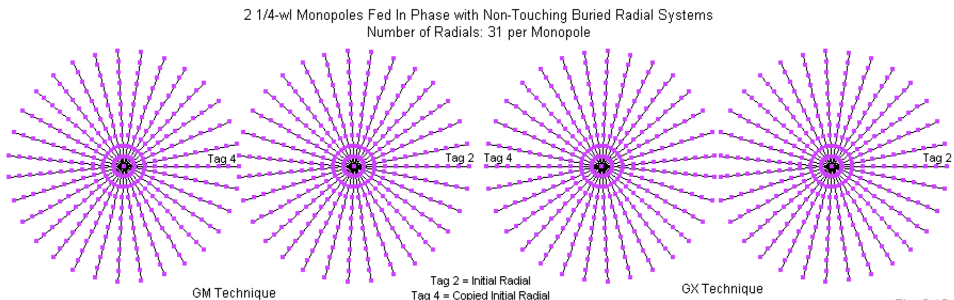


Fig. 2-12

The figure also suggests that we can use a different technique to arrive at the same goal. In the process, we may save nearly half the model run time (30.3 seconds vs. 56.1 seconds on the test computer). Instead of using the last GM line to create a moved replica of the model, we may use the symmetry or GX command. Then the geometry lines of model look like these.

```
GW 1 11 0 0 10.067 0 0 0 .125
GW 2 1 0 0 0 0 .95 -.042 .002
GW 2 10 0 .95 -.042 0 10.48225 -.042 .002
GM 0 30 0 0 11.612903 0 0 0 2 1 2 11
GM 0 0 0 0 0 0 10.482255 0
GX 2 010
GE -1 -1 0
```

All but one of the new lines are identical to those in the preceding example. The GX line increments the tag numbers by 2 and creates a mirror image of the first monopole system on the other side of the Y-axis that divides the two antennas. Excitation and all other control commands remain the same. However, note that the process creates a true mirror image so that the new initial radial points away from the potential junction of the ground-plane fields. At the junction, we have for each field a pair of radials that almost touch, as shown in **Fig. 2-12** on the right side. In fact, the differences between the two models are too small to mention: a 0.001-Ω difference in the reported source resistance.

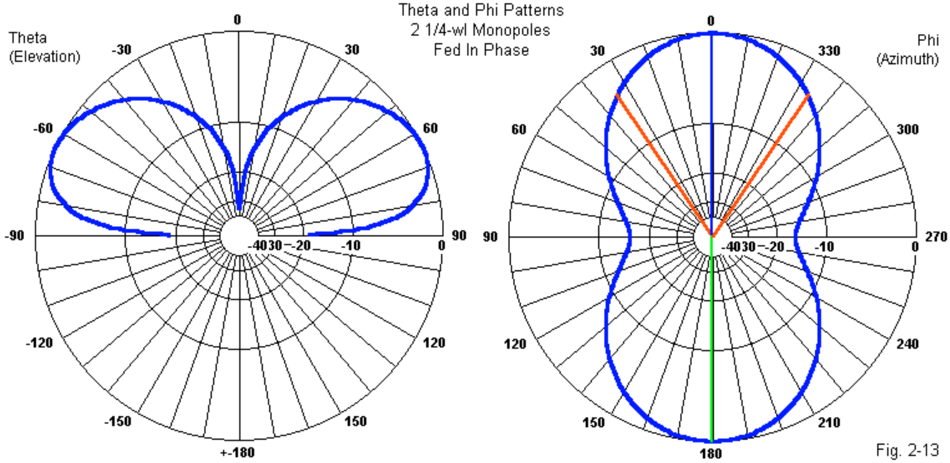
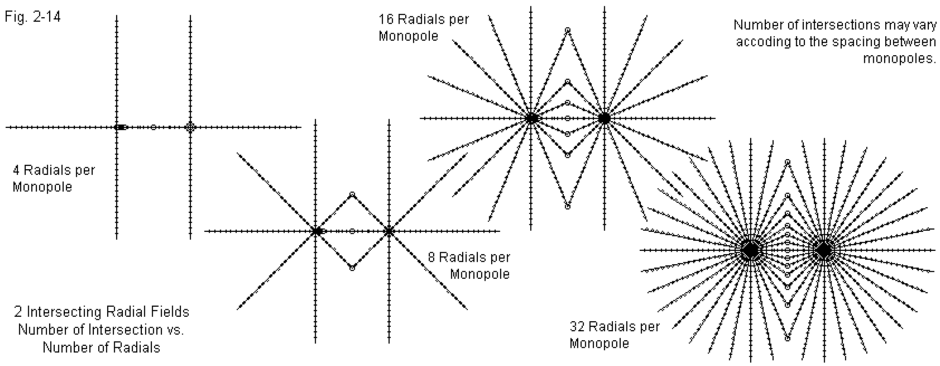


Fig. 2-13

For reference, **Fig. 2-13** shows the theta and phi patterns for both array models. No differences exist among the reported values for gain, TO angle, or horizontal beamwidth. As usual, we can usually find more than one way to model an antenna. Picking a technique should be a matter of what is most important to the modeling task, but very often it derives mostly from habit.

There are occasions on which we need to create touching radial fields. For example, if we have a multi-element array of monopoles that are closely spaced–regardless of whether the array is all-driven or parasitic–then the necessary radial fields will overlap. Some builders simply lay down radials for each element and let them overlap. We do not have this license in a model, since inevitably, some radial wires would cross at points other than wire or segment junctions. To save wire and for other reasons, some builders create neat sets of radials that join in the middle, with each joining radial also terminating at the junction.

Fig. 2-14 shows several possibilities for joining fields for 2 monopoles using different numbers of radials. The monopoles are about 1/8 λ apart to ensure a require junction between 2 fields of ¼-λ radials. Note the number of junctions for each increase in field size. Some builders connect the junction dots with a wire. In a model replicating this practice, we must use separate wires for each connection, since they differ in length.



In most cases requiring a junction of 2 radial fields, we should likely use separate wires or GW entries for each radial. To effect the junctions, we shall have to use some wires with different lengths than the normal radials. Hence, the GM replication-and-rotation command has only limited utility. As well, most commercial implementations of NEC have radial-field generation facilities to create the two radial sets. All we need to do is modify those that require a midpoint junction.

Fig. 2-15 illustrates the process. First, determine the midpoint line coordinate for the field junctions. In the graphic, the point lies along the X-axis with a value of A. Next, determine which radials in each set cross each other, and remember their tag numbers as crossing pairs. Some wires may cross more than 1 radial from the other field; select pairs by reference to crossing on the midpoint line. For each of these pairs, in this example, the new X-coordinate value will be A.

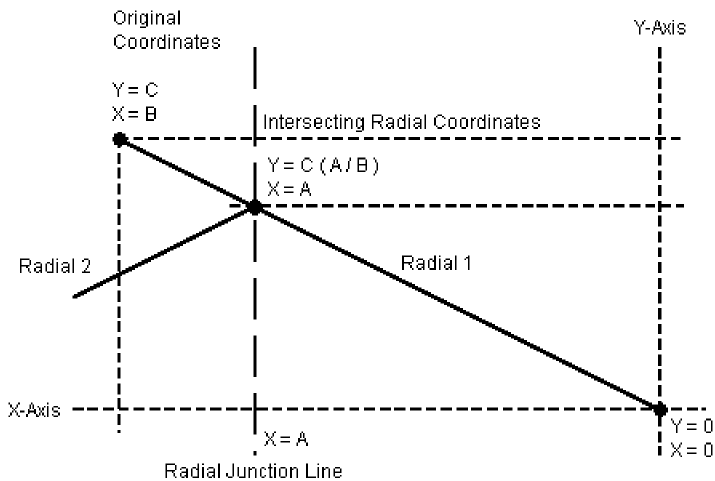
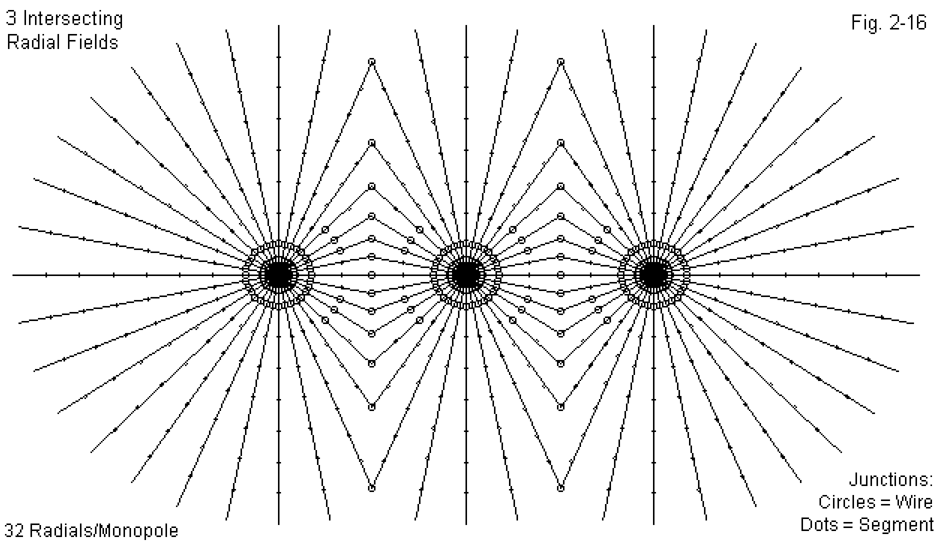


Fig. 2-15

The old termination point for any one of the radials showed values of X = B and Y = C. We already know the new X value (A), and the ratio of the old X value to the new one determines how much to shorten the Y-coordinate value. The new Y-coordinate value will be C times the ratio of A to B. Use the same ratio (A to B) to determine the revised number of segments in the radial so that–to the degree feasible–the segment junctions in the radial field are well aligned, especially as the wires approach each other at the hub. Be certain to use the new coordinates on both of the radials for which a crossing becomes a junction.

For modest radial fields, you can arrive at all of the necessary revisions by hand calculation. However, if you regularly work with such fields, you may create a spreadsheet page to perform the tedious calculations. For example, consider the problem of three intersecting radial systems outlined in **Fig. 2-16**. At first sight, the problem appears to require more time than the effort may be worth. However, we may simplify the problem, especially if the two side monopole structures are equally spaced from the center monopole. If we place the center monopole at the system origin, then the calculated junctions left and right of the monopole will be the same, with only a sign change along the line of monopoles. As well, those junctions "above" and "below" (relative to the figure) will also share numerical values with only a sign change. The largest part of the set-up time will involve ensuring accurate entry for the correct tag numbers.



Attend closely to the circles and dots in the diagram. To preserve relatively equal lengths of wire segments close to the hub of the radials, the model uses separate wires for the first two radial sections on 6 radials. The remaining length of the intersecting radials is less critical to accuracy of segment-junction alignment.

Under some circumstances, we may wish to create overlapping radial fields rather than to create an intersecting master field. One such case might be the required radials for a large log periodic monopole array (LPMA). Since each element is actively fed, we cannot take shortcuts on the radial field modeling (which is also bad practice even with parasitic monopole elements). If the LPMA has many elements, creating an intersecting radial field may require more time than the task may allow.

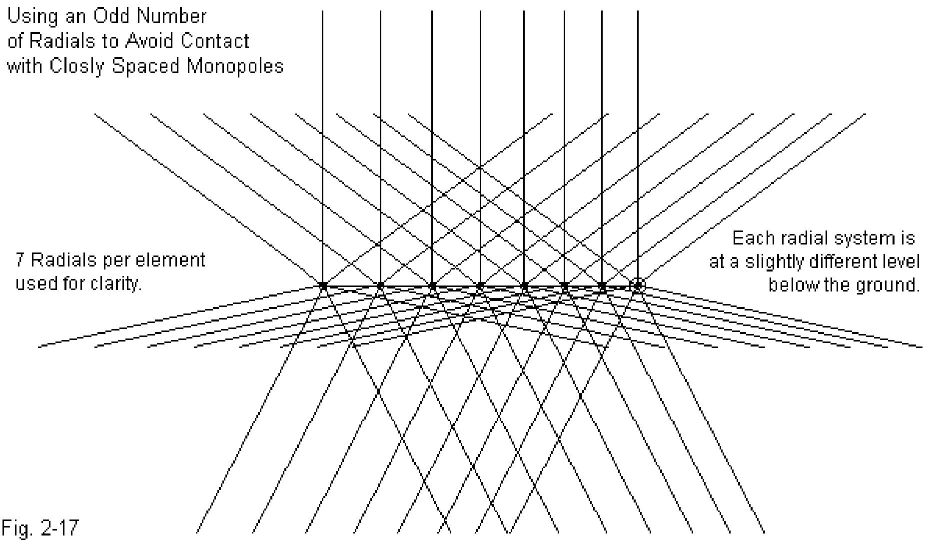


Fig. 2-17

Fig. 2-17 shows part of the technique for creating overlapping radial fields so that none of the radials will intersect any monopole. For clarity, the illustration uses only 7 radials per element. There are 2 keys to radial formation. First, use an odd number of radials. Second, start the first radial at right angles to the line of monopoles. Under these conditions, no radial will lie along the line of monopoles.

To prevent the radials from intersecting, set each radial system at a different level below ground, beginning at one end of the array and going deeper toward the other end. Using normal wire sizes for the radials, set each radial system deeper by about 3 or more times the radial wire radius. If we separate the monopoles at least slightly beyond the limits of the sloping portions of each radial system, the fields will not intersect anywhere within the system. Indeed, since most LPMA systems use wire elements, the thin-wire version of monopole modeling may well apply to simplify the monopole spacing problem.

These notes only introduce and do not foreclose the many potential challenges presented by overlapping and intersecting radial systems for complex monopole arrays. Nevertheless, the techniques should go some distance in easing the quandaries presented by such modeling.

The Next Steps

In this chapter, I have laid out techniques for modeling many basic ground-plane antenna assemblies, whether we place the radials above or below the ground. Along the way, we have mentioned limitation of and guidelines to NEC modeling, with special attention to NEC-4, since this program allows us to model ground-plane antennas with buried wires. Part of my goal was to inform newer modelers of some very useful modeling techniques. The other part of my goal was to reveal the nature of the models used throughout this volume and attached to it.

It would seem that we are now ready to gather lots of data and reach significant conclusions about ground-plane antennas. However, we have one more preliminary matter calling for attention: how to understand what goes on in a ground-plane vertical. How we think about ground-plane verticals affects what we expect from them. So perspective is an important issue in working with this class of antennas and will be the next step in our journey.

3. A Matter of Perspective

Most treatments on ground-plane antennas–especially monopoles–begin with the monopole in contact with the ground and the radials buried beneath the earth's surface. From that starting point, we obtain two fundamental pictures of the ground-plane monopole, sketched incompletely in **Fig. 3-1**.

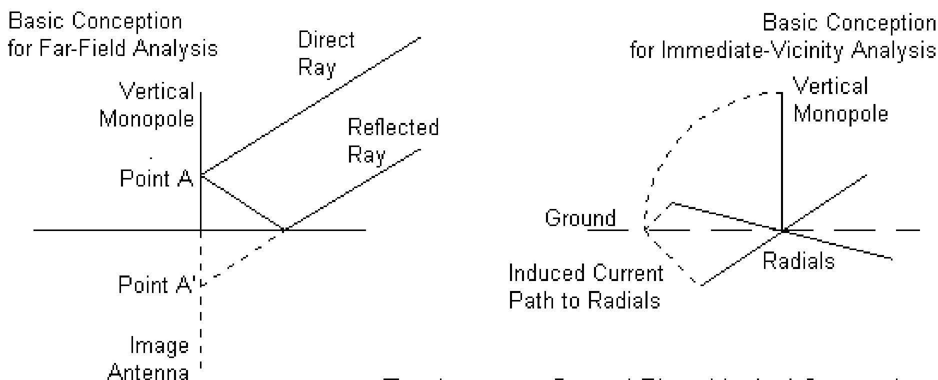
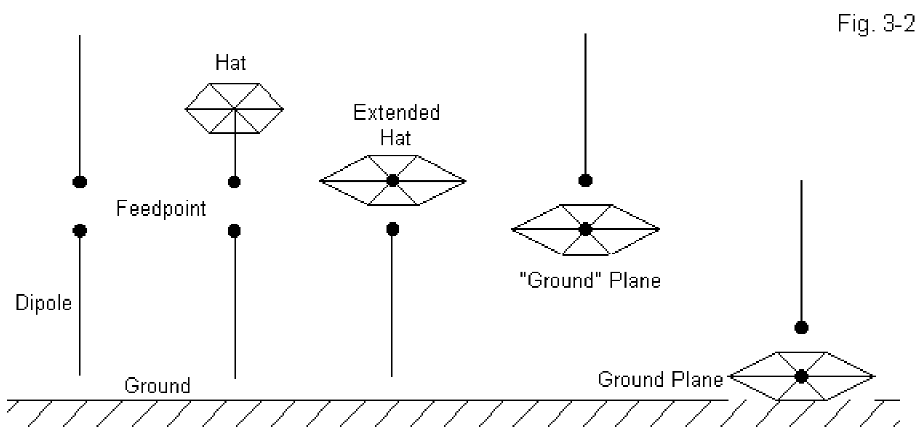


Fig. 3-1 Two Important Ground-Plane Vertical Conceptions

On the left is the familiar explanation of far-field radiation as the product of direct and reflected rays, with the reflected rays further analyzed on principles derived from optical studies. Hence, we obtain the idea of a virtual image antenna. On the right, we have the bare bones of the analysis used in analyzing the relationship between the monopole and its ground plane radials. The terms of the analysis include the idea of the antenna as a circuit in which we have currents induced in the ground returning to the antenna via paths that may vary in loss, depending upon the relative density of the radial field and the distance from any point of current induction to the nearest radials. As part of that analysis, theory introduces us to the concept of the displacement (sometimes called the imaginary) current. Chapter 3 of *The ARRL Antenna Book* (20th Ed.) contains a succinct summary of these ideas, and we need not rehearse them here.

Modeling ground-plane monopoles and similar antennas gives us a different perspective from which to work, one that begins in free space. Free space is simply an environment containing no ground surface, that is, something like outer space. Around the antenna model that we create, there is nothing but a vacuum in every possible direction. Therefore, except for certain conventions that make it easier to transfer the antenna to an environment with a ground surface, it makes no difference how we orient the antenna model. For example, radiation perpendicular to the line formed by a dipole will be the same, no matter how we turn the antenna in the free-space environment.

The free-space environment gives us a new starting point for looking at the ground plane monopole. Indeed, in free space, we can gather together a number of antennas that relate to the ground-plane monopole and examine the evolution from a simple starting point to what we call the ground-plane monopole. **Fig. 3-2** provides one way to look at the progression.



Evolution of the Ground Plane from the Dipole

For example, we can begin with the dipole, using its centered feedpoint as a point of reference. We may shorten one or both ends of the dipole by replacing the end-most portion of the element with a hat, that is, a series of spokes. The spokes are symmetrical around the element end and may also use (optionally) a perimeter wire that connects the tips of the spokes. As we shorten the dipole element half, the required spoke length to restore resonance becomes longer. In all cases, the current at the linear element end divides among the spokes as a continuation of the element. However, the symmetrical spoke arrangement results in a radiation field from each spoke from each element that the fields from the other spokes virtually cancel. Hence, we tend to think of the hat assembly as having no radiation, although this is true only of the entire assembly, not of the individual parts.

Ultimately, we may replace the entire half element with a hat assembly. The sketch shows a complex 6-spoke hat with a perimeter wire. However, any symmetrical assembly will do. A simple Tee arrangement would yield a familiar antenna, although many users would voltage-feed it at the lower end. However, a high feeding point–at the junction of the vertical and the tee elements–will also work. If we flip the assembly, we obtain a conventional elevated ground-plane monopole, like those used extensively in the VHF and UHF regions. Since we began with the premise of working in a free-space environment, we have actually made no change at all. The so-called ground plane is nothing more (or less) than the completion of the dipole using an arrangement of wires whose radiation at right angles to the linear element is self-canceling. The ground-plane monopole thus becomes a special version of the dipole. Only when we move the antenna to an environment that includes a ground and lower the antenna until it touches or almost touches the ground do we encounter the traditional picture of the lower HF monopole in widespread use among radio amateurs. However, the radial system remains an antenna completion "ground" and not the ground itself.

But do we not always connect the braid of the coax to the plane and the center to the monopole? Most of us do, but it is not required if we separate our DC and RF grounds from the antenna end of the transmission line. We can feed a monopole through an inductively coupled balanced ATU and then connect either side of the line to either antenna terminal. Once again, we collect a number of functions into a single configuration, like connecting the case to the coax braid and the braid to the monopole ground rod as our station ground: then we forget to sort out the functions, and the configuration makes it hard to separate them. Nonetheless, the antenna, as an antenna alone, does not in principle need a ground for its ground plane. (But add one anyway for lightning, static discharge, RF, and DC grounding, as briefly described in Chapter 1.)

The Hat

If we are to succeed in looking at ground plane monopoles the new way–as special forms of a dipole–then we must understand some things about so-called capacity hats. While this discussion may seem to be a digression, we shall see in later parts that almost all of what can be said about hats can also be said about so-called ground planes–except this: hats go on top, planes go on the bottom.

A true hat is a symmetrical conductive structure that we place on the end of an antenna element, and at right angles to it, so that two effects occur. First, the net radiation from the hat is zero, due to the cancellation of radiation from one part of the structure by that from another part. Second, by using the hat as a path for antenna currents, we may shorten the main element length and still achieve resonance or some other specified condition.

We may also use slightly non-symmetrical structures to achieve, what is usually called top loading. So long as the structure does not radiate a field more than about -30 dB relative to the field from the main element, the radiation from the field will not materially affect the overall pattern or the feedpoint impedance of the antenna. Non-symmetrical top loading may, however, have an affect on the operating bandwidth and gain of the antenna element.

Although we refer to these methods as top loading, they are quite distinct from base or mid-element loading. All that the two forms of loading have in common is that they allow us to use a shorter main element in our antenna. Base-loading and mid-element loading normally use either solenoid inductors or shorted transmission line stubs to introduce into the antenna an inductive reactance that compensates for the capacitive reactance that emerges as the element is shortened. Inductive reactance comes at the cost of resistance that transforms some of the energy reaching the antenna into heat. Every mode of inductive loading, including the use of inductive transmission line stubs, has a finite Q, and that means a source of gain loss in addition to the loss of gain which is natural to the shortening of an antenna element.

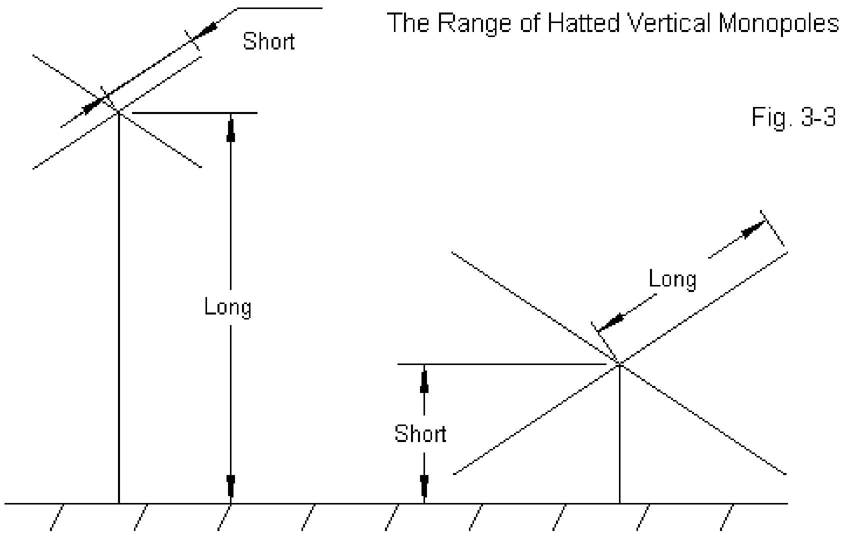
A hat is simply a form of antenna length completion so that the current has a path of a correct length to achieve resonance, despite the use of a shortened main element. The only losses are those associated with the shortening of the element and the materials used to construct the hat.

From the perspective of modeling, we may drop the word "capacitive" when referring to hats. That term arose from a method of calculating the size of hats for LF and VLF and rests on using an open transmission line analogy for antennas. From the start, the technique was considered only an approximation, and it breaks down severely at HF, where the diameter and relatively uniform diameter of antenna elements violates the fundamental terms of the analogy. Hence, from this point forward, I shall simply refer to hats or top hats.

We may construct hat structures in many forms. The most common form is a series of radials extending from the end of the main element outward. The radials are spaced at equal angles to each other. Hats require a minimum of 2 opposing radials, but may have any larger number until they form a solid disk. Along the way, we shall examine an alternative to this structure that has some interesting properties.

The length of a hat radial (or "spoke," as it is sometimes informally called) depends on many variables: the length of the main element relative to the frequency of interest, the diameter of the main element, the diameter of the radial wire, and the number of radials. As an exercise, we can adopt the 7.15-MHz monopole over perfect ground that we employed in the first chapter. The main element has a radius of 0.0125 m (or about a 1" diameter). Alone, the monopole is resonant over perfect ground at a length of 10.067 m. For a hat, we shall use 4 spokes initially, each with a radius of 0.002 m (or a bit over 1/8" in diameter). We shall start with the arrangement shown in **3-3**. Here we have a vertical monopole atop perfect ground. We shall use a top hat consisting of 4 spokes, and then shorten the antenna 10% at a time and see what length the spokes must be to re-

resonate the antenna.



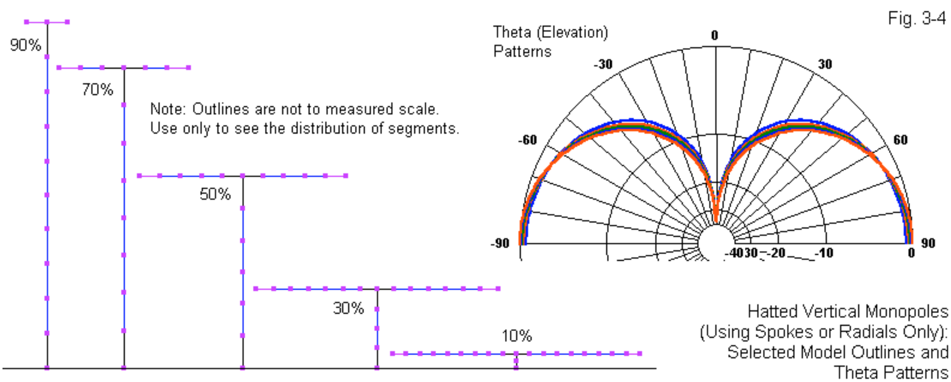
The following lines show one of the models in the series. The monopole is 50% of full length, with the radial wires adjusted for resonance. The model requires only one initial radial wire (GW2), with the other 3 radials replicated by the GM entry.

```
GW 1 6 0 0 0 0 0 5.0335 .0125
GW 2 5 0 0 5.0335 2.726 0 5.0335 .002
GM 1 3 0 0 90 0 0 0 2 1 2 5
GE 1 -1 0
GN 1
EX 0 1 1 0 1 0
FR 0 1 0 0 7.15 1
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

Table 3-1 summarizes the series of 4-spoke hat models (including the full-size monopole) over perfect ground. The data include the gain and feedpoint impedance data so that we can track what happens to performance as we shorten the monopole.

					Table 3-1
Hatted Vertical Monopoles Over Perfect Ground (4 Spokes Only)					
Monopole (M) Radius 0.0125 m; Spoke (S) Radius 0.002 m					
M-Len %	M-Len m	S-Len m	Gain dBi	Resist.	React.
100	10.067	0	5.14	36.08	0.07
90	9.0603	0.535	5.13	35.31	0.03
80	8.0536	1.016	5.09	33.02	0
70	7.0469	1.517	5.04	29.34	0.08
60	6.0402	2.073	4.98	24.48	0.02
50	5.0335	2.726	4.91	18.89	0.03
40	4.0268	3.531	4.84	13.13	0
30	3.0201	4.577	4.77	7.84	0.07
20	2.0134	6.005	4.69	3.65	0.01
10	1.0067	8.05	4.56	0.95	-0.02

Fig. 3-4 shows the general outlines of selected models. The outlines are not to perfect scale, but are useful in seeing the adjustment in the number of segment in both the main element and the spokes as we proceed in the series.



Hatted Vertical Monopoles (Using Spokes or Radials Only): Selected Model Outlines and Theta Patterns

Fig. 3-5 converts the tabular data on element lengths into graphical form. Although the length of the main element decreases linearly, the lengths of the spokes required for resonance is not linear. Rather, the rate of spoke-length increase itself increases as we shorten the monopole.

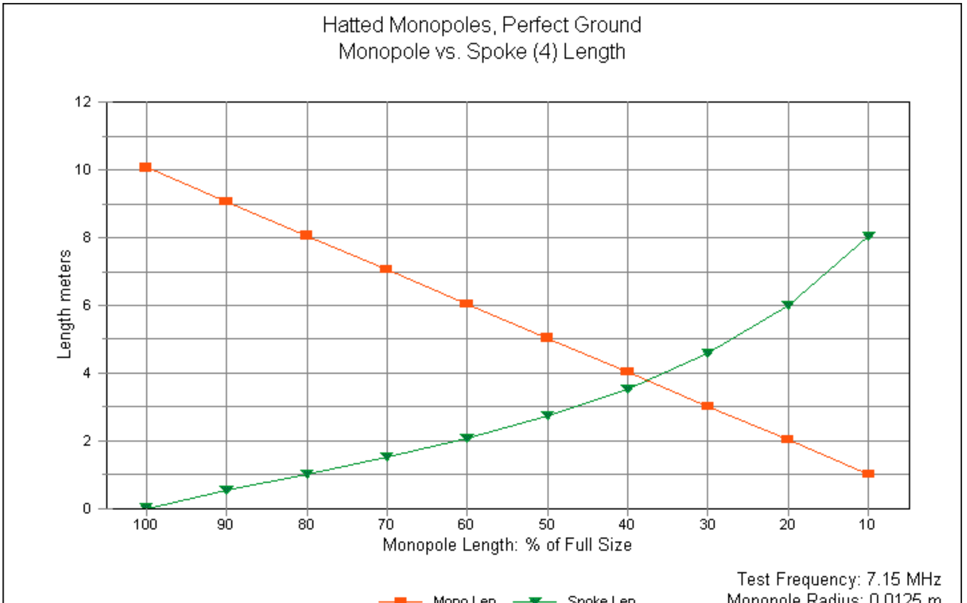
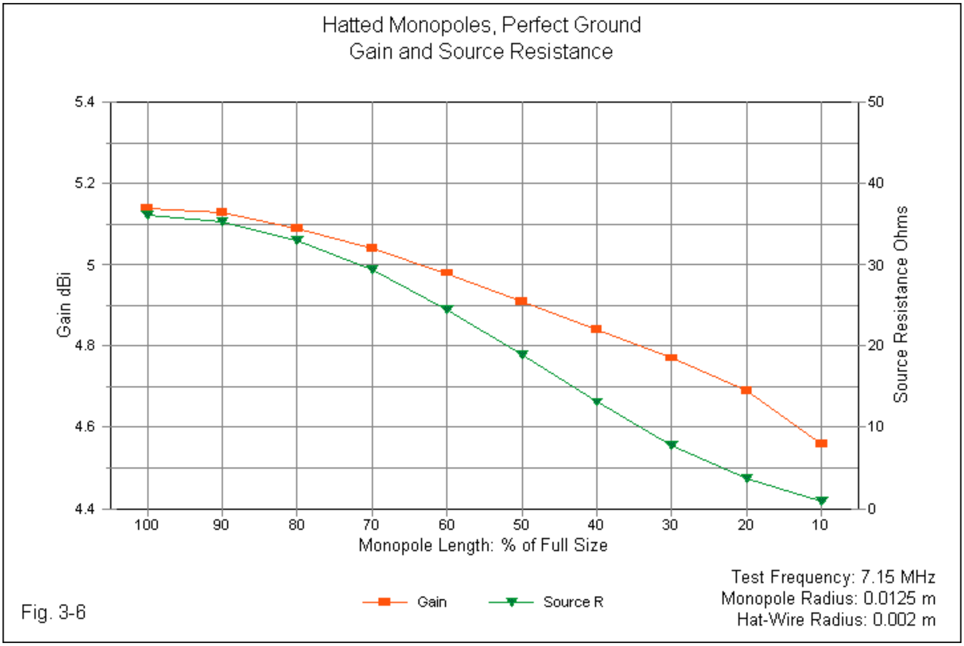


Fig. 3-5

The table and figure both show that despite the radical shortening of the monopole with an end hat, we lose only a bit over a half-dB of gain over perfect ground. (Remember that the elements are also lossless so that we reduce the number of variables in the exercise to just the effects of shortening the monopole and lengthening the spokes. Had we used a common value for material loss, such as aluminum, we might find a gain decrease closer to a full dB over the range of the exercise.) The table also shows the decrease in feedpoint impedance as we shorten the monopole. Whatever the difficulties in working with any of the impedance values shown, the hatted monopole shows the highest impedance at any length relative to all other methods of loading back to resonance. **Fig. 3-6** portrays the gain and impedance information graphically.



The use of hats is not restricted to vertical monopoles. We may employ them on dipoles with equal results. NEC programs model vertical monopoles over perfect ground by the use of the antenna image, essentially a copy of the antenna below the ground level. If we move each of these resonant antennas along with its image into free space, we obtain a resonant dipole whose feedpoint impedance is simply twice the figure for the monopole. Gain reductions will parallel those for the vertical monopole (although starting in the vicinity of about 2.13 dBi in free space for the dipole). In the end, a short dipole with a hat on either end will still have very usable gain. A 2-element Yagi with hatted elements about 70% full-size will rival its full-size cousin in both gain and front-to-back ratio, although the feedpoint impedance will be lower. Indeed, the failure of the hatted

2-element Yagi to achieve the kinds of front-to-back ratio that are achieved by linear and coil loaded Yagis is further evidence of the difference between the two routes to shorter elements.

We may construct a hat using any practical number of spoke or radial wires. **Fig. 3-7** portrays spoke systems ranging from 4 to 64 wires. We shall shortly see why I cut off the exercise at 64 spoke wires.

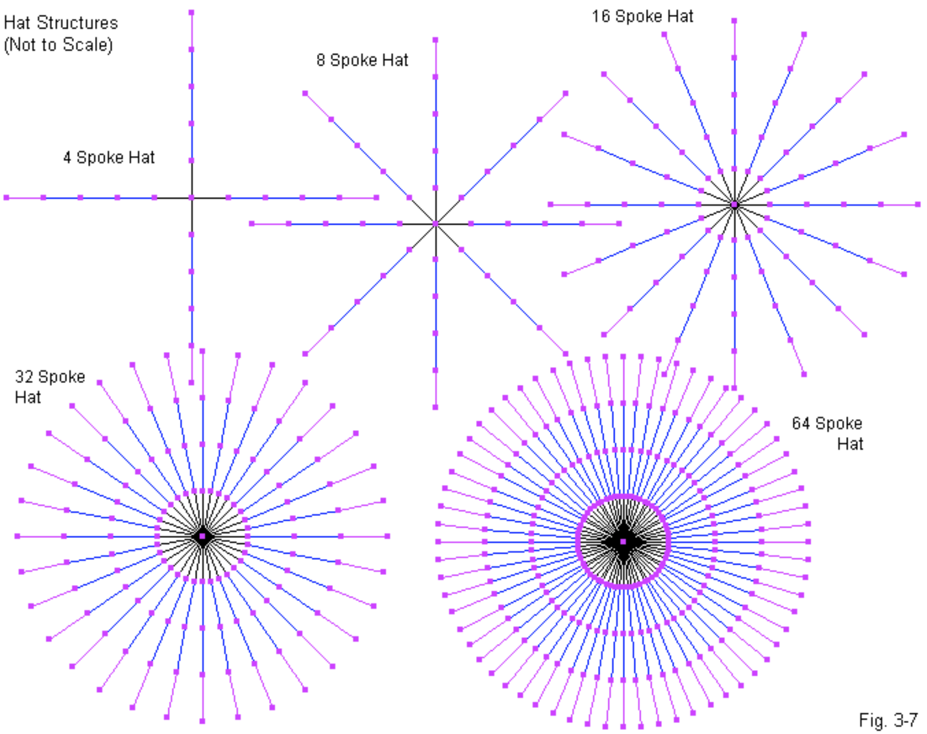


Fig. 3-7

To sample the effects of adding spokes to the hat system, let's select 2 monopole lengths: the 70% and the 50% versions (relative to a hatless full-length monopole. In each case, the model requires no more lines. Instead it requires only an adjustment to the GM line and, of course, an adjustment to the length of the initial spoke, GW2. The following lines come from the 50% model with 32 spokes. You may compare it with the earlier 4-spoke 50% model.

```
GW 1 6 0 0 0 0 0 5.0335 .0125
GW 2 4 0 0 5.0335 1.225 0 5.0335 .002
GM 1 31 0 0 11.25 0 0 0 2 1 2 4
GE 1 -1 0
GN 1
EX 0 1 1 0 1 0
FR 0 1 0 0 7.15 1
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

Table 3-2 provides the modeled data on the spoke length required for each sample model as we increase the number of spokes in the hat. S-Len is the length of the individual spokes in meters. Note that the gain remains virtually unchanged across the range of spokes. The feedpoint resistance changes by under 0.5% for the 70% monopole and by about 1% for the 50% monopole. The reactance column establishes the limits of resonance.

				Table 3-2
Hat Radius vs. Number of Hat Spokes				
70% Monopole (7.0469 m)				
No. Sp	S-Len	Gain dBi	Resist	React
4	1.517	5.04	29.34	0.08
8	1.048	5.04	29.41	0.07
16	0.798	5.05	29.45	0.08
32	0.678	5.05	29.48	0.06
64	0.633	5.05	29.48	-0.05
50% Monopole (5.0335 m)				
4	2.726	4.91	18.89	0.03
8	1.868	4.93	19	0.07
16	1.43	4.93	19.08	0.04
32	1.225	4.93	19.1	0.05
64	1.119	4.93	19.12	-0.05

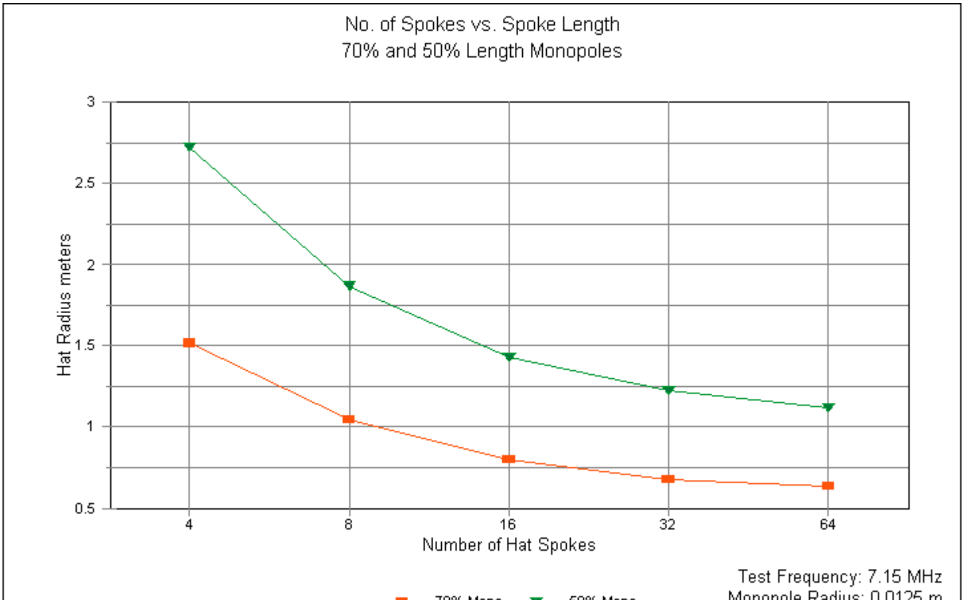


Fig. 3-8

Fig. 3-8 shows why I cut off the exercise at 64 radials. In both cases, the curve is approaching a flat line, indicating also an approach to a simulation of a solid disk hat.

An alternative way to construct hats is to connect the spoke tips with a perimeter wire. **Fig. 3-9** compares the general outline of the spoke-only and the spoke-plus-perimeter wire systems. Note that there is a rough correspondence between the length of a spoke in the spoke-only system to the combined length in the perimeter system of the spoke plus half the length of one perimeter wire. The relationship is not exact because the current at the end of each spoke divides between two perimeter wire sections.

Fig. 3-9

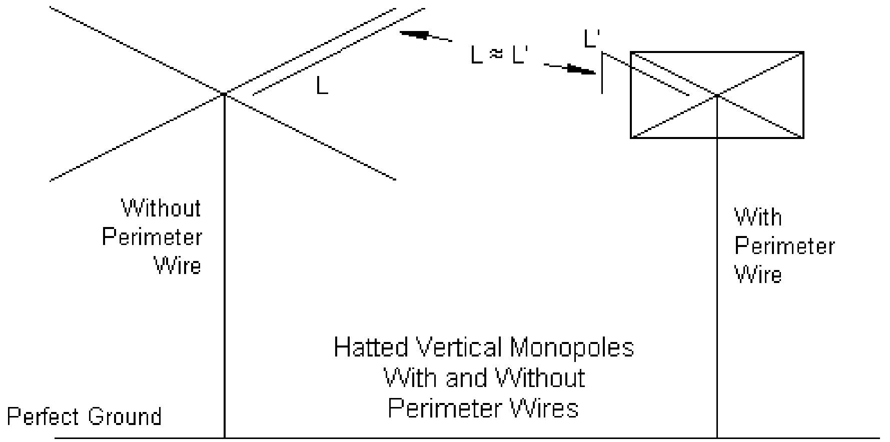


Table 3-3 provides modeling data on various monopole lengths vs. hat sizes, measured as the length of spokes on a 4-spoke system with a perimeter wire.

						Table 3-3
Hatted Vertical Monopoles Over Perfect Ground (4 Spokes + Perimeter Wire)						
Monopole (M) Radius 0.0125 m; Spoke (S) Radius 0.002 m						
M-Len %	M-Len m	S-Len m	Gain dBi	Resist.	React.	
100	10.067	0	5.14	36.08	0.07	
90	9.0603	0.3273	5.14	35.32	0.06	
80	8.0536	0.6278	5.1	33.07	0.08	
70	7.0469	0.915	5.04	29.4	0.08	
60	6.0402	1.218	4.99	24.58	0.05	
50	5.0335	1.572	4.93	18.99	0.07	
40	4.0268	2.003	4.87	13.2	0.02	
30	3.0201	2.545	4.82	7.88	0.07	
20	2.0134	3.23	4.77	3.6	0.05	
10	1.0067	4.088	4.56	0.91	0.03	

Compare the data in **Table 3-3** with the corresponding data for spoke-only hats in **Table 3-1**. Within the limits of the models, there is virtually no performance difference between the two types of hat systems. **Fig. 3-9** compares the spoke lengths for the two systems for each monopole length in the exercise. Because the perimeter wire, as measured from one spoke-tip to the next, is an appreciable part of the total hat-wire length, the two spoke-length curves grow at different rates. For the 10% monopole, the perimeter spoke is only about 50% of the spoke in the other system. However, for a 70% monopole, the ratio is over 60%.

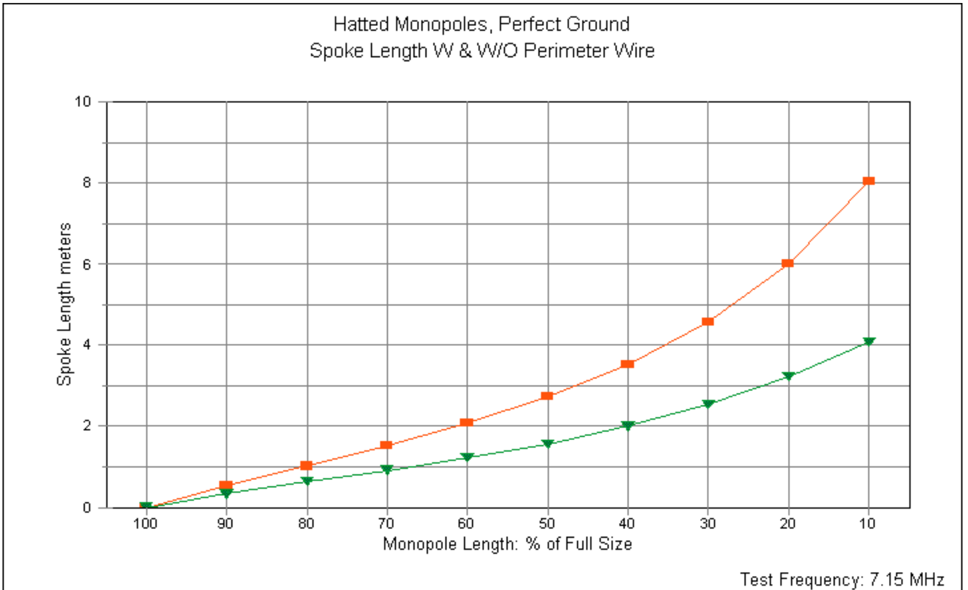


Fig. 3-10

Both sets of models use 0.0125-m radius main elements and 0.002-m radius hat wires. The following sample lines, using a 50% monopole length, show the technique used to produce a compact model. Wire GW2 defines the initial spoke, and wire GW3 defines one perimeter wire. The GM command then replicates the pair, rotating them 90 degrees for each new pair.

```
GW 1 6 0 0 0 0 0 5.0335 .0125
GW 2 4 0 0 5.0335 1.572 0 5.0335 .002
GW 3 5 1.572 0 5.0335 0 1.572 5.0335 .002
GM 1 3 0 0 90 0 0 0 2 1 3 5
GE 1 -1 0
GN 1
EX 0 1 1 0 1 0
FR 0 1 0 0 7.15 1
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

The use of a perimeter wire permits more compact hat structures than are possible with the open radial structure. However, we accrue no weight savings. In very approximate terms, the current path for a perimeter model is equal to the length of the radial plus one-half the length of the perimeter segment to the next radial. Hence, one will use more wire in the perimeter version, but will be able to place it more securely closer to the main element.

Understanding the behavior of top hats is important in itself. Hatted vertical monopoles are growing more common as hams use ingenuity in finding ways to support such structures and as they learn of the reduced losses and wider operating bandwidth possible with such antennas in comparison to base-loaded and mid-element-loaded verticals.

From Free-Space Dipoles to Free-Space Monopoles–and More

We are very comfortable modeling dipoles in free space. We use such models as the starting point for many a disquisition on dipole properties. So let's begin our journey just here. We should note that, in free space, we may model a dipole along any of the three Cartesian coordinates (or even traversing them at an angle). Free space has nothing in any direction and in every direction. Wherever the dipole broadside is, off that broadside will be maximum gain.

This reminder of free space properties is to remove any initial anxiety about modeling our dipole along the Z-axis–which would be height, if we had a ground below. Since we are interested in vertical antennas relative to ground, this strategy will be handy for modeling over ground.

Let's not be too hasty in getting close to the ground. For present purposes, we shall stay 2 wavelengths above average ground (C 0.005 S/m, P 13). At this height and above, antennas show virtually the same feedpoint impedance they show in free space, and some basic gain comparisons will be instructive as we move from full size dipoles toward monopoles with planes.

We shall retain our 0.0125-m radius lossless main element. If we add a plane or a hat, it will be composed of 0.002-m radius lossless radials. This procedure will preserve consistency throughout the exercise, as will the use of our 7.15-MHz test frequency. Note that as soon as we introduce the ground into the model, there will be slight differences in values than we would obtain for scaled models at 3.6 and 1.85 MHz. However, we shall look at those differences in a later chapter.

Building a full size dipole in free space means nothing more than doubling the length of a full size monopole over perfect ground. NEC does the same thing for us with the monopole as it constructs an image during calculations. In theory, the only difference shows up in the feedpoint impedance: values will be twice those reported for the monopole over perfect ground. But we must make a very slight adjustment because we wish to place the source or feedpoint at the exact center of the dipole. To do this with a single source (rather than a split source), we must use an odd number of NEC segments. Since the monopoles used 11 segments per quarter wavelength, the dipole may approximate the same segment density with 21 segments for its electrical half wavelength. To restore a precise resonance, I extended the length by 0.008 m, about 1/20 of 1%.

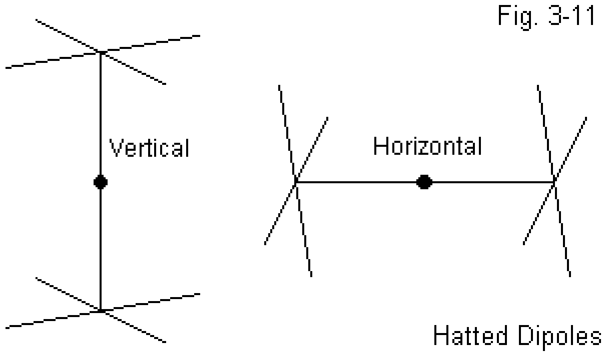
```
GW 1 21 0 0 -10.071 0 0 10.071 .0125
GE 0 -1 0
GN -1
EX 0 1 11 0 1 0
FR 0 1 0 0 7.15 1
RP 0 361 1 1000 -90 0 1.00000 1.00000
EN
```

Let's compare the monopole and the dipole. Gain figures list the monopole over perfect ground and the dipole in free space. They are not significant here, but will become so later. As **Table 3-4** shows, the monopoles over perfect ground show an almost exact 3-dB gain increase over the dipoles in free space. As well, the dipole resonant feedpoint resistance values are well within 1% of exactly double the monopole feedpoint values.

						Table 3-4
Vertical Dipoles in Free Space vs. Monopoles Over Perfect Ground						
Element Radius 0.0125 m; Radial-Spoke Radius 0.002 m						
Length	Type	El Len m	S Len m	Gain dBi	Resist	React
100%	Mono	10.067	0	5.14	36.08	0.07
	Dipole	20.142	0	2.13	71.9	0.07
70%	Mono	7.0469	1.517	5.04	29.34	0.08
	Dipole	14.0994	1.5124	2.03	58.47	0.01
50%	Mono	5.0335	2.726	4.91	18.89	0.03
	Dipole	10.071	2.718	1.9	37.68	0.08
20%	Mono	2.0134	6.005	4.69	3.65	0.01
	Dipole	4.0284	5.975	1.69	7.27	0.04

Using the same principles as we employed for shortening monopoles with hats, we may do the same for dipoles. We simply place the hat assembly on each end of the dipole, as shown in **Fig. 3-11**. Note that in free space, the hatting applies regardless of the orientation of the dipole. Moreover, each hat assembly will have virtually the same length spokes on each end as the single hat for a monopole, if we assume the same degree of shortening. Hence, a monopole that is 50% of full size will require spokes of a certain length. A dipole that is 50% of full size will require 2 hats, each with spokes of that same length.

As earlier noted for monopoles, the exact spoke length depends on the number of spokes, the element radius, and the hat wire radius. For our demonstration, we shall us 0.002-m lossless wire for the hat spokes and initially use only 4 spokes.



The following sample lines illustrate the modeling techniques for creating a 50% long dipole in free space with the dipole oriented along the Z-axis. We have 2 hats, each one with an initial radial or spoke, followed by a GM command to replicate that wire 3 more times at 90° angles from the preceding spoke.

```
GW 1 11 0 0 -5.0355 0 0 5.0355 .0125
GW 2 5 0 0 5.0355 2.718 0 5.0355 .002
GM 1 3 0 0 90 0 0 0 2 1 2 5
GW 6 5 0 0 -5.0355 2.718 0 -5.0355 .002
GM 1 3 0 0 90 0 0 0 6 1 6 5
GE 0 -1 0
GN -1
EX 0 1 6 0 1 0
FR 0 1 0 0 7.15 1
RP 0 361 1 1000 -90 0 1.00000 1.00000
EN
```

We shall sample the performance of the hatted dipoles in free space and again 2 λ over average ground. The goal is to provide an initial starting point for developing gain and source impedance expectations relative to the free-space model. For this exercise, we shall not survey all possible monopole lengths, but instead just sample dipoles that are 70%, 50%, and 20% of full size. You may use the data graphs for the monopoles to extrapolate a full curve from 100% to 10% dipoles. **Fig. 3-12** outlines the various models in the test, showing the segmentation and well as the overall relative sizes. **Table 3-4** provides the dimensions

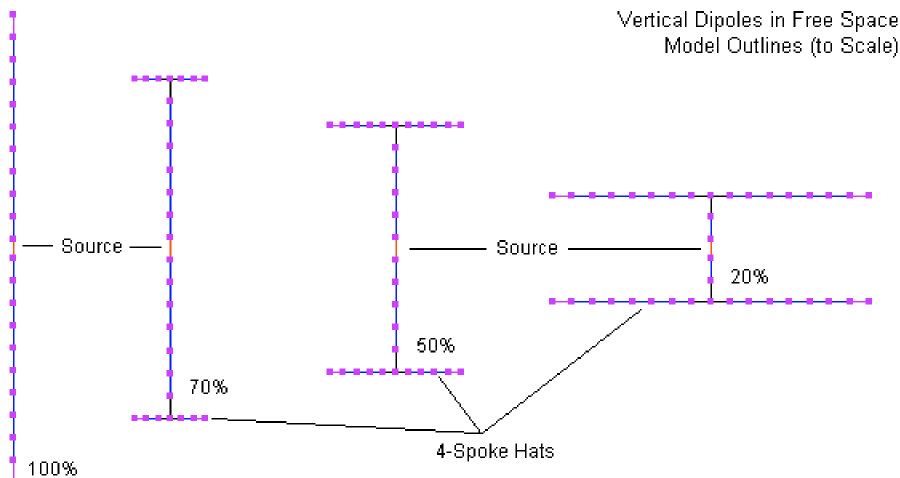


Fig. 3-12

The data from our modeling experiment appear in **Table 3-5**.

					Table 3-5
Vertical Dipoles: Free Space vs. 2-WL Above Average Ground					
Ground: Conductivity 0.005 S/m; Permittivity 13					
Length	Environ	Gain	TO Angle	Resist	React
100%	Free Sp	2.13	90	71.9	0.07
	Ground	4.45	83	71.75	0.11
70%	Free Sp	2.03	90	58.47	0.01
	Ground	4.35	83	58.33	0.05
50%	Free Sp	1.9	90	37.68	0.08
	Ground	4.24	83	37.58	0.11
20%	Free Sp	1.69	90	7.27	0.04
	Ground	4.04	83	7.25	0.05

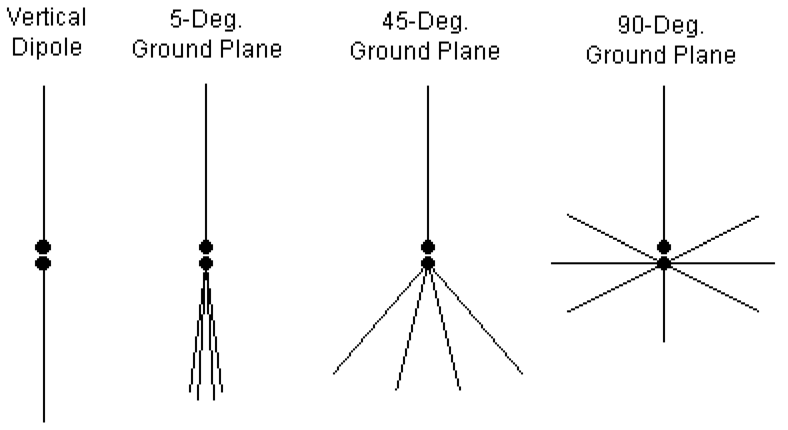
Regardless of the shortened dipole length, the gain over ground at a height of 2 λ (83.858 m at 7.15 MHz) is between 2.32-dB and 2.35-dB higher than the free-space model. Of course, gain over ground will vary with the ground quality, even at this seemingly extreme height. (The height is only extreme if we consider lower-HF vertical dipoles. We often use height up to 20 times the 2-λ values with vertical dipoles at VHF and UHF.) The feedpoint resistance changes by only a slight amount between the two environments.

The dipole only 20% of full size loses only a half dB relative to a full size dipole, as do equivalently shrunken monopoles. If we can handle the low feedpoint impedances involved, these antennas can be useful.

The shortest of the hatted antennas has hat radials far longer than the main element itself. However, the radiation from these hats fully cancels so that all radiation in the far field pattern is vertically polarized. Moreover, the hats do not interact, as evidenced by the fact that the shortest dipole reflects the same feedpoint impedance doubling and gain reduction amount as the monopole over perfect ground. Each hat is the antenna current completion path for each of the monopoles forming the dipole.

Our hat experiment shortens the dipole by attacking both ends. However, we may take another approach, illustrated in **Fig. 3-13**. We may convert one half of the dipole element into 4 wires and gradually spread them, using 4 (or more) wires to replace the straight element half. To reduce the work, we shall use an initial angle of 5° (actually 5.25°) off true vertical for the new set of 0.002-m radius wires. Then we shall increase the angle to 45° and finally arrive at a set of wires that are 90° relative to the remaining upper vertical wire. As we did for the shortened vertical dipoles, we shall hold the vertical wire constant at 10.071 m and select wire lengths for the lower section that allow us to resonate the assembly.

When thinking about the antennas, remember that only the 90° radial wire set self-cancels the radiation from individual wires. At intermediate angle, think of the radiation as having 2 components. The horizontal component will cancel, but the vertical component will not. Rather, it will contribute to the total assembly radiation.



A Dipole-to-Ground-Plane-Monopole Transition Fig. 3-13

The models for this exercise are identical except for the formation of the radials. The following extracts show only the wires for the 3 models with radial wires. To place the models 2 wavelengths over ground, using the feedpoint as a reference, we would use a single additional GM command:

```
GM 0 0 0 0 0 0 0 83.858
```

5° Model

```
GW 1 11 0 0 0 0 0 10.071 .0125
GW 2 11 .8 0 -8.705 0 0 0 .002
GM 1 3 0 0 90 0 0 0 2 1 2 11
GE 0 -1 0
```

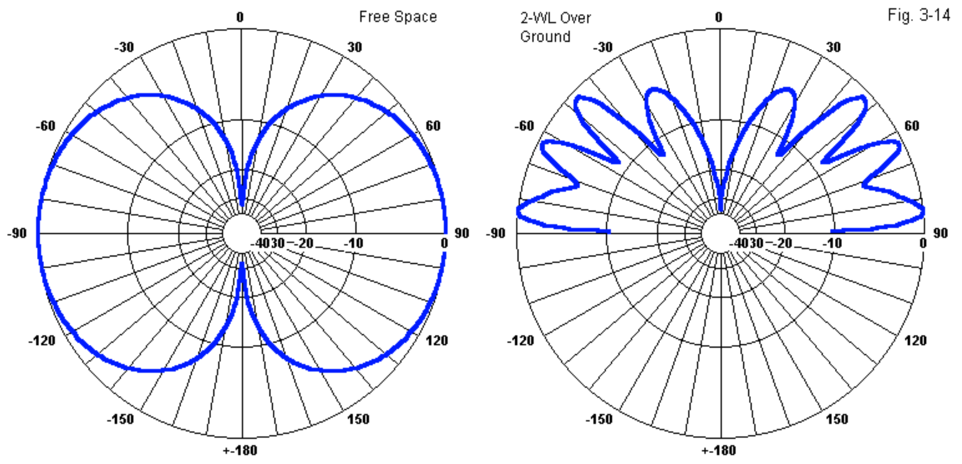
45° Model

```
GW 1 11 0 0 0 0 0 10.071 .0125
GW 2 11 6.786 0 -6.786 0 0 0 .002
GM 1 3 0 0 90 0 0 0 2 1 2 11
GE 0 -1 0
```

90° Model

```
GW 1 11 0 0 0 0 0 10.071 .0125
GW 2 11 11.57 0 0 0 0 0 .002
GM 1 3 0 0 90 0 0 0 2 1 2 11
GE 0 -1 0
```

All free-space models in this series produce patterns resembling the one on the left in **Fig. 3-14**. All of the models that are 2 λ above average ground produce patterns resembling the one on the right.



Theta Patterns Applicable to All Free-Space and Over-Ground Verticals in This Section

I designed this little experiment to illustrate several points, some about actual antennas and some about antenna models. With respect to actual antennas, the radial lengths will vary as we change the angle away from a true vertical dipole. The goal was not only to maintain the length of the upper vertical element, but as well to ensure equal current division between the upper and lower sections of the antenna. Of course, the maximum current in each radial is ¼ the value of the maximum current in the upper element and both occur at the junction of these antenna parts. For the models in our test, the maximum deviation from the goal is about 0.5%.

With respect to modeling, we may perform extra work on these models to ensure that we have sensible reports of performance. For each model, I performed an average gain test and used the results to correct the initial reports for gain and the resistive impedance. For models close to resonance, the basic free-space AGT score times the reported feedpoint impedance provides the corrected figure. If we convert the AGT value to dB (by taking 10 times the $\log_{10}$ of the score), we obtain an amount to add or subtract from the gain report. For scores under 1.00, we add gain, and for scores over 1.00, we subtract gain. Although we shall apply the gain corrective to the recorded value of maximum gain, it actually applies to the reported gain at any angle relative to the antenna. **Table 3-6** shows the results of the work. It does not implement the corrective to the source impedance, but does introduce the gain correction in the "Adj Gain" column.

										Table 3-6
Transition From Vertical Dipole to 90-Deg. Radial Ground-Plane Monopole: Free Space vs. 2-WL Above Average Ground										
Ground: Conductivity 0.005 S/m; Permittivity 13										
Model	Environ	Up-L m	Rad-L m	Gain	AGT	Adj Gain	Bmwidth	TO Angle	Resist	React
Dipole	Free Sp	10.071	10.071	2.13	0	2.13	80		71.9	0.07
	Ground		(1/2 dpl)	4.45	0	4.45		83	71.75	0.11
5-Deg M	Free Sp	10.071	8.705	2.38	-0.29	2.09	80		61.2	-0.03
	Ground			4.71	-0.29	4.42		83	61.07	0.03
45-Deg M	Free Sp	10.071	9.597	2	-0.1	1.9	86		50.25	0.01
	Ground			4.39	-0.1	4.29		83	50.16	0.11
90-Deg M	Free Sp	10.071	11.57	1.35	0.09	1.44	102		21.34	0.06
	Ground			3.88	0.09	3.97		84	21.38	0.13

Note that if we had used only the raw data from NEC, the 5° model would appear to yield more gain than the dipole itself, even though some small part of the radiation from the lower radials self-cancels. The corrected gain values for both the free-space and the over-ground models yield a more sensible progression. Equally interesting is the fact that we lose a bit more gain in the progression in free space than we do over ground. However, at the same time, note the increasing beamwidth of the free-space models as we bend the lower radials outward.

The 5° radial system shows the greatest amount of necessary correction due to the close spacing of the radials and the very shallow angle at which the radials approach the junction with the main element. If we add enough radials, we eventually will simulate a solid cone that some folks refer to as a decoupling sleeve. However, this so-called sleeve is an active part of the radiating antenna and is used widely at VHF. The 45° model shows an impedance close to the characteristic impedance of the most common coaxial cables. Hence, we often find this version of the antenna used at VHF and UHF. The 90° radial system most closely coincides with what we find in ground-mounted HF verticals, and we shall focus our attention on this system for the remainder of this chapter. However, we shall return to the sloping radial systems in a later chapter.

At this point, the basic question is what happens when we increase the number of radials while maintaining the wire radius (0.002 m), the upper or vertical elements, and resonance at the test frequency (7.15 MHz). Let's sample the effects of more radials using a progression of 4, 8, 16, 32, and 64 radials. We shall be interested in several facets of the model reports. For example, we shall wish to know the radial length and whether it shrinks with more radials, like the hat spokes that we used to shorten both monopole and dipoles. We shall also wish to see if maximum gain improves or not with more radials–and why. The following lines show the ease of setting up models for the test by modifying the GM line that establishes the number of radials. The models set up 64 free-space radials with the standard upper vertical element.

```
GW 1 11 0 0 0 0 0 10.071 .0125
GW 2 11 12.52 0 0 0 0 0 .002
GM 1 63 0 0 5.625 0 0 0 2 1 2 11
GE 0 -1 0
GN -1
EX 0 1 1 0 1 0
FR 0 1 0 0 7.15 1
RP 0 361 1 1000 -90 0 1.00000 1.00000
EN
```

Of course, we have a situation in which the increasing number of radials will reduce the angle between radials at the junction with the vertical element. Hence, we shall wish to track the AGT scores and apply correctives as applicable. **Table 3-7** supplies the data drawn from the series of models for free space and for 2 λ over average ground.

											Table 3-7
Performance vs. Number of Radials: 90-Degree Ground-Plane Monopole: Free Space vs. 2-WL Above Average Ground											
Ground: Conductivity 0.005 S/m; Permittivity 13											
No. Rad	Rad-L m	Environ	Gain	AGT	Adj Gain	Bmwidth	TO Angle	Resist	AGT	Adj Res	React
4	11.57	Free Sp	1.35	0.09	1.44	102		21.34	0.98	20.92	0.06
		Ground	3.88	0.09	3.97		84	21.38		20.95	0.13
8	11.97	Free Sp	1.29	0.1	1.39	104		21.77	0.977	21.27	0.08
		Ground	3.83	0.1	3.93		84	21.8		21.31	0.15
16	12.31	Free Sp	1.21	0.11	1.32	105		22.22	0.975	21.66	0.02
		Ground	3.78	0.11	3.89		84	22.26		21.71	0.15
32	12.52	Free Sp	1.15	0.12	1.27	107		22.63	0.974	22.04	0
		Ground	3.72	0.12	3.84		84	22.69		22.09	0.08
64	12.52	Free Sp	1.12	0.11	1.23	109		22.86	0.975	22.3	-0.06
		Ground	3.7	0.11	3.81		84	22.91		22.35	0.01

In this instance, I have corrected both the gain and the impedance reports. The latter changes are very small and likely would have no operational significance. However, our goal is to track the numerical trends in the data.

One immediately noticeable trend is the fact that radials become longer as we increase their numbers in order for the array to be resonant. The total growth is almost 1 m or about 9%. The growth slows as the radials exceed 16 and virtually stops by 64 radials, the level that approaches (in hats) a simulation of a solid disk. The actual radial length, of course, depends in part upon the wire size and the radius of the main element, so different numbers will emerge from models that vary from our sample. As well, the density of the radials also affects the exact point of equal current division between the main element and the radials, which in turn has an effect on the required relative lengths of element and radials.

If we examine the free-space versions of the antenna, we find that the denser the radial system, the wider the beamwidth as measured in the E-plane or parallel to the vertical element. One consequence of the increasing beamwidth is a lowering of the maximum gain value as the number of radials increases. The decrease is equally apparent in the gain values over average ground. For this set of reasons, elevated-radial ground-plane monopole systems generally show their highest gain potential with few radials, so long as the radials form a symmetrical plane.

The feedpoint impedance varies over a very small range–about 1.5 Ω. As we add more radials, even the corrected values of resistance show an increase. This increase may result from the slight changes in current distribution among the models. Perhaps the most notable result of the free-space models of the 90° radial system is the value of resonant impedance. Where the vertical element is ½ the length of a resonant vertical monopole and the radial length brings the system to resonance in the new configuration, the feedpoint impedance is in the low 20s. This value contrasts to the 36-Ω value produced by full ¼-λ monopole over perfect ground. Many radio amateur erroneously transport the 36-Ω value from ground up to highly elevated VHF ground-plane monopoles. However, to obtain a 36-Ω impedance for a highly elevated ground-plane monopole requires an easy but significant re-design of the system. The simplest method is to lengthen the monopole and shorten the radials, thus resulting in an off-center-fed monopole system. Alternatively, the designer can slope the radials at about a 45° angle.

Bringing the Ground-Plane Monopole Down to Earth

Having worked our way through the relationship of element-shortening hats to ground-plane radial systems, we may now draw the high-flying ground-plane monopole closer to the surface of the earth. The result will be a collection of data tables containing a large volume of information. The models will be the same ones used in the preliminary investigation of 90° radial systems. Hence, we shall use models with 4, 8, 16, 32, and 64 radials, structured in the same way as the sample shown earlier. However, for each height above ground, I simply altered the final GM entry that set the base height of the model at the desired distance above ground.

The models handling the two levels of buried ground radials used the sloping radial system. See Chapter 2 for more details on this system of modeling ground-plane antennas with buried radials, drawn from the 16-radial model buried at the lower of the two levels sampled. The other models follow exactly the same pattern, with all changes confined to the GM line. The monopole just reaches ground (Z=0). Each radial has 2 parts. The first segment angles from the monopole base to the selected level of the buried radial. The second radial wire completes the radial in a level manner. The following lines show a sample. Note that there are 2 GW2 entries. In NEC, it is not necessary to give each wire a separate tag number.

```
GW 1 11 0 0 0 0 0 10.071 .0125
GW 2 1 1.05 0 -.21 0 0 0 .002
GW 2 10 11.57 0 -.21 1.05 0 -.21 .002
GM 1 15 0 0 22.5 0 0 0 2 1 2 11
GE -1 -1 0
GN 2 0 0 0 13.0000 0.0050
EX 0 1 1 0 1 0
FR 0 1 0 0 7.15 1
RP 0 361 1 1000 -90 0 1.00000 1.00000
EN
```

A second dimension of data gathering involves the sequence of heights above ground. Although performance data changes slowly as we move downward from 2 λ above ground, the rate of change increases below about 0.5 λ. The rate further increases below 0.1 λ. At 7.15 MHz, a wavelength is 41.929 m or 137.562'. Therefore, I used the follow set of heights above ground for the tables to come.

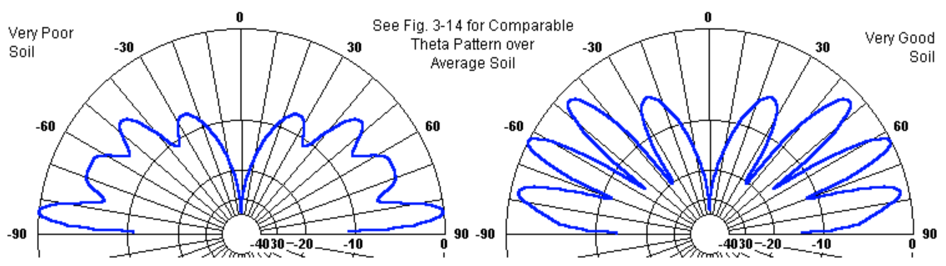
Wavelengths	Meters	Feet	Wavelengths	Meters	Feet
2.0	83.858	275.124	0.1	4.193	13.756
1.5	62.894	206.343	0.05	2.096	6.878
1.0	41.929	137.562	0.025	1.048	3.439
0.5	20.965	68.781	0.01	0.419	1.376
0.375	15.723	51.586	0.005	0.210	0.688
0.25	10.482	34.391	0.001	0.042	0.138
0.2	8.386	27.512	-0.001	-0.042	-0.138
0.15	6.289	20.634	-0.005	-0.210	-0.688

The third sampling dimension consisted of the ground quality beneath the antenna. For each size antenna, I started with perfect ground. Of course, this ground selection excludes buried radials. Because salt water holds considerable interest to vertical antenna users, I included this ground. Finally, I ran the models using 3 widely separated qualities of dry land. The common names for these soils are very good, average, and very poor. The following list shows the related values of conductivity and permittivity for the range of sample runs.

Soil Quality Name	Conductivity (S/m)	Relative Permittivity
Salt water	5.0	81
Very Good	0.0303	20
Average	0.005	13
Very Poor	0.001	5

See the tables in Chapter 1 to learn how each value set fits into the overall range of soil qualities for which measurements exist.

For each run, I recorded the maximum gain, the TO (or take-off) angle, and the source resistance. All TO angles appear as theta angles, that is, counting from the zenith downward. Subtract the value shown from 90° to obtain the corresponding elevation angle. The source impedance will show considerable variation in both resistance and reactance, since the models were resonated in free space and not modified as they approached and reached the ground surface. Indeed, one goal of gathering the data was to see what performance changes followed from lowering the antenna height.



Theta (Elevation) Patterns for 2-WL High Monopole Over Different Soils   Fig. 3-15

As **Fig. 3-15** shows, theta or elevation patterns can change considerably just by changing the soil conditions. The two antennas are not only identical, but also at the same height above ground (2 λ). See **Fig. 3-14** for the corresponding pattern over average ground.

Tables 3-8 through **3-12** appear on the next set of pages.

4-Radial 90-Degree Ground-Plane Monopole From 2-WL Up to Below Ground: Performance with Various Ground Types											Table 3-8
Free-Space Reference Performance				Monopole: Len 10.071 m, Radius 0.0125 m						Freq.: 7.15 MHz	
Rad-L m	Rad-R m	Gain dBi	Bmwidth	Resist	React						
11.57	0.002	1.35	102	21.34	0.06						
Ground Type		Perfect				Ground Type		Salt Water: C 5.0, P 81			
Height wl	Height m	Gain dBi	TO Angle	Resist	React	Height wl	Height m	Gain dBi	TO Angle	Resist	React
2	83.858	7.37	90	21.37	0.17	2	83.858	6.95	77	21.37	0.17
1.5	62.894	7.37	90	21.4	0.25	1.5	62.894	6.88	72	21.39	0.24
1	41.929	7.35	90	21.47	0.46	1	41.929	6.59	65	21.45	0.41
0.5	20.965	7.26	90	21.94	1.25	0.5	20.965	5.78	86	22.51	1.09
0.375	15.723	7.75	90	19.6	1.12	0.375	15.723	7.1	85	17.37	1.63
0.25	10.482	7.82	90	19.17	-2.63	0.25	10.482	6.84	84	19.17	-2.57
0.2	8.386	7.46	90	20.78	-4.32	0.2	8.386	6.57	84	20.73	-4.25
0.15	6.289	6.89	90	23.61	-5.26	0.15	6.289	6.1	83	23.51	-5.21
0.1	4.193	6.24	90	27.52	-4.66	0.1	4.193	5.54	83	27.34	-4.69
0.05	2.096	5.6	90	32.1	-1.34	0.05	2.096	4.99	82	31.89	-1.51
0.025	1.048	5.32	90	34.5	2.41	0.025	1.048	4.74	81	34.34	2.15
0.01	0.419	5.16	90	35.9	6.31	0.01	0.419	4.56	81	36.16	6.3
0.005	0.21	5.12	90	36.31	8.31	0.005	0.21	4.42	81	37.41	9.27
0.001	0.042	5.12	90	36.3	10.09	0.001	0.042	3.8	81	43.19	22.04
						-0.001	-0.042	4.54	81	36.66	0.06
						-0.005	-0.21	4.54	81	36.66	0.06
Ground Type		Very Good: C 0.0303, P 20				Ground Type		Average: C 0.005, P 13			
Height wl	Height m	Gain dBi	TO Angle	Resist	React	Height wl	Height m	Gain dBi	TO Angle	Resist	React
2	83.858	5.14	63	21.38	0.15	2	83.858	3.88	84	21.38	0.13
1.5	62.894	4.84	73	21.41	0.21	1.5	62.894	3.66	54	21.4	0.17
1	41.929	5.12	65	21.48	0.35	1	41.929	3.28	66	21.47	0.27
0.5	20.965	3.66	46	22.58	0.85	0.5	20.965	2.49	46	22.48	0.57
0.375	15.723	2.77	38	17.75	1.79	0.375	15.723	1.68	39	18.34	1.75
0.25	10.482	1.81	78	19.02	-1.95	0.25	10.482	0.16	75	19.27	-1.27
0.2	8.386	2.04	77	20.12	3.7	0.2	8.386	0.27	75	19.92	-2.78
0.15	6.289	2.08	75	22.42	-5.04	0.15	6.289	0.3	72	21.55	-4.15
0.1	4.193	1.99	74	25.96	-5.29	0.1	4.193	0.24	70	24.35	-4.84
0.05	2.096	1.81	71	30.83	-3.12	0.05	2.096	0.1	67	28.64	-3.48
0.025	1.048	1.66	70	34.15	0.88	0.025	1.048	-0.04	65	31.75	0.22
0.01	0.419	1.44	69	37.35	8.59	0.01	0.419	-0.22	64	34.64	7.85
0.005	0.21	1.25	69	39.49	16.75	0.005	0.21	-0.38	64	36.52	16.53
0.001	0.042	0.33	69	48.75	55.06	0.001	0.042	-1.37	64	47.26	52.34
-0.001	-0.042	0.46	69	51.03	8.57	-0.001	-0.042	-2.37	64	64.75	7.98
-0.005	-0.21	0.35	69	52.37	10.21	-0.005	-0.21	-2.49	64	66.25	10.3
Ground Type		Very Poor: C 0.001, P 5									
Height wl	Height m	Gain dBi	TO Angle	Resist	React						
2	83.858	5.11	84	21.37	0.1						
1.5	62.894	4.54	82	21.39	0.13						
1	41.929	3.52	79	21.44	0.19						
0.5	20.965	1.39	74	22.21	0.29						
0.375	15.723	1.32	73	19.25	1.51						
0.25	10.482	0.56	71	19.78	-0.6						
0.2	8.386	0.33	70	20.01	-1.71						
0.15	6.289	0.05	68	20.93	-2.87						
0.1	4.193	-0.28	66	22.76	-3.76						
0.05	2.096	-0.65	64	25.84	-3.37						
0.025	1.048	-0.87	62	28.2	-0.96						
0.01	0.419	-1.1	61	30.58	4.64						
0.005	0.21	-1.27	61	32.26	10.93						
0.001	0.042	-1.91	60	38.9	32.14						
-0.001	-0.042	-4.49	60	99.01	16.29						
-0.005	-0.21	-4.62	60	99.05	11.32						

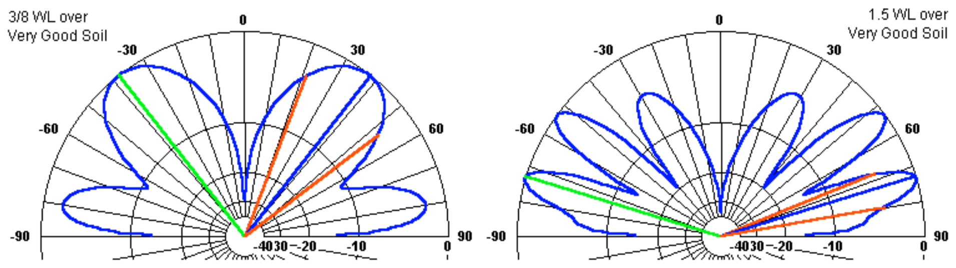
8-Radial 90-Degree Ground-Plane Monopole From 2-WL Up to Below Ground: Performance with Various Ground Types											Table 3-9
Free-Space Reference Performance				Monopole: Len 10.071 m, Radius 0.0125 m						Freq.: 7.15 MHz	
Rad-L m	Rad-R m	Gain dBi	Bmwidth	Resist	React						
11.97	0.002	1.29	104	21.77	0.08						
Ground Type		Perfect				Ground Type		Salt Water: C 5.0, P 81			
Height wl	Height m	Gain dBi	TO Angle	Resist	React	Height wl	Height m	Gain dBi	TO Angle	Resist	React
2	83.858	7.3	90	21.8	0.2	2	83.858	6.9	77	21.8	0.19
1.5	62.894	7.3	90	21.84	0.28	1.5	62.894	6.84	73	21.83	0.27
1	41.929	7.28	90	21.93	0.49	1	41.929	6.6	65	21.9	0.44
0.5	20.965	7.18	90	22.49	1.27	0.5	20.965	5.67	86	23.12	1.07
0.375	15.723	7.67	90	20.06	1.35	0.375	15.723	7	85	17.82	1.85
0.25	10.482	7.81	90	19.27	-2.47	0.25	10.482	6.82	84	19.28	-2.4
0.2	8.386	7.48	90	20.76	-4.38	0.2	8.386	6.58	84	20.71	-4.26
0.15	6.289	6.92	90	23.54	-5.52	0.15	6.289	6.12	83	23.42	-5.47
0.1	4.193	6.26	90	27.45	-5.29	0.1	4.193	5.56	83	27.27	-5.31
0.05	2.096	5.61	90	32.1	-2.74	0.05	2.096	5	82	31.84	-2.93
0.025	1.048	5.31	90	34.53	0.06	0.025	1.048	4.75	81	34.24	-0.31
0.01	0.419	5.15	90	35.97	3.12	0.01	0.419	4.6	81	35.76	2.63
0.005	0.21	5.1	90	36.44	4.99	0.005	0.21	4.52	81	36.53	4.81
0.001	0.042	5.11	90	36.42	7.61	0.001	0.042	4.17	81	39.68	13.76
						-0.001	-0.042	4.56	81	36.52	-0.09
						-0.005	-0.21	4.56	81	36.52	-0.09
Ground Type		Very Good: C 0.0303, P 20				Ground Type		Average: C 0.005, P 13			
Height wl	Height m	Gain dBi	TO Angle	Resist	React	Height wl	Height m	Gain dBi	TO Angle	Resist	React
2	83.858	5.15	63	21.81	0.17	2	83.858	3.83	84	21.8	
1.5	62.894	4.83	54	21.84	0.23	1.5	62.894	3.41	54	21.83	
1	41.929	5.11	66	21.93	0.37	1	41.929	3.26	66	21.91	
0.5	20.965	3.76	46	23.18	0.82	0.5	20.965	2.59	46	23.04	
0.375	15.723	2.98	38	18.22	1.99	0.375	15.723	1.88	39	18.82	
0.25	10.482	1.73	78	19.19	-1.75	0.25	10.482	0.12	75	19.52	
0.2	8.386	2	77	20.14	-3.62	0.2	8.386	0.25	74	20.03	
0.15	6.289	2.06	76	22.32	-5.18	0.15	6.289	0.29	72	21.52	
0.1	4.193	1.98	74	25.77	-5.81	0.1	4.193	0.25	70	24.16	
0.05	2.096	1.83	71	30.44	-4.68	0.05	2.096	0.15	67	28.1	
0.025	1.048	1.74	70	33.24	-2.54	0.025	1.048	0.09	65	30.59	
0.01	0.419	1.66	69	35.2	1.4	0.01	0.419	0.04	64	32.32	
0.005	0.21	1.61	69	36.05	5.77	0.005	0.21	0	64	33.06	
0.001	0.042	1.1	69	40.47	29.42	0.001	0.042	-0.53	64	38.69	
-0.001	-0.042	0.89	69	46.36	6.18	-0.001	-0.042	-1.4	64	53.56	
-0.005	-0.21	0.78	69	47.76	8.1	-0.005	-0.21	-1.51	64	55.04	
Ground Type		Very Poor: C 0.001, P 5									
Height wl	Height m	Gain dBi	TO Angle	Resist	React						
2	83.858	5.06	84	21.79							
1.5	62.894	4.49	82	21.82							
1	41.929	3.49	79	21.88							
0.5	20.965	1.38	74	22.73							
0.375	15.723	1.32	73	19.72							
0.25	10.482	0.59	71	20.11							
0.2	8.386	0.37	70	20.34							
0.15	6.289	0.1	68	21.02							
0.1	4.193	-0.21	66	22.68							
0.05	2.096	-0.55	64	25.4							
0.025	1.048	-0.71	62	27.28							
0.01	0.419	-0.85	61	28.87							
0.005	0.21	-0.92	61	29.78							
0.001	0.042	-1.19	60	33.1							
-0.001	-0.042	-2.46	60	61.94							
-0.005	-0.21	-2.65	60	66.36							

16-Radial 90-Degree Ground-Plane Monopole From 2-WL Up to Below Ground: Performance with Various Ground Types											Table 3-10
Free-Space Reference Performance				Monopole: Len 10.071 m, Radius 0.0125 m						Freq.: 7.15 MHz	
Rad-L m	Rad-R m	Gain dBi	Bmwidth	Resist	React						
12.31	0.002	1.21	105	22.22	0.02						
Ground Type		Perfect				Ground Type		Salt Water: C 5.0, P 81			
Height wl	Height m	Gain dBi	TO Angle	Resist	React	Height wl	Height m	Gain dBi	TO Angle	Resist	React
2	83.858	7.23	90	22.27	0.14	2	83.858	6.85	77	22.26	0.14
1.5	62.894	7.22	90	22.31	0.23	1.5	62.894	6.8	73	22.3	0.21
1	41.929	7.2	90	22.43	0.43	1	41.929	6.58	65	22.39	0.38
0.5	20.965	7.08	90	23.09	1.18	0.5	20.965	5.56	86	23.78	0.94
0.375	15.723	7.58	90	20.58	1.5	0.375	15.723	6.88	85	18.33	2.02
0.25	10.482	7.81	90	19.39	-2.33	0.25	10.482	6.8	84	19.39	-2.26
0.2	8.386	7.5	90	20.72	-4.38	0.2	8.386	6.6	84	20.68	-4.29
0.15	6.289	6.95	90	23.43	-5.83	0.15	6.289	6.15	83	23.31	-5.76
0.1	4.193	6.28	90	27.36	-5.89	0.1	4.193	5.58	83	27.17	-5.9
0.05	2.096	5.61	90	32.08	-3.72	0.05	2.096	5	82	31.81	-3.91
0.025	1.048	5.31	90	34.55	-1.43	0.025	1.048	4.75	81	34.23	-1.82
0.01	0.419	5.15	90	36.02	0.82	0.01	0.419	4.62	81	35.64	0.16
0.005	0.21	5.09	90	36.54	2.21	0.005	0.21	4.57	81	36.16	1.47
0.001	0.042	5.08	90	36.66	5.33	0.001	0.042	4.38	81	37.85	8.2
						-0.001	-0.042	4.57	81	36.46	-0.17
						-0.005	-0.21	4.57	81	36.44	-0.16
Ground Type		Very Good: C 0.0303, P 20				Ground Type		Average: C 0.005, P 13			
Height wl	Height m	Gain dBi	TO Angle	Resist	React	Height wl	Height m	Gain dBi	TO Angle	Resist	React
2	83.858	5.14	63	22.27	0.11	2	83.858	3.78	84	22.26	0.09
1.5	62.894	4.87	54	22.31	0.17	1.5	62.894	3.45	54	22.3	0.14
1	41.929	5.09	66	22.41	0.3	1	41.929	3.24	66	22.39	0.22
0.5	20.965	3.84	46	23.81	0.68	0.5	20.965	2.67	46	23.64	0.39
0.375	15.723	3.17	38	18.75	2.11	0.375	15.723	2.07	39	19.35	1.98
0.25	10.482	1.66	78	19.38	-1.57	0.25	10.482	0.09	75	19.8	-0.9
0.2	8.386	1.97	77	20.16	-3.56	0.2	8.386	0.24	74	20.15	-2.55
0.15	6.289	2.05	76	22.2	-5.34	0.15	6.289	0.29	72	21.49	-4.22
0.1	4.193	1.99	74	25.58	-6.26	0.1	4.193	0.26	70	24.01	-5.45
0.05	2.096	1.84	71	30.23	-5.57	0.05	2.096	0.17	67	27.81	-5.58
0.025	1.048	1.75	70	32.98	-4.17	0.025	1.048	0.11	66	30.18	-4.86
0.01	0.419	1.7	69	34.67	-2.15	0.01	0.419	0.08	64	31.73	-3.51
0.005	0.21	1.69	69	35.1	-0.15	0.005	0.21	0.08	64	32.22	-1.37
0.001	0.042	1.35	69	37.95	15.24	0.001	0.042	-0.3	64	36.68	9.58
-0.001	-0.042	1.27	69	42.72	4.29	-0.001	-0.042	-0.53	64	45.1	5.34
-0.005	-0.21	1.13	69	44.42	6.68	-0.005	-0.21	-0.65	63	47.08	8.17
Ground Type		Very Poor: C 0.001, P 5									
Height wl	Height m	Gain dBi	TO Angle	Resist	React						
2	83.858	5	84	22.25	0.06						
1.5	62.894	4.43	82	22.28	0.09						
1	41.929	3.44	79	22.34	0.14						
0.5	20.965	1.36	74	23.28	0.12						
0.375	15.723	1.3	73	20.24	1.63						
0.25	10.482	0.6	71	20.48	-0.32						
0.2	8.386	0.4	70	20.49	-1.46						
0.15	6.289	0.15	68	21.15	-2.77						
0.1	4.193	-0.16	66	22.65	-4						
0.05	2.096	-0.48	64	25.17	-4.74						
0.025	1.048	-0.63	62	26.85	-4.63						
0.01	0.419	-0.73	61	28.19	-3.87						
0.005	0.21	-0.75	61	28.79	-2.73						
0.001	0.042	-0.85	60	30.83	3.31						
-0.001	-0.042	-1.08	60	41.33	11.19						
-0.005	-0.21	-1.17	60	44.48	15.09						

32-Radial 90-Degree Ground-Plane Monopole From 2-WL Up to Below Ground: Performance with Various Ground Types											Table 3-11
Free-Space Reference Performance				Monopole: Len 10.071 m, Radius 0.0125 m						Freq.: 7.15 MHz	
Rad-L m	Rad-R m	Gain dBi	Bmwidth	Resist	React						
12.52	0.002	1.15	107	22.63	0						
Ground Type		Perfect				Ground Type		Salt Water: C 5.0, P 81			
Height wl	Height m	Gain dBi	TO Angle	Resist	React	Height wl	Height m	Gain dBi	TO Angle	Resist	React
2	83.858	7.16	90	22.69	0.13	2	83.858	6.8	77	22.69	0.12
1.5	62.894	7.15	90	22.74	0.21	1.5	62.894	6.76	73	22.73	0.2
1	41.929	7.12	90	22.88	0.42	1	41.929	6.57	65	22.84	0.36
0.5	20.965	6.99	90	23.63	1.13	0.5	20.965	5.45	86	24.39	0.85
0.375	15.723	7.49	90	21.09	1.7	0.375	15.723	6.77	85	18.83	2.21
0.25	10.482	7.8	90	19.49	-2.12	0.25	10.482	6.78	85	19.51	-2.05
0.2	8.386	7.52	90	20.68	-4.34	0.2	8.386	6.61	84	20.63	-4.24
0.15	6.289	6.99	90	23.31	-6.02	0.15	6.289	6.18	83	23.19	-5.95
0.1	4.193	6.3	90	27.26	-6.34	0.1	4.193	5.6	83	27.05	-6.35
0.05	2.096	5.62	90	32.05	-4.42	0.05	2.096	5.01	82	31.77	-4.61
0.025	1.048	5.31	90	34.56	-2.29	0.025	1.048	4.75	81	34.23	-2.69
0.01	0.419	5.14	90	36.06	-0.45	0.01	0.419	4.61	81	35.63	-1.16
0.005	0.21	5.08	90	36.61	0.49	0.005	0.21	4.58	81	36.06	-0.47
0.001	0.042	5.05	90	36.93	2.84	0.001	0.042	4.52	81	36.63	3.33
						-0.001	-0.042	4.57	81	36.43	-0.21
						-0.005	-0.21	4.57	81	36.41	-0.2
Ground Type		Very Good: C 0.0303, P 20				Ground Type		Average: C 0.005, P 13			
Height wl	Height m	Gain dBi	TO Angle	Resist	React	Height wl	Height m	Gain dBi	TO Angle	Resist	React
2	83.858	5.13	63	22.69	0.1	2	83.858	3.72	84	22.69	0.08
1.5	62.894	4.92	54	22.74	0.16	1.5	62.894	3.5	54	22.72	0.12
1	41.929	5.08	66	22.86	0.28	1	41.929	3.22	66	22.83	0.2
0.5	20.965	3.92	46	24.39	0.57	0.5	20.965	2.76	47	24.19	0.28
0.375	15.723	3.35	38	19.27	2.26	0.375	15.723	2.24	39	19.86	2.08
0.25	10.482	1.59	78	19.57	-1.32	0.25	10.482	0.05	75	20.08	-0.68
0.2	8.386	1.93	77	20.17	-3.42	0.2	8.386	0.22	74	20.27	-0.238
0.15	6.289	2.04	76	22.08	-5.4	0.15	6.289	0.29	72	21.47	-4.17
0.1	4.193	1.99	74	25.39	-6.58	0.1	4.193	0.26	70	23.86	-5.59
0.05	2.096	1.84	72	30.04	-6.19	0.05	2.096	0.18	67	27.55	-5.96
0.025	1.048	1.75	70	32.8	-5.02	0.025	1.048	0.12	66	29.85	-5.44
0.01	0.419	1.69	69	34.51	-3.69	0.01	0.419	0.09	65	31.35	-4.72
0.005	0.21	1.67	69	34.93	-2.82	0.005	0.21	0.1	64	31.85	-3.61
0.001	0.042	1.41	69	37.31	6.21	0.001	0.042	-0.1	64	35.1	1.7
-0.001	-0.042	1.59	69	39.79	2.77	-0.001	-0.042	0.1	64	38.76	3.38
-0.005	-0.21	1.45	69	41.72	5.75	-0.005	-0.21	0.02	63	40.81	6.88
Ground Type		Very Poor: C 0.001, P 5									
Height wl	Height m	Gain dBi	TO Angle	Resist	React						
2	83.858	4.94	84	22.67	0.05						
1.5	62.894	4.38	82	22.7	0.08						
1	41.929	3.41	79	22.77	0.12						
0.5	20.965	1.41	48	23.78	0.03						
0.375	15.723	1.29	73	20.73	1.68						
0.25	10.482	0.62	71	20.84	-0.16						
0.2	8.386	0.44	70	20.74	-1.3						
0.15	6.289	0.19	68	21.27	-2.65						
0.1	4.193	-0.1	66	22.63	-3.97						
0.05	2.096	-0.41	64	24.99	-4.83						
0.025	1.048	-0.55	62	26.54	-4.82						
0.01	0.419	-0.62	61	27.8	-4.52						
0.005	0.21	-0.62	61	28.32	-3.78						
0.001	0.042	-0.6	60	29.54	-0.93						
-0.001	-0.042	-0.48	60	33.45	4.08						
-0.005	-0.21	-0.5	60	35.38	8.32						

64-Radial 90-Degree Ground-Plane Monopole From 2-WL Up to Below Ground: Performance with Various Ground Types											Table 3-12
Free-Space Reference Performance				Monopole: Len 10.071 m, Radius 0.0125 m						Freq.: 7.15 MHz	
Rad-L m	Rad-R m	Gain dBi	Bmwidth	Resist	React						
12.52	0.002	1.12	109	22.86	-0.06						
Ground Type		Perfect				Ground Type		Salt Water: C 5.0, P 81			
Height wl	Height m	Gain dBi	TO Angle	Resist	React	Height wl	Height m	Gain dBi	TO Angle	Resist	React
2	83.858	7.12	90	22.92	0.06	2	83.858	6.78	77	22.92	0.06
1.5	62.894	7.11	90	22.98	0.15	1.5	62.894	6.75	73	22.97	0.13
1	41.929	7.08	90	23.14	0.35	1	41.929	6.57	65	23.09	0.29
0.5	20.965	6.94	90	23.94	1.02	0.5	20.965	5.4	86	24.73	0.7
0.375	15.723	7.43	90	21.4	1.76	0.375	15.723	6.7	85	19.14	2.27
0.25	10.482	7.8	90	19.53	-2.01	0.25	10.482	6.78	85	19.55	-1.93
0.2	8.386	7.54	90	29.6	-4.33	0.2	8.386	6.63	84	20.56	-4.23
0.15	6.289	7.01	90	23.18	-6.17	0.15	6.289	6.2	83	23.06	-6.09
0.1	4.193	6.33	90	27.13	-6.65	0.1	4.193	5.62	83	26.92	-6.65
0.05	2.096	5.63	90	31.97	-4.87	0.05	2.096	5.02	82	31.68	-5.05
0.025	1.048	5.32	90	34.5	-2.79	0.025	1.048	4.76	81	34.16	-3.18
0.01	0.419	5.15	90	36	-1.03	0.01	0.419	4.62	81	35.58	-1.75
0.005	0.21	5.09	90	36.55	-0.31	0.005	0.21	4.59	81	35.98	-1.32
0.001	0.042	5.04	90	36.98	0.84	0.001	0.042	4.6	81	35.97	-0.19
						-0.001	-0.042	4.57	81	36.42	-0.23
						-0.005	-0.21	4.57	81	36.39	-0.21
Ground Type		Very Good: C 0.0303, P 20				Ground Type		Average: C 0.005, P 13			
Height wl	Height m	Gain dBi	TO Angle	Resist	React	Height wl	Height m	Gain dBi	TO Angle	Resist	React
2	83.858	5.14	63	22.92	0.03	2	83.858	3.7	84	22.91	0.01
1.5	62.894	4.96	54	22.97	0.09	1.5	62.894	3.54	54	22.96	0.05
1	41.929	5.07	66	23.1	0.21	1	41.929	3.22	66	23.06	0.13
0.5	20.965	3.98	46	24.72	0.42	0.5	20.965	2.83	47	24.49	0.14
0.375	15.723	3.49	39	19.59	2.29	0.375	15.723	2.37	39	20.17	2.08
0.25	10.482	1.55	78	19.66	-1.19	0.25	10.482	0.04	75	20.23	-0.58
0.2	8.386	1.91	77	20.14	-3.35	0.2	8.386	0.22	74	20.32	-2.3
0.15	6.289	2.05	76	21.95	-5.45	0.15	6.289	0.3	72	21.41	-4.16
0.1	4.193	1.99	74	25.21	-6.8	0.1	4.193	0.28	70	23.71	-5.69
0.05	2.096	1.84	72	29.86	-6.6	0.05	2.096	0.19	67	27.32	-6.21
0.025	1.048	1.74	70	32.63	-5.54	0.025	1.048	0.13	66	29.55	-5.76
0.01	0.419	1.67	69	34.33	-4.4	0.01	0.419	0.11	65	31.02	-5.12
0.005	0.21	1.64	69	34.8	-3.95	0.005	0.21	0.14	64	31.58	-4.41
0.001	0.042	1.49	69	36.56	0.23	0.001	0.042	0.16	64	33.22	-2.18
-0.001	-0.042	1.8	69	37.57	1.49	-0.001	-0.042	0.41	63	35.16	1.18
-0.005	-0.21	1.69	69	39.53	4.99	-0.005	-0.21	0.35	63	36.93	4.91
Ground Type		Very Poor: C 0.001, P 5									
Height wl	Height m	Gain dBi	TO Angle	Resist	React						
2	83.858	4.91	84	22.9	-0.02						
1.5	62.894	4.35	82	22.93	0.01						
1	41.929	3.39	79	23	0.04						
0.5	20.965	1.48	48	24.06	-0.09						
0.375	15.723	1.3	73	21.02	1.65						
0.25	10.482	0.65	71	21.04	-0.1						
0.2	8.386	0.47	70	20.88	-1.23						
0.15	6.289	0.24	68	21.32	-2.6						
0.1	4.193	-0.05	66	22.58	-3.97						
0.05	2.096	-0.35	64	24.82	-4.89						
0.025	1.048	-0.47	62	26.31	-4.87						
0.01	0.419	-0.51	61	27.57	-4.59						
0.005	0.21	-0.49	61	28.07	-4.14						
0.001	0.042	-0.39	60	28.75	-2.7						
-0.001	-0.042	-0.28	60	30.66	0.46						
-0.005	-0.21	-0.29	60	32.2	4.5						

Some of the data might be amenable to graphing for easier visual digestion. However, virtually every progression contains anomalies, especially with respect to the maximum gain values. As sampled in **Fig. 3-16**, the strongest lobe may not be the lowest lobe. On the left is an obvious case in which the second elevation lobe is stronger than the lowest lobe. The case on the right is subtler. At some heights, the elevation lobes of vertical antennas may fold together to give the impression of a single lobe. However, the shaping of the lobes shows that the seeming lowest lobe is actually 2 lobes, with the higher having greater gain than the lower. In both cases, a graph of maximum gain would fail to indicate the lobe that exhibits maximum gain. Hence, in scanning the tabular data, be certain to note the TO angle that corresponds to any gain value in which you are interested.

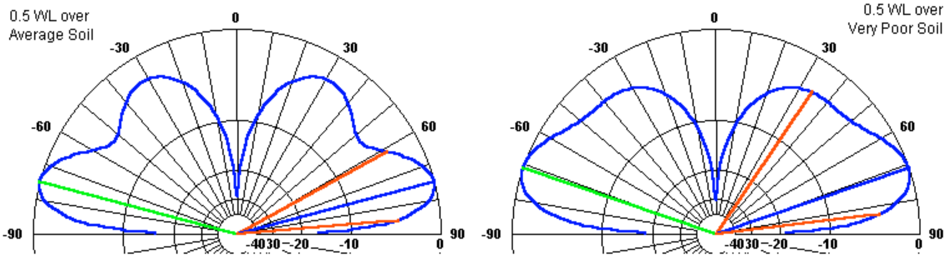


High Lobes May Show Maximum Gain at Certain Heights over Certain Soils

Fig. 3-16

Lobe formation is evolutionary as we change the height of a vertical antenna (or any other antenna, for that matter). Close to the ground, we may see only a single lobe. At some height (taking due note of the ground quality in play), we may see a small secondary lobe at a high angle. The lobe may grow until it dominates the elevation pattern.

At some point in the growth cycle, the lower and upper lobes may approach parity in strength. The resulting pattern may still show a low elevation (high theta) angle as the TO angle. However, as shown in the two samples in **Fig. 3-17**, the result may be a very broad beamwidth such that the maximum gain shows a significant reduction from one or both maximum gain values at adjacent sampled heights. Since there is no effective way to show every pattern over every soil at every height, the models attached to this volume will have to be your guide. I have provided modeling samples along the way to provide guidance in handling them so that you can replicate any part of the data-gathering exercise.



Multiple Wide Lobes May Reduce Maximum Gain

Fig. 3-17

Down to a height about 0.5 λ above ground, the source impedance undergoes only small changes, although the pattern itself exhibits a wide range of shape shifts, including changes in the lobe of maximum gain. Between base heights of 0.375 λ and 0.05 λ, we find an almost universal swing of the reactance toward the capacitive side, with fluctuations in the resistance from below to above the free-space value. In this region, we find a systematic reduction in gain and an increase in the TO elevation angle (a reduction in the theta angle) as we approach the surface. These changes–within any given soil type–tend to be consistent for any number of radials in the ground plane.

Below a height of about 0.05 λ, we begin to see a much larger set of differences based on the number of radials in the ground plane. The degree of difference tends to vary with both the quality of the soil and the number of radials together. For example, for the two lowest levels of ground quality and only 4 radials, we see a very large change of both resistance and reactance as we pass from 0.001 λ above ground to 0.001 λ below ground, a distance of just over 3". If we move to the 64-radial model and look at the progression for average and very poor soil, we find that the resistance and reactance values tend to look more like natural parts of a progression.

In contrast, for very good soil and salt water, we find only small changes in the value of source resistance, even for small number of radials. The major differences appear in the reactance columns, with the 64-radial set showing a much smoother curve. One useful way to track values is to scan the same height and soil quality across all sizes of radial systems. For example, if we track the antenna at a height of 0.001 λ over salt water, we find the following list of values.

No. Radials	Gain dBi	TO Angle	Resistance	Reactance
4	3.80	81	43.19	22.04
8	4.17	81	39.68	13.76
16	4.38	81	37.85	8.20
32	4.52	81	36.63	3.33
64	4.60	81	35.97	-0.19

Of course, we cannot take the data in isolation, but should examine the surrounding values. For example, the gain values with the radials below the surface level varies between 5.45 dBi for 4 radials and 4.57 dBi for 64 radials. Only the 64-radial system produces a higher gain (although only marginally so) at the height above ground of 0.001 λ. In addition, the resistive component of the source impedance is higher than adjacent values for all but the 64-radial system. Finally, the reactance column shows a transition from being highly inductive to nearly resonant as we increase the size of the radial field. More significantly, only with the largest radial field is the value close to forming a smooth progression with the values for adjacent sampled heights.

Because the data has 3 dimensions of variation, there are too many possible ways to examine it productively for listing here. The sample listing and the other notes do provide some guidance, but much room remains for creative extrapolation. The data is subject to some limitations that we have elsewhere expressed. For example, the soils are each uniform and universal beneath the antennas. NEC software presumes a homogenous earth once the modeler has selected the ground constant for a given set of runs. This limitation means that the modeled figures are for general guidance only. They cannot account for stratified soil in which conductivity and permittivity may change radically from one depth to another, even within the main penetration region for an antenna.

All of the reported values use the raw NEC reports. For 90° radial systems, the AGT corrections are remarkably similar and vary only between 0.08 and 0.11 dB. Hence, for comparative purposes, the values in the tables are completely usable. If you wish to make corrections, increase all gain values by 0.1 dB.

A further limitation follows from the selection of sampling heights. I selected heights to show a reasonable set of value transitions, shrinking the intervals as the model approached the surface. The sampling does not uncover what we might wish to term as ideal antenna heights. This concept might apply to both buried and elevated radial systems. The buried wires are about 1.65" below ground at a depth of 0.001 λ and 8.25" at a depth of 0.005 λ. These depths provide some guidance as to differences in performance that may occur as a result of different installation techniques, but they do not answer the question of the best depth for radials at 7.15 MHz. Even less are the results directly transferable to other operating frequency bands, since frequency plays a role in determining the effects of ground on antennas.

Likewise, the data cannot answer directly the question of what height to use for an elevated radial system at 7.15 MHz, where elevated may indicate a height above ground of some few feet. The selected sampling heights may suggest some regions for more intensive investigation. The required height where an 8-radial elevated system exceeds the gain of a buried 64-radial system varies with the soil type. Over very poor soil, the 8-radial system would require a height between 0.05 λ and 0.1 λ. Over average soil, the required height may be much higher, although the pattern shape between 0.25 λ and 0.5 λ may not be desired. (Be certain to examine the TO angles as well as the reported gain.)

What This Perspective Shows

We have examined the ground-plane monopole by first relating the radials to top hats. In free-space, the ground-plane radial set performs like a radical set of top hat that occupies fully ½ of a dipole–except inverted. However, inversion means nothing in free space. We next drew the ground-plane radial toward the ground surface, beginning at a height at which only far-field reflections influenced gain. Losses from the immediate vicinity of the antenna started out as negligible, but gradually increased as we brought the ground-plane monopole closer to the ground. The final steps for each size of radial field took the radials below ground into a medium other than a vacuum. Within the ground medium, we found that ground losses are inversely proportional to the size of the radial field (but not in a simple way). Hence, scant radial systems yield lower gain values than fuller ones.

Many radio amateurs view the second medium that we call ground as a lossy version of a perfect ground. This idea follows from the lower gain that we obtain from lower ground qualities. It has resulted in some simplified equations and some equally simplified interpretations of them. For example, we might express the source resistance (R_S) of a ground-plane monopole in the following way.

$$R_S = R_R + R_L + R_M$$

R_R is the radiation resistance of the monopole. R_L is the ground loss equivalent resistance. R_M is the loss due to the less-then-perfect conductivity of real antenna material, which has been eliminated in these exercises. An over-simplified interpretation of this equation begins with the idea that, for a resonant monopole, R_R is (very close to) the value for a perfect radiator over perfect ground, that is, about 36 Ω. The difference between the reported source resistance and the presumed radiation resistance is the loss due to ground.

If we take this over-simplification seriously, then the tables suggest that in some cases, we obtain a negative value for ground losses. The reported source resistance already is below 36 Ω. See for example, the reports on buried radials for very poor soil using 32 and 64 radials. A reactionary response might suggest that there must be something wrong with the SN ground calculation system in NEC.

A more deliberate response would take into account the range of values by which we express ground conductivity and permittivity. We often start with a perfect ground with an indefinitely high value of conductivity. As we shall discover in the next chapter, high values of conductivity allow us largely to ignore the relative permittivity of a medium. However, consider the other end of the value range. Our simple survey used very poor soil as a limiting pair of values. The conductivity was 0.001 S/m, and the relative permittivity was 5. Now consider the relative permittivity of a vacuum, the environment of free space. By definition that value is 1.0. The conductivity of a vacuum is 0 S/m. The values for very poor soil begin to approach those for a vacuum.

Let's define a new ground quality called "horrendous soil." By definition the conductivity is 0.0001 S/m, about 1/10th the value for very poor soil. As well, the relative permittivity will be 1, as low as we can go. With this type of soil, the reported source resistance falls between 23 and 25 Ω for 32-radial systems (depending upon the depth of the radials). Note that the free-space source resistance for a 32-radial monopole–the same antenna–is about 22.6 Ω. The losses due to the soil quality are very low indeed, if we use the free-space source resistance as a standard (instead of the perfect-ground source resistance). As well, the TO angle actually becomes lower (65° theta compared to 60° theta for very poor soil). The reason is straightforward: with virtually no immediate reflections, the high-angle components of the overall reflection situation decreases, resulting in a lower angle of radiation relative to the horizon. Indeed, that angle is approaching (but remains far from reaching) the 90° theta angle that applies to free-space pattern for the monopole.

Before we carry this data too far, let's note that the SN ground calculation system has a severe limitation. It presumes a homogenous soil composition from the defined surface at Z = 0 in the coordinate system to an indefinitely large distance downward. Real soil exhibits irregularities and stratification. If we find truly horrendous soil conditions at an antenna site, they will not persist indefinitely downward. One or more layers of a different level of soil quality will yield the high-angle reflections absent at the surface of our hypothetical site.

However, the goal of this small exercise is not to envision highly improbable antenna sites for ground-plane monopoles with buried radials. Instead, the goal is to expand the way in which we as radio amateurs think about the ground. The ground is simply a second medium below the vertical element and surrounding the radial system for buried ground planes. As well, it is not merely a poor version of perfect ground. Instead, it exhibits properties that range widely from near perfect reflection (as in the case of salt water) to near perfect penetration. The source impedance of a monopole with buried radials is not simply the value for a monopole without radials over perfect ground plus ground losses. Rather the source resistance value is far more complex, since the radiation resistance will be some value between the ideal monopole and the monopole with radials in free space. Even from a modeling perspective, there is nothing simple about simple soil.

The Next Steps

In this chapter, we have examined an alternative perspective on ground-plane monopoles. The perspective begins by taking the dipole in free space as the basic unit of study. By examining the end-hat in details for both monopoles and dipoles, we have gradually adopted a view of the ground-plane radials as simple current paths, just like those of the hat. In an elevated or free-space ground-plane monopole, the current at the monopole base divides equally among the radials. The current magnitude decreases along the radial in the same manner that it does along the monopole.

As the ground-plane monopole approaches and makes contact with the ground, interactions increase so as to affect the performance of the antenna immediately, that is, in and around the elements. The best evidence of this interaction appears in the source impedance jumps that occur with shallow buried radials, especially with sparse radial fields.

In NEC models, the ground properties make use of two parameters that we call conductivity and relative permittivity. We saw a brief account of how NEC combines the two values into a complex relative permittivity value for use in its calculations. However, as a practical matter, we have only scattered samples of ground qualities. Both conductivity and permittivity rose or declined together. So we have no clear insight into the effects of either as a practical matter that may affect the performance of the monopoles that we might construct with buried radials. Spending some time on that question may prove useful, at least as background information to give us more accurate expectations of our ground-plane monopoles.

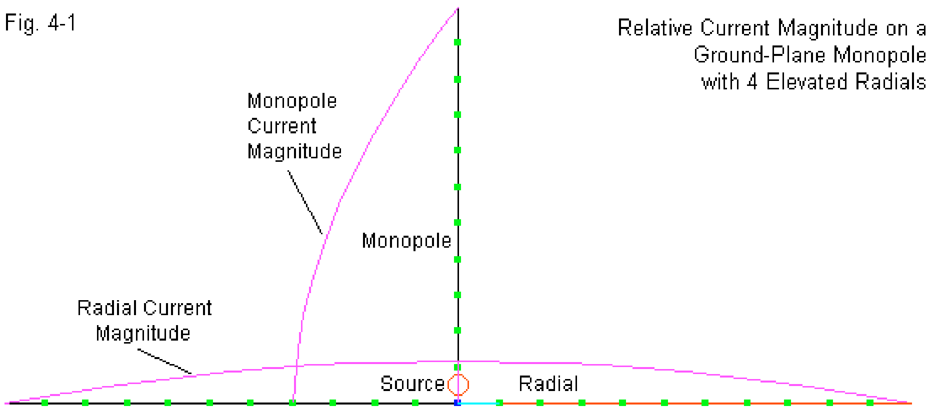
4. Conductivity and Permittivity

In the data collection in the preceding chapter, we encountered an apparent discontinuity as the ground plane sank below the surface of the ground. As the ground plane field (that is, the number of radials) grew larger, the discontinuity became less apparent. Although the maximum gain showed some signs of the discontinuity, the most apparent change occurred in the source impedance report, especially with small numbers of ground-plane radials.

Obviously, much in the nature of the ground and its calculation of its effects within NEC remains to be understood and appreciated. In this chapter, we shall explore 2 avenues. The first road leads us to some overlooked features of what NEC-4 does with the calculation of currents for buried wires. The second path leads to another data collection based on a more refined look at the ides of conductivity and (relative) permittivity, the 2 terms that define ground properties. In lists of ground properties, we often see the two values rise and fall together. We may fairly ask about the relative effects of each term that goes into the complex permittivity calculation. Our goal will be practical: what differences in ground-plane monopole operation will changes in each term create?

PS: I Change

If we compare the current distribution on models of ground-plane monopoles with buried radials and with radials wholly above ground, we can notice a significant difference. **Fig. 4-1** shows the relative current magnitude along the vertical monopole and along 2 of the 4 radials forming the ground plane. The antenna is like the 7.15-MHz models used in Chapter 3, with all elements above ground. I have set the maximum monopole current on the 4th segment of the radial as a marker. Note that the maximum radial current is just above the first monopole segment, indicating that we have very close to equal currents on the radials and on the monopole. Of course, each radial carries ¼ of the total current below the feedpoint.

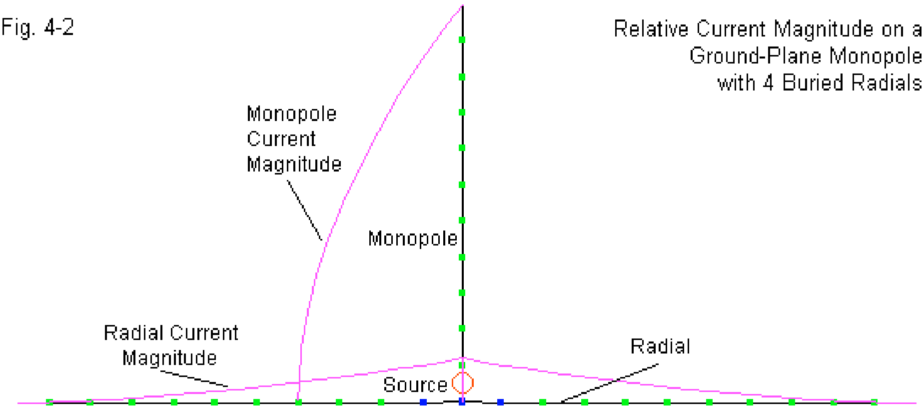


Both current curves have very similar shapes. However, current magnitude does not tell us the complete story. The following list shows both the relative current magnitude and the current phase angle relative to a source current of 1.0 at 0°. If we count upward on the monopole to the 5th entry, we find a magnitude of 0.81245. The corresponding entry for the radial, counting downward, is 0.21420, very close the ¼ the monopole value. As well, note the similarity of current-phase value at the monopole top and the radial end.

Monopole		Radial	
Magnitude (A.)	Phase (Deg.)	Magnitude (A.)	Phase (Deg.)
.09260	-2.93	.25147	-0.08
.24609	-2.71	.24966	-0.27
.38339	-2.49	.24298	-0.43
.50941	-2.26	.23114	-0.56
.62371	-2.01	.21420	-0.67
.72512	-1.75	.19237	-0.78
.81245	-1.47	.16600	-0.89
.88456	-1.17	.13553	-0.99
.94034	-0.82	.10146	-1.09
.97902	-0.42	.06417	-1.19
1.0000	0.00	.02318	-1.29

If we lower the antenna so that the radials are below ground, we shall have to modify the model slightly. The monopole will just touch the ground. The radial wires will have 2 sections. The innermost segment will slope from ground level at the monopole base down to 0.001 λ below ground (about 0.042 m or 1.65"). The remaining segments will extend to 11.75 m to produce the same total length as the radials in the above-ground model. **Fig 4-2** shows the model and the relative current magnitudes, followed by a tabular listing of magnitudes and phase angles.

Fig. 4-2



Monopole Magnitude (A.)	Phase (Deg.)	Radial Magnitude (A.)	Phase (Deg.)
.09286	-6.00	.24242	-7.83
.24693	-5.66	.21041	-28.95
.38486	-5.30	.17479	-51.49
.51154	-4.90	.14094	-73.58
.62647	-4.47	.11038	-95.00
.72839	-3.99	.08337	-115.4
.81606	-3.44	.05966	-134.6
.88806	-2.81	.03914	-152.5
.94333	-2.06	.02223	-170.1
.98087	-1.10	.00972	170.08
1.0000	0.00	.00222	139.95

Since the models differ very slightly in construction due to the need to develop subsurface radials, the monopole current magnitudes are very close, but not identical, to the values for the preceding model. However, we do find a difference in the current phase angle range. For identical source values (1.0 A. at 0°), the preceding model tip current phase angle was only -2.93°, whereas the model with buried radials has a tip-segment phase angle of -6.0°. The above-ground model is a free-space version of the antenna with a source impedance of 21.35 + j0.07 Ω. The model with buried radials uses average ground (C 0.005 S/m, P 13) and reports a source impedance of 64.69 - j 7.84 Ω.

The differences between the radial currents are far more dramatic. Visually, the radial curve differs by rapidly decreasing in current magnitude as we move from the hub outward. The table confirms the curve. At the 5^{th} entry upward, the monopole shows a value of 0.81606, while the corresponding radial entry shows a value of 0.11038, or half the magnitude for that position on the above-ground radial. The current phase changes along the buried radial are far more radical than those along the above-ground radial. One NEC convention is to maintain all phase reports in the 0°-180° range. The outer-most value is equivalent to a value of -220.05°, about 214° out of phase with the tip of the monopole. Note that these values are not true tip values, but the values at a position roughly comparable to the center of the relevant wire segments in the models.

The comparison makes clear that the common above-ground portions of the two antennas yield essentially the same current distribution. However, the parts that move from above ground to below ground change their current distribution. Most modelers seem to be wholly unaware of this phenomenon. So it bears some exploration. Let's proceed by reviewing a small point made in Chapter 1 and then adding a "PS."

For any given ground quality, we measure or find in some table values for conductivity (σ) and relative permittivity (ε_r). As noted in the first chapter, relative permittivity rests on the permittivity in free space (ε_0). Essentially, the program combines the listed values for conductivity and permittivity into a complex relative permittivity (ε_g):

$$\varepsilon_g = \varepsilon_r - j\sigma / (2\pi f \varepsilon_0)$$

The term f is the frequency in Hz. As f changes, so too does the value of ε_g. Therefore, the effects of ground on a ground-plane antenna performance vary with conductivity, permittivity, and frequency.

NEC also calculates another value called k_s, the wave number in the sinusoidal current expansion in NEC. This value applies to any wire within a medium other than free-space. Hence, it applies to all insulated wires and to any wires below ground level (assuming that a real ground is operative in the model). The value of k_s modifies the calculation of current along a wire the length of a wave. Hence,

$$\lambda_s = 2\pi / k_s$$

The current-propagation wave number has the effect of lengthen every applicable segment with respect to current calculations. The exact amount of lengthening depends upon the frequency and ground constants that the modeler selects.

We can easily determine the effect of the wave number on segment length by employing the PS command in NEC-4. In fact, we can perform segment-length adjustment calculations without further model execution by following the PS command with EN, as in the following sample model. The model contains all of the GW, GN, FR, and EX elements to form a complete model, except that it lacks an output request other than the PS command. Hence, calculations stop after the PS command has done its work.

```
GW 1 11 0 0 0 0 0 10.067 .0125
GW 2 10 10.4823 0 -.04193 .953 0 -.04193 .002
GW 2 1 .953 0 -.04193 0 0 0 .002
GM 1 3 0 0 90 0 0 0 2 1 2 11
GE -1 -1 0
GN 2 0 0 0 13 .005
EX 0 1 1 0 1 0
FR 0 1 0 0 7.15 1
PS
EN
```

Although the report in the NEC output file shows the value of k_s, we may confine our attention to the effects on segment lengths. I ran models of the 160-m and the 40-m ground-plane monopoles with 4 buried radials through the PS command, using 3 diverse ground-quality values, those for very good, for average, and for very poor soil. I also ran the same model in free space to illustrate how much wire values change as we bury the radials. Note that in the following lists, all values are normalized to fractions of a wavelength. As well, I converted the entries from engineering to decimal notation. In both cases, the monopole segment length is 0.02183 λ with a radius of 0.000298 λ

Radial Segment Length and Radius

Frequency	Soil Quality	Segment Length	Segment Radius
1.85 MHz	None	0.02273 λ	0.0000477 λ
	Very Good	0.3904	0.0008194
	Average	0.1612	0.0003383
	Very Poor	0.0713	0.0001577
7.15 MHz	None	0.02273 λ	0.0000477 λ
	Very Good	0.2017	0.0004233
	Average	0.09664	0.0002028
	Very Poor	0.05376	0.0001128

To extract a simple example from the listing, the 7.15-MHz average-ground segment length is about 4.3 times the physical length, that is, the length in free-space when normalized to a fraction of a wavelength. With respect to current expansion, the radial point corresponding to the 5^{th} monopole entry in the earlier model (**Fig. 4-2**) actually lies just inside the second segment, where we find a current magnitude of about 0.21. However, notice that the radius increases to the same degree, resulting in what appears to be a more rapid change of current phase angle. Since the current does not go to zero until we reach the radial tip, most of the earlier table entries for the buried radial show very low values compared to the free-space model.

The NEC-4 manual recommends that we use λ_s as the basis for calculating segment lengths for any wire within a medium other than free space, where free space includes any region above a real ground. Examining the PS command report shows that the calculated segment length for current expansion along a buried radial no longer agrees with the segment length for the monopole that is above ground. The segment-length difference appears at one end of the source segment, suggesting a possible error source in the model. The AGT cannot show this potential error, since the test uses free space as its venue. So the next question is what degree of error we might expect from not adjusting the segment length in accord with the value of λ_s.

To obtain a sense of what error might be possible, I used the 40-m monopole from the last chapter and ran it in two forms using very good, average, and very poor soil. The first run used the standard segmentation of the sloping-radial construction with a total of 11 segments per radial. The following lines sample the model over average ground.

```
GW 1 11 0 0 0 0 0 10.067 .0125
GW 2 10 10.4823 0 -.04193 .953 0 -.04193 .002
GW 2 1 .953 0 -.04193 0 0 0 .002
GM 1 3 0 0 90 0 0 0 2 1 2 11
GE -1 -1 0
GN 2 0 0 0 13.0000 0.0050
EX 0 1 1 0 1 0
FR 0 1 0 0 7.15 1
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

Next, I adjusted the number of segments in the radial entries (GW2) so that the calculated segment length for current expansion would more evenly match the monopole segment length. Again, here is a sample over average ground. Note the use of the PS command to allow confirmation of the segmentation.

```
GW 1 11 0 0 0 0 0 10.067 .0125
GW 2 40 10.4823 0 -.04193 .953 0 -.04193 .002
GW 2 4 .953 0 -.04193 0 0 0 .002
GM 1 3 0 0 90 0 0 0 2 1 2 44
GE -1 -1 0
GN 2 0 0 0 13 .005
EX 0 1 1 0 1 0
FR 0 1 0 0 7.15 1
PS
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

From the total of 6 models, I obtained the following results. The entries showing 11 segments per radial represent the unaltered models.

Soil Quality	Segments/Radial	Gain dBi	Source Impedance
Very Poor	11	-4.24	88.94 + j29.22 Ω
	26	-4.13	86.63 + j26.22
Average	11	-2.36	64.60 + j7.29
	46	-2.35	64.44 + j4.28
Very Good	11	0.46	50.91 + j8.19
	98	0.24	53.53 + j5.75

None of the possible error differences are either fatal or unambiguous. For example, the amount of difference is greatest for the antenna over very good soil, but so too is the increase in the radial wire radius. The calculated radius is greater than the monopole radius. In some instances, using the calculated values of segment length and radius as a basis for adjustment may lead to an impossible conflict among NEC guidelines. For precision work, the problem would require considerable thought before finalizing a model. However, changing values of conductivity and permittivity for general guidance in determining the trends creates our work in this chapter. Therefore, using unaltered models with 11 segments per radial will largely suffice.

Within the context of NEC models using buried radials, the exercise does provide a foundation for understanding the different current distributions that we find in those radials, relative to above-ground models.

Practical Consequences of Conductivity and Permittivity

Within the limitations of NEC-4 and the Sommerfeld-Norton ground calculation system, we may still obtain the best available models of the effects of varying ground conditions on buried-radial ground-plane antennas. Although the calculation of ground effects remains a continuing research effort, no better system than the one in NEC-4 allows ready access to calculating the interactions of antennas and the immediate ground. Still, most modelers remain wedded to using only a few of the available combinations of values that make up the complex relative permittivity value used by the program. That tendency limits our understanding of the range of ground effects.

In most tables, improving ground consists of rising values of both conductivity and relative permittivity. Hence, we fail to appreciate the degree to which each element in the complex permittivity value contributes to improved antenna performance.

Soil conductivity is measurable in units of Siemens (or "mhos") per meter (S/m), the inverse of resistivity in Ohms per meter. Of the two relevant ground quality properties, it is the more intuitive. Measurements are relatively frequency specific so that a general DC or low frequency RF measurement may not be exact for a proposed antenna system in the MF or lower HF region. The calculation systems in which conductivity plays a role normally do not account for variations in the value by virtue of soil stratification, but instead presume an average value that characterizes a homogenous soil beneath the antenna.

Permittivity or the relative dielectric constant is less well understood by many amateurs. The main use of the dielectric constant with which most of us are familiar pertains to capacitors: a capacitor can become more compact by using a dielectric with a high value. Soils exhibit the same property. As noted in Chapter 1, the value of permittivity that we use in calculations is relative to the permittivity of a vacuum (or free space) and is measured in Farads per meter.

There is a pattern of mutual increases in both conductivity and permittivity, and the range of each is finite. (I shall omit both fresh and salt water as too special to warrant inclusion here.) Conductivity ranges from 0.001 S/m to a bit over 0.03 S/m, with a greater degree of differentiation among lower values. Permittivity values tend to be more linearly arranged, with a maximum value of 20. The minimum "vacuum" or free space value would be 1. With these patterns in mind, we stand a chance of acquiring an appreciation for the relative effects of each of the two variables on vertical antenna performance over the full span of possibilities within a finite project.

The span of conductivity values lends itself to a Fibonacci sequence: 1, 2, 3, 5, 8, 13, 21, and 34 mS/m. A linear progression of dielectric constants (1, 5, 9, 13, 17, 21) covers this range well. Within the matrix of these values are combinations either exactly or very close to values in the standard soil quality chart. However, if we look at all of the values in the matrix, we might acquire a perspective on the relative effects of each component. Finding where the standard values fit within the overall matrix of possible values is the goal of our exercise.

Because ground effects vary with conductivity, permittivity, and frequency, I have developed data tables for the listed values of conductivity and permittivity using our 3 sample lower-HF antennas for 1.85, 3.6, and 7.15 MHz. The original models for these antennas are perfectly scaled versions of each other. Hence, all show a maximum gain of 5.14 dBi and a source impedance of 36.08 + 0.07 Ω. All use lossless or perfect conductors so that the performance changes in the tables will result solely from changes in the ground conditions.

For each pair of ground constants, the data will survey versions of the antennas with 4, 8, 16, 32, and 64 radials. All radials will lie 0.001 λ below the ground surface. The modeling technique will bring the monopole to ground level (Z=0). The innermost radial segment will slope downward from the monopole base to a point 0.001 λ lower and outward far enough to yield a segment length about equal to the segment lengths in the remaining portions of the radial. All radials extend exactly ¼ λ outward from the monopole. The following 160-m models shows the general modeling technique.

```
CM monopole 1.85 MHz 96-mm dia.
CM average ground: 4 radials: GM
CE
GW 1 11 0 0 0 0 0 38.9076 .04826
GW 2 10 40.5125 0 -.16205 3.68 0 -.16205 .00773
GW 2 1 3.68 0 -.16205 0 0 0 .00773
GM 1 3 0 0 90 0 0 0 2 1 2 11
GE -1 -1 0
GN 2 0 0 0 13.0000 0.0050
EX 0 1 1 0 1 0
FR 0 1 0 0 1.85 1
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

The GM entry controls the number of radials by specifying the number of replications (1 less than the total number of radials) and the angle between radials. Changing the ground constant simply requires a systematic change in the GN line. The sample model shows values for average ground to start, but setting values only requires changing the entries for permittivity and conductivity (in that order within the command).

For each antenna, there are 8 tables, proceeding in the order of conductivity from the lowest (0.001 S/m) to the highest (0.034 S/m). Individual tables proceed through the permittivity values, ranging from 1 to 21 in increments of 4. Within each permittivity value, there are entries for each size of radial field from 4 to 64. For each combination of frequency, conductivity, permittivity, and radial-field size, the tables list the reported maximum gain in dBi, the TO angle in degrees theta, and the source resistance and reactance, both in Ohms. The left-most column contains a few entries that note the closest approximation to standard ground quality labels. However, the entries are not exact since the tables do not fall exactly on the tabulated values shown in Chapter 1. The ultimate accuracy of the NEC reports is subject to limitations of AGT variations that reflect the changing geometry of the models and NEC's the segmentation calculations that affect the electrical length of segments used in current distribution. Nevertheless, the trends in values for any of the variables in the data remain sufficiently accurate for general guidance.

1.85-MHz Data

The following 8 tables provide the modeled data for the 1.85-MHz monopole with 4 to 64 radials. The monopole is 38.9076-m long with a 0.04826-m radius. Each radial is 40.5125-m long with a 0.00773-m radius. The radial system is buried 0.16205-m deep, that is, 0.001 λ.

Table 4-160-1

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
1.85 MHz		38.9076	0.04826	40.5125	0.00773	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.001	1	4	-3.88	62	68.038	18.574
		8	-2.89	62	53.601	10.132
		16	-2.17	62	44.278	3.759
		32	-1.76	62	38.884	-0.759
		64	-1.56	62	36.083	-3.446
Vry Poor	5	4	-3.48	62	69.42	14.117
		8	-2.38	62	54.014	9.325
		16	-1.53	62	43.657	4.56
		32	-1.05	62	37.752	0.397
		64	-0.83	62	34.887	-2.292
	9	4	-3	63	68.651	9.163
		8	-1.91	63	54.631	7.717
		16	-0.99	63	44.064	5.091
		32	-0.43	63	37.597	1.54
		64	-0.19	63	34.538	-1.156
	13	4	-2.54	63	66.085	5.997
		8	-1.53	63	54.313	5.797
		16	-0.61	63	44.654	4.917
		32	0.01	63	37.992	2.257
		64	0.27	63	34.629	-0.322
	17	4	-2.17	64	63.909	4.642
		8	-1.22	64	53.637	4.486
		16	-0.33	64	44.917	4.442
		32	0.32	64	38.307	2.614
		64	0.61	64	34.846	0.244
	21	4	-1.9	64	62.573	3.536
		8	-0.95	64	52.452	3.735
		16	-0.1	64	44.909	3.956
		32	0.56	64	38.63	2.805
		64	0.88	64	35.058	0.665

Table 4-160-2

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
1.85 MHz		38.9076	0.04826	40.5125	0.00773	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.002	1	4	-2.17	64	61.011	15.264
		8	-1.42	64	51.301	9.329
		16	-0.85	64	44.356	4.79
		32	-0.48	64	39.746	1.215
		64	-0.29	64	37.112	-1.252
	5	4	-2.14	64	61.623	13.166
		8	-1.35	64	51.534	8.467
		16	-0.71	64	44.23	4.682
		32	-0.3	64	39.342	1.419
		64	-0.09	64	36.598	-0.979
	9	4	-2.03	64	61.683	11.06
		8	-1.21	64	51.621	7.564
		16	-0.53	64	44.192	4.592
		32	-0.07	64	39.09	1.703
		64	0.15	64	36.325	-0.614
Poor	13	4	-1.86	64	61.281	9.168
		8	-1.04	64	51.535	6.668
		16	-0.34	64	44.21	4.456
		32	0.16	64	38.982	1.98
		64	0.4	64	36.02	-0.241
	17	4	-1.67	64	60.592	7.594
		8	-0.86	64	51.287	5.85
		16	-0.15	64	44.23	4.259
		32	0.37	64	38.979	2.198
		64	0.63	64	35.924	0.093
	21	4	-1.47	64	59.77	6.324
		8	-0.68	64	50.94	5.153
		16	0.02	64	44.231	4.029
		32	0.56	64	39.048	2.352
		64	0.84	64	35.992	0.38

Table 4-160-3

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
1.85 MHz		38.9076	0.04826	40.5125	0.00773	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.003	1	4	-1.26	66	57.272	13.484
		8	-0.63	66	49.62	8.593
		16	-0.14	66	43.953	4.861
		32	0.21	66	39.92	1.855
		64	0.39	66	37.443	-0.369
	5	4	-1.29	66	57.694	12.263
		8	-0.63	65	49.791	8.008
		16	-0.1	65	43.923	4.695
		32	0.27	65	39.722	1.901
		64	0.47	66	37.157	-0.262
	9	4	-1.27	65	57.887	11.016
		8	-0.59	65	49.877	7.409
		16	-0.03	65	43.9	4.536
		32	0.37	65	39.568	1.979
		64	0.58	66	36.992	-0.113
	13	4	-1.21	66	57.865	9.811
		8	-0.52	65	49.878	6.816
		16	0.06	66	43.882	4.38
		32	0.48	66	39.46	2.076
		64	0.7	66	36.738	0.063
	17	4	-1.12	66	57.671	8.695
		8	-0.43	66	49.805	6.25
		16	0.16	66	43.87	4.218
		32	0.6	66	39.403	2.173
		64	0.84	66	36.613	0.249
	21	4	-1.01	66	57.348	7.705
		8	-0.33	66	49.671	5.731
		16	0.26	66	43.852	4.054
		32	0.72	66	39.384	2.259
		64	0.97	66	36.536	0.43

Table 4-160-4

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
1.85 MHz		38.9076	0.04826	40.5125	0.00773	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.005	1	4	-0.24	67	53.282	11.416
		8	0.26	67	47.594	7.598
		16	0.66	67	43.247	4.664
		32	0.97	67	39.928	2.279
		64	1.14	67	37.691	0.4
	5	4	-0.27	67	53.534	10.819
		8	0.24	67	47.709	7.278
		16	0.66	67	43.262	4.536
		32	0.98	67	39.858	2.266
		64	1.16	67	37.566	0.432
	9	4	-0.29	67	53.716	10.204
		8	0.23	67	47.792	6.95
		16	0.67	67	43.27	4.409
		32	1	67	39.795	2.263
		64	1.19	67	37.451	0.477
Average	13	4	-0.29	67	53.83	9.584
		8	0.24	67	47.845	6.618
		16	0.69	67	43.273	4.28
		32	1.03	67	39.741	2.264
		64	1.24	67	37.349	0.532
	17	4	-0.28	67	53.879	8.971
		8	0.25	67	47.869	6.289
		16	0.71	67	43.273	4.152
		32	1.07	67	39.7	2.268
		64	1.28	67	37.264	0.592
	21	4	-0.26	67	53.87	8.378
		8	0.28	67	47.865	5.967
		16	0.75	67	43.268	4.024
		32	1.12	67	39.668	2.274
		64	1.34	67	37.197	0.656

Table 4-160-5

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
1.85 MHz		38.9076	0.04826	40.5125	0.00773	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.008	1	4	0.57	69	50.281	9.678
		8	0.97	69	45.94	6.655
		16	1.3	69	42.539	4.297
		32	1.56	69	39.813	2.367
		64	1.73	69	37.83	0.793
	5	4	0.54	69	50.43	9.37
		8	0.95	69	46.016	6.477
		16	1.29	69	42.561	4.213
		32	1.56	69	39.792	2.347
		64	1.73	69	37.776	0.802
	9	4	0.52	69	50.556	9.053
		8	0.93	69	46.08	6.296
		16	1.28	69	42.579	4.127
		32	1.56	69	39.771	2.327
		64	1.74	69	37.724	0.814
	13	4	0.51	69	50.66	8.73
		8	0.92	69	46.132	6.111
		16	1.28	69	42.593	4.041
		32	1.56	69	39.751	2.308
		64	1.75	69	37.675	0.829
	17	4	0.5	69	50.74	8.404
		8	0.92	69	46.172	5.924
		16	1.28	69	42.603	3.955
		32	1.57	69	39.732	2.291
		64	1.76	69	37.631	0.858
	21	4	0.49	69	50.797	8.078
		8	0.92	69	46.202	5.737
		16	1.28	69	42.611	3.868
		32	1.58	69	39.715	2.274
		64	1.78	69	37.59	0.877

Table 4-160-6

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
1.85 MHz		38.9076	0.04826	40.5125	0.00773	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.013	1	4	1.29	70	47.73	8.018
		8	1.6	70	44.446	5.75
		16	1.87	70	41.81	3.88
		32	2.09	70	39.617	2.339
		64	2.25	70	37.91	1.05
	5	4	1.27	70	47.812	7.951
		8	1.59	70	44.491	5.654
		16	1.86	70	41.828	3.828
		32	2.08	70	39.613	2.32
		64	2.24	70	37.887	1.049
	9	4	1.25	70	47.888	7.791
		8	1.57	70	44.533	5.556
		16	1.85	70	41.845	3.776
		32	2.08	70	39.608	2.301
		64	2.24	70	37.866	1.049
Good	13	4	1.24	70	47.956	7.628
		8	1.56	70	44.571	5.456
		16	1.84	70	41.859	3.723
		32	2.08	70	39.604	2.282
		64	2.24	70	37.844	1.05
	17	4	1.23	70	48.017	7.462
		8	1.55	70	44.604	5.355
		16	1.84	70	41.872	3.669
		32	2.07	70	39.599	2.264
		64	2.24	70	37.825	1.053
	21	4	1.22	70	48.071	7.295
		8	1.55	70	44.634	5.254
		16	1.83	70	41.883	3.615
		32	2.07	70	39.594	2.245
		64	2.25	70	37.805	1.055

Table 4-160-7

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
1.85 MHz		38.9076	0.04826	40.5125	0.00773	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.021	1	4	1.89	72	45.652	6.768
		8	2.14	72	43.156	4.933
		16	2.35	72	41.114	3.451
		32	2.53	72	39.362	2.224
		64	2.68	72	37.92	1.186
	5	4	1.88	72	45.699	6.688
		8	2.13	72	43.185	4.881
		16	2.34	72	41.128	3.42
		32	2.53	72	39.365	2.21
		64	2.67	72	37.913	1.183
	9	4	1.87	72	45.742	6.605
		8	2.12	72	43.21	4.828
		16	2.33	72	41.14	3.389
		32	2.52	72	39.366	2.196
		64	2.67	72	37.905	1.18
	13	4	1.86	72	45.782	6.522
		8	2.11	72	43.234	4.774
		16	2.33	72	41.152	3.357
		32	2.52	72	39.367	2.181
		64	2.67	72	37.897	1.176
	17	4	1.85	72	45.821	6.438
		8	2.1	72	43.257	4.719
		16	2.32	72	41.162	3.325
		32	2.52	72	39.367	2.167
		64	2.67	72	37.888	1.173
	21	4	1.84	72	45.846	6.353
		8	2.1	72	43.278	4.664
		16	2.32	72	41.172	3.293
		32	2.51	72	39.368	2.153
		64	2.66	72	37.88	1.171

Table 4-160-8

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
1.85 MHz		38.9076	0.04826	40.5125	0.00773	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.034	1	4	2.41	73	43.878	5.619
		8	2.6	73	41.979	4.195
		16	2.77	73	40.401	3.037
		32	2.92	73	39.008	2.079
		64	3.05	73	37.809	1.256
	5	4	2.4	73	43.902	5.577
		8	2.6	73	41.994	4.166
		16	2.77	73	40.409	3.019
		32	2.92	73	39.01	2.069
		64	3.05	73	37.806	1.252
	9	4	2.39	73	43.925	5.535
		8	2.59	73	42.009	4.137
		16	2.76	73	40.416	3
		32	2.92	73	39.012	2.059
		64	3.05	73	37.803	1.248
	13	4	2.39	73	43.947	5.492
		8	2.59	73	42.023	4.108
		16	2.76	73	40.424	2.982
		32	2.91	73	39.013	2.049
		64	3.04	73	37.8	1.244
	17	4	2.38	73	43.969	5.45
		8	2.58	73	42.036	4.079
		16	2.75	73	40.431	2.963
		32	2.91	73	39.015	2.039
		64	3.04	73	37.797	1.24
Vry Good	21	4	2.38	73	43.99	5.406
		8	2.58	73	42.05	4.05
		16	2.75	73	40.438	2.944
		32	2.91	73	39.017	2.029
		64	3.04	73	37.794	1.236

1.85-MHz Notes

To make sense of the trends that we may detect from the tabulated data for the 160-m models, we should remind ourselves of a few facts about the performance data. The source resistance and reactance derive mostly from the local conditions surrounding the monopole, that is, from the area within the radius of the ground plane. Although this statement is not absolutely true, it does allow us to distinguish these reports and their trends from the trends in gain and the TO angle. The TO angle results mostly from reflections beyond the limits of the radial field. The maximum gain value is a joint product that includes losses to immediate ground (in the form of an increase in the source resistance) and of losses in the reflected radiation from the lossy ground beyond the radials.

At 1.85 MHz, the test model shows the following extreme limits of gain and source resistance. Cond. = conductivity in S/m, and Perm. = relative permittivity.

Cond.	Perm.	Radials	Gain dBi	Source Resistance Ω
0.001	1	4	-3.88	68.038
0.034	21	64	3.04	37.794
	Range of Values		6.92 dB	30.244 Ω

As we increase the number of radials, the range between the lowest and highest values decreases.

Radials	Cond.	Perm.	Gain dBi	Source Resistance Ω
4	0.001	1	-3.88	68.038
	0.034	21	2.41	43.878
	Range of Values		6.29 dB	24.160 Ω
64	0.001	1	-1.56	38.884
	0.034	21	3.04	37.794
	Range of Values		4.60 dB	1.090 Ω

The listing also shows clearly that the number of radials has the greatest effect upon the source resistance, regardless of the soil quality. However, within the limits set for the data, soil quality does have an effect on the source resistance, although a somewhat small one. Within the lower ranges of conductivity, permittivity appears to affect the source reactance, although at higher values of conductivity and for higher number of radials, the variations may result from either the permittivity or the error sources discussed earlier in this chapter.

In contrast, the TO angle is almost solely a function of the ground quality and is relatively independent of the number of radials, especially above the 2 lowest levels of conductivity. In fact, the TO angle above the very lowest values of conductivity is almost solely a function of conductivity.

Maximum gain depends upon both the ground quality and the number of radials. Therefore, let's chart some extremes of permittivity for various conductivity values and see what trends emerge.

		Conductivity (S/m) and Maximum Gain (dBi)				
Radials	Perm.	0.001	0.002	0.003	0.005	0.008
4	1	-3.88	-2.17	-1.26	-0.24	0.57
	21	-1.90	-1.47	-1.01	-0.26	0.49
	Difference	1.98	0.70	0.25	0.02	0.08
64	1	-1.56	-0.29	0.39	1.14	1.73
	21	0.88	0.84	0.97	1.34	1.78
	Difference	2.44	1.13	0.58	0.20	0.05

Beyond a conductivity of about 0.005 S/m (or certainly beyond 0.008 S/m), changes in permittivity have almost no effect on the maximum gain yielded by a monopole, regardless of the ground plane size. The effects of permittivity upon the gain performance of a monopole are largest when soils fall into the poor or worse ranges.

3.6-MHz Data

The following 8 tables provide the modeled data for the 3.6-MHz monopole with 4 to 64 radials. The monopole is 19.9942-m long with a 0.02480-m radius. Each radial is 20.8189-m long with a 0.00397-m radius. The radial system is buried 0.08328-m deep, that is, 0.001 λ.

Table 4-80-1

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
3.6 MHz		19.9942	0.0248	20.8189	0.003972	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.001	1	4	-5.45	60	72.539	20.622
		8	-4.22	60	53.585	8.837
		16	-3.37	60	42.704	0.968
		32	-2.88	60	36.958	-3.785
		64	-2.63	60	34.083	-6.224
Vry Poor	5	4	-4.18	61	77.976	16.967
		8	-2.68	61	54.609	11.959
		16	-1.65	61	41.304	5.15
		32	-1.15	61	35.176	-0.087
		64	-0.94	61	32.587	-2.949
	9	4	-3.42	62	75.928	3.741
		8	-2.1	62	58.548	8.199
		16	-0.92	62	43.965	6.736
		32	-0.28	62	36.138	2.274
		64	-0.04	62	33.033	-0.884
	13	4	-2.65	63	67.184	0.913
		8	-1.65	63	56.693	3.917
		16	-0.58	63	45.513	5.557
		32	0.16	63	37.314	2.952
		64	0.44	63	33.729	0.038
	17	4	-2.23	63	63.766	2.92
		8	-1.27	63	54.232	2.771
		16	-0.31	63	45.71	4.427
		32	0.44	63	38.027	3.13
		64	0.76	63	34.224	0.592
	21	4	-2.13	64	64.524	2.823
		8	-1.02	64	52.927	2.667
		16	-0.09	64	45.477	3.716
		32	0.67	64	38.515	3.233
		64	1.01	64	34.633	1.032

Table 4-80-2

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
3.6 MHz		19.9942	0.0248	20.8189	0.003972	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.002	1	4	-3.81	62	67.772	18.445
		8	-2.83	62	53.544	10.128
		16	-2.12	62	44.309	3.836
		32	-1.71	62	38.938	-0.651
		64	-1.51	62	36.141	-3.337
	5	4	-3.44	62	69.089	14.079
		8	-2.35	62	53.942	9.277
		16	-1.51	62	43.714	4.562
		32	-1.03	62	37.839	0.438
		64	-0.81	62	34.972	-2.242
	9	4	-2.97	63	68.365	9.297
		8	-1.89	63	54.504	7.704
		16	-0.99	63	44.079	5.05
		32	-0.43	63	37.666	1.531
		64	-0.19	63	34.611	-1.149
Poor	13	4	-2.52	63	65.951	6.171
		8	-1.52	63	54.216	5.848
		16	-0.61	63	44.633	4.889
		32	0	63	37.963	2.234
		64	0.27	63	34.681	-0.329
	17	4	-2.16	64	63.841	4.754
		8	-1.21	64	53.304	4.553
		16	-0.33	64	44.886	4.418
		32	0.32	64	38.327	2.593
		64	0.61	64	34.881	0.233
	21	4	-1.88	64	62.488	3.622
		8	-0.95	64	52.412	3.791
		16	-0.1	64	44.882	3.961
		32	0.56	64	38.641	2.784
		64	0.87	64	35.095	0.649

Table 4-80-3

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
3.6 MHz		19.9942	0.0248	20.8189	0.003972	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.003	1	4	-2.8	63	63.534	16.476
		8	-1.96	63	52.321	9.741
		16	-1.34	63	44.478	4.578
		32	-0.95	63	39.531	0.627
		64	-0.76	63	36.82	-1.959
	5	4	-2.69	63	64.416	13.581
		8	-1.79	63	52.602	8.732
		16	-1.08	63	44.224	4.624
		32	-0.63	63	38.907	1.038
		64	-0.42	63	36.082	-1.488
	9	4	-2.46	64	64.255	10.688
		8	-1.54	64	52.739	7.601
		16	-0.78	63	44.232	4.672
		32	-0.28	63	38.617	1.556
		64	-0.05	64	35.661	-0.901
	13	4	-2.19	64	63.353	8.298
		8	-1.28	64	52.584	6.438
		16	-0.5	64	44.363	4.563
		32	0.04	64	38.589	1.998
		64	0.29	64	35.495	-0.356
	17	4	-1.92	64	62.191	6.545
		8	-1.04	64	52.171	5.435
		16	-0.26	64	44.469	4.322
		32	0.31	64	38.697	2.317
		64	0.58	64	35.482	0.107
	21	4	-1.67	65	61.019	5.217
		8	-0.82	65	51.625	4.653
		16	-0.06	65	44.475	4.018
		32	0.53	65	38.848	2.494
		64	0.82	64	35.55	0.445

Table 4-80-4

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
3.6 MHz		19.9942	0.0248	20.8189	0.003972	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.005	1	4	-1.6	65	58.646	14.147
		8	-0.93	65	50.267	8.882
		16	-0.4	65	44.134	4.865
		32	-0.05	65	39.877	1.649
		64	0.13	65	37.335	-0.673
	5	4	-1.61	65	59.133	12.641
		8	-0.9	65	50.458	8.195
		16	-0.34	65	44.075	4.706
		32	0.05	65	39.613	1.738
		64	0.25	65	36.973	-0.518
	9	4	-1.56	65	59.296	11.112
		8	-0.83	65	50.539	7.488
		16	-0.23	65	44.038	4.558
		32	0.19	65	39.419	1.875
		64	0.4	65	36.687	-0.305
Average	13	4	-1.47	65	59.168	9.663
		8	-0.73	65	50.508	6.79
		16	-0.11	65	44.021	4.399
		32	0.34	65	39.302	2.023
		64	0.57	65	36.484	-0.071
	17	4	-1.35	65	58.824	8.365
		8	-0.61	65	50.384	6.133
		16	0.02	65	44.016	4.224
		32	0.49	65	39.257	2.159
		64	0.74	65	36.366	0.165
	21	4	-1.21	65	58.332	7.253
		8	-0.48	65	50.181	5.547
		16	0.15	65	44.002	4.044
		32	0.64	65	39.259	2.276
		64	0.9	65	36.304	0.389

Table 4-80-5

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
3.6 MHz		19.9942	0.0248	20.8189	0.003972	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.008	1	4	-0.61	67	54.716	12.185
		8	-0.07	67	48.348	7.984
		16	0.37	67	43.536	4.767
		32	0.69	67	39.95	2.158
		64	0.87	67	37.616	0.147
	5	4	-0.65	67	55.025	11.399
		8	-0.09	67	48.483	7.577
		16	0.37	66	43.54	4.62
		32	0.71	67	39.844	2.158
		64	0.9	67	37.444	0.198
	9	4	-0.66	67	55.223	10.588
		8	-0.08	67	48.57	7.159
		16	0.4	67	43.538	4.474
		32	0.75	66	39.753	2.173
		64	0.95	67	37.289	0.269
	13	4	-0.65	66	55.312	9.778
		8	-0.06	67	48.61	6.738
		16	0.43	66	43.531	4.327
		32	0.81	66	39.667	2.194
		64	1.02	66	37.157	0.354
	17	4	-0.61	67	55.306	8.996
		8	-0.02	67	48.609	6.329
		16	0.48	66	43.523	4.185
		32	0.87	66	39.624	2.225
		64	1.1	67	37.051	0.454
	21	4	-0.57	67	55.218	8.263
		8	0.03	67	48.571	5.949
		16	0.54	67	43.512	4.053
		32	0.94	67	39.589	2.266
		64	1.18	67	36.969	0.566

Table 4-80-6

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
3.6 MHz		19.9942	0.0248	20.8189	0.003972	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.013	1	4	0.28	68	51.361	10.319
		8	0.71	68	46.547	7.01
		16	1.07	68	42.811	4.446
		32	1.35	68	39.867	2.355
		64	1.52	68	37.783	0.666
	5	4	0.25	68	51.545	9.922
		8	0.69	68	46.437	6.786
		16	1.06	68	42.833	4.345
		32	1.35	68	39.832	2.334
		64	1.52	68	37.708	0.68
	9	4	0.22	68	51.694	9.512
		8	0.67	68	46.71	6.556
		16	1.05	68	42.849	4.243
		32	1.35	68	39.8	2.316
		64	1.54	68	37.638	0.699
Good	13	4	0.21	68	51.808	9.096
		8	0.67	68	46.766	6.324
		16	1.05	68	42.861	4.141
		32	1.36	68	39.77	2.3
		64	1.56	68	37.572	0.724
	17	4	0.2	68	51.887	8.679
		8	0.67	68	46.805	6.091
		16	1.06	68	42.869	4.039
		32	1.38	68	39.743	2.287
		64	1.58	68	37.513	0.753
	21	4	0.21	68	51.993	8.266
		8	0.67	68	46.828	5.86
		16	1.08	68	42.872	3.939
		32	1.4	68	39.719	2.276
		64	1.61	68	37.46	0.786

Table 4-80-7

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
3.6 MHz		19.9942	0.0248	20.8189	0.003972	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.021	1	4	1.03	70	48.652	8.683
		8	1.37	70	44.998	6.09
		16	1.66	70	42.091	4.047
		32	1.9	70	39.703	2.365
		64	2.06	70	37.888	0.974
	5	4	1	70	48.756	8.48
		8	1.35	70	45.053	5.968
		16	1.65	70	42.111	3.984
		32	1.89	70	39.695	2.348
		64	2.06	70	37.857	0.977
	9	4	0.99	70	48.857	8.271
		8	1.34	70	45.113	5.844
		16	1.64	70	42.138	3.925
		32	1.89	70	39.965	2.334
		64	2.06	70	37.834	0.987
	13	4	0.97	70	48.939	8.059
		8	1.33	70	45.157	5.718
		16	1.63	70	42.154	3.861
		32	1.88	70	39.686	2.315
		64	2.06	70	37.804	0.991
	17	4	0.96	70	49.01	7.845
		8	1.32	70	45.195	5.592
		16	1.63	70	42.167	3.798
		32	1.88	70	39.677	2.296
		64	2.06	70	37.776	0.997
	21	4	0.95	70	49.07	7.628
		8	1.31	70	45.227	5.463
		16	1.62	70	42.178	3.733
		32	1.89	70	39.699	2.277
		64	2.07	70	37.75	1.004

Table 4-80-8

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
3.6 MHz		19.9942	0.0248	20.8189	0.003972	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.034	1	4	1.67	71	46.401	7.246
		8	1.94	71	43.629	5.222
		16	2.17	71	41.377	3.596
		32	2.37	71	39.467	2.252
		64	2.52	71	37.926	1.12
	5	4	1.66	71	46.458	7.142
		8	1.93	71	43.662	5.155
		16	2.16	71	41.392	3.558
		32	2.37	71	39.467	2.236
		64	2.52	71	37.914	1.116
	9	4	1.64	71	46.513	7.036
		8	1.92	71	43.694	5.088
		16	2.16	71	41.407	3.52
		32	2.36	71	39.468	2.22
		64	2.51	71	37.904	1.114
	13	4	1.63	71	46.563	6.928
		8	1.91	71	43.723	5.02
		16	2.15	71	41.42	3.481
		32	2.36	71	39.468	2.203
		64	2.51	71	37.892	1.111
	17	4	1.62	71	46.609	6.819
		8	1.9	71	43.75	4.95
		16	2.14	71	41.432	3.441
		32	2.35	71	39.468	2.186
		64	2.51	71	37.881	1.109
Vry Good	21	4	1.61	71	46.652	6.708
		8	1.89	71	43.775	4.88
		16	2.14	71	41.443	3.402
		32	2.35	71	39.467	2.17
		64	2.51	71	37.87	1.106

3.6-MHz Notes

The 80-m ground-plane monopole tables exhibit many of the same trends as the 160-m tables. For example, above a conductivity of 0.005 S/m, the source resistance and reactance have–for any given number of radials–largely stabilized across the range of permittivity values. Above a conductivity of 0.008 S/m, the gain has stabilized across the range of permittivity values. There may be changes of 0.001 dB among entries for the same number of radials but an increasing permittivity. However, from the data alone, we cannot say whether that change is real or a function of the potential error sources. The fact that the values are so consistent suggests that the error sources do not create any major difficulties for this exercise.

At a conductivity of 0.008 S/m, we find a seemingly random flipping of the TO angle between 2 adjacent values. The most likely source of this data change is a situation in which the actual angle is very close to 66.5° (theta or 23.5° elevation). It is likely that the slight model changes with different numbers of radials combined with the changing permittivity and its effect on the segment length for current expansion combine to supply an angle value just above or just below that mark, with a resulting occasional flip of the integer value.

Despite similarities between the 160-m and 80-m tables, we also find differences. For example, let's explore the total range of maximum gain and source resistance values. At 3.6 MHz, the test model shows the following extreme limits of gain and source resistance. Cond. = conductivity in S/m, and Perm. = relative permittivity.

Cond.	Perm.	Radials	Gain dBi	Source Resistance Ω
0.001	1	4	-5.45	72.539
0.034	21	64	2.51	37.870
	Range of Values		7.96 dB	34.669 Ω
(1.85-MHz Range of Values			6.92 dB	30.244 Ω)

In addition, the maximum gain of the 160-m ground-plane monopole is about 3.05 dBi, compared to the 2.51-dBi maximum value for the 80-m version.

We may also compare the range of value-change for the radial fields at the extremes of the charts.

Radials	Cond.	Perm.	Gain dBi	Source Resistance Ω
4	0.001	1	-5.45	72.539
	0.034	21	1.61	46.652
	Range of Values		7.06 dB	25.887 Ω
64	0.001	1	-2.63	34.083
	0.034	21	2.51	37.870
	Range of Values		5.14 dB	-3.787 Ω

The range of values is in each case greater than for the 1.85-MHz antenna. As well the gain values are systematically lower than for the 160-m monopole. In addition, the TO angle for the 3.6-MHz antenna is systematically higher (relative to the horizon) than for the 1.85 MHz model. The following listing compares the range of TO theta angles for each level of conductivity in the tables for both frequencies.

Cond.	TO Theta Angle Range	
S/m	1.85 MHz	3.6 MHz
0.001	62-64	60-64
0.002	64-65	62-64
0.003	65-66	63-65
0.005	67	65
0.008	69	66-67
0.013	70	68
0.021	72	70
0.034	73	71

Nonetheless, the TO angle remains a function almost solely of the conductivity for all but the lowest levels of conductivity. For values between 0.001 S/m and 0.003 S/m, increasing the permittivity does bring the TO angle slightly closer to the horizon. The progression of source reactance values shows its usual variations, while the source resistance generally goes down with increasing permittivity values. A major exception to this rule occurs with the lowest value of permittivity for small radial systems (4 or 8 radials) at all levels of conductivity. The reported source resistance values for a permittivity of 5 are higher than for a permittivity of 1. The trend reverses as the relative permittivity reaches a value of 9.

At some values of permittivity (with a fixed number of radials), the gain may not show the anticipated steady increase with increasing conductivity. For example, we may examine maximum gain values for 64 radials with a relative permittivity of 21, the maximum value in the study.

	Perm.	Radials	Conductivity (S/m)			
	21	64	0.001	0.002	0.003	0.005
Gain dBi			1.01	0.87	0.82	0.90

From a conductivity of 0.005 S/m upward, the curve is normal. But, in the portion of the curve highlighted here, the maximum gain value decreases by more than we would expect from the potential error sources from 0.001 S/m to 0.003 S/m.

The tables also contain some interesting features in isolation. For example, for a conductivity of 0.034 S/m and 32 radials, the source resistance does not vary more than 0.001 Ω across the range of permittivity values. At the same conductivity, but with 64 radials, the reactance does not vary by more than 0.014 Ω. These items represent possible coincidences rather than significant matters, since the tables are at the one extreme of the value combinations. Nonetheless, the 3.6-MHz data and the simple comparisons we made with the 1.85-MHz data suggest some potential features of the 7.15-MHz data that deserve careful scrutiny.

7.15-MHz Data

The following 8 tables provide the modeled data for the 7.15-MHz monopole with 4 to 64 radials. The monopole is 10.0672-m long with a 0.0125-m radius. Each radial is 10.4823-m long with a 0.002-m radius. The radial system is buried 0.04193-m deep, that is, 0.001 λ.

Table 4-40-1

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
7.15 MHz		10.067	0.0125	10.4823	0.002	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.001	1	4	-6.32	58	70.656	16.021
		8	-4.92	58	50.376	3.389
		16	-3.92	58	39.365	-3.521
		32	-3.3	59	33.631	-7.065
		64	-2.93	59	30.721	-8.648
Vry Poor	5	4	-4.24	60	88.943	29.218
		8	-2.26	60	52.799	18.818
		16	-1.16	60	37.76	7.197
		32	-0.74	60	32.437	0.47
		64	-0.59	60	30.48	-2.621
	9	4	-3.58	61	81.634	-6.275
		8	-2.16	61	64.295	7.588
		16	-0.71	61	44.931	9.068
		32	0.02	61	35.447	3.569
		64	0.23	61	32.243	-0.155
	13	4	-2.51	62	65.012	-3.784
		8	-1.66	62	58.012	1.374
		16	-0.52	62	46.619	5.787
		32	0.31	62	37.249	3.51
		64	0.6	62	33.379	0.385
	17	4	-2.08	63	61.396	2.915
		8	-1.23	63	54.105	1.346
		16	-0.28	63	46.315	4.23
		32	0.55	63	37.955	3.442
		64	0.88	63	33.9	0.832
	21	4	-2.37	64	66.983	4.849
		8	-1.03	64	52.834	2.339
		16	-0.06	64	45.817	3.461
		32	0.76	64	38.473	3.537
		64	1.13	64	34.385	1.321

Table 4-40-2

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
7.15 MHz		10.067	0.0125	10.4823	0.002	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.002	1	4	-5.43	60	72.521	20.629
		8	-4.2	60	53.601	8.875
		16	-3.36	60	42.709	1.013
		32	-2.87	60	36.984	-3.745
		64	-2.62	60	34.098	-6.206
	5	4	-4.18	61	77.881	16.91
		8	-2.68	61	54.617	11.919
		16	-1.66	61	41.337	5.142
		32	-1.15	61	35.206	-0.082
		64	-0.94	61	32.612	-2.943
	9	4	-3.41	62	75.853	3.828
		8	-2.09	62	58.499	8.201
		16	-0.92	62	43.962	6.718
		32	-0.28	62	36.15	2.267
		64	-0.05	62	33.045	-0.885
Poor	13	4	-2.65	63	67.194	0.974
		8	-1.65	63	56.674	3.947
		16	-0.58	62	45.502	5.557
		32	0.15	63	37.317	2.949
		64	0.43	63	33.376	0.038
	17	4	-2.24	63	63.784	2.932
		8	-1.27	63	54.231	2.794
		16	-0.31	63	45.703	4.432
		32	0.44	63	38.029	3.13
		64	0.76	63	34.229	0.593
	21	4	-2.13	64	64.503	2.821
		8	-1.02	64	52.927	2.679
		16	-0.09	64	45.473	3.723
		32	0.67	64	38.517	3.233
		64	1.01	64	34.637	1.033

Table 4-40-3

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
7.15 MHz		10.067	0.0125	10.4823	0.002	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.003	1	4	-4.51	61	70.289	19.693
		8	-3.42	61	53.941	10.008
		16	-2.66	61	43.875	2.926
		32	-2.22	61	38.301	-1.812
		64	-2.01	61	35.463	-4.478
	5	4	-3.84	61	72.549	14.641
		8	-2.59	61	54.519	9.952
		16	-1.67	61	42.973	4.625
		32	-1.17	62	36.863	0.1
		64	-0.95	62	34.053	-2.667
	9	4	-3.2	62	71.353	7.636
		8	-2.02	62	55.906	7.895
		16	-1.01	62	43.942	5.59
		32	-0.41	62	36.973	1.738
		64	-0.17	62	33.889	-1.124
	13	4	-2.63	63	66.996	4.208
		8	-1.6	63	55.289	5.224
		16	-0.61	63	44.911	5.185
		32	0.05	63	37.609	2.504
		64	0.32	63	34.207	-0.209
	17	4	-2.24	64	64.241	3.745
		8	-1.26	63	53.851	3.844
		16	-0.33	63	45.221	4.462
		32	0.36	63	38.158	2.829
		64	0.67	63	34.559	0.381
	21	4	-1.99	64	63.306	2.943
		8	-0.99	64	52.734	3.255
		16	-0.1	64	45.152	3.885
		32	0.6	64	38.568	2.989
		64	0.93	64	34.871	0.818

Table 4-40-4

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
7.15 MHz		10.067	0.0125	10.4823	0.002	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.005	1	4	-3.23	63	65.441	17.382
		8	-2.34	63	52.92	9.972
		16	-1.67	63	44.464	4.339
		32	-1.27	63	39.316	0.142
		64	-1.08	63	36.563	-2.502
	5	4	-3.03	63	66.389	13.805
		8	-2.05	63	53.242	8.937
		16	-1.29	63	44.085	4.588
		32	-0.83	63	38.504	0.775
		64	-0.61	63	35.647	-1.824
	9	4	-2.71	63	66.015	10.219
		8	-1.72	63	53.488	7.633
		16	-0.89	63	44.188	4.792
		32	-0.37	63	38.225	1.512
		64	-0.14	63	35.216	-1.04
Average	13	4	-2.36	63	64.6	7.492
		8	-1.41	63	53.287	6.222
		16	-0.57	63	44.467	4.682
		32	0	64	38.311	2.071
		64	0.26	63	35.134	-0.372
	17	4	-2.05	64	63.049	5.763
		8	-1.13	64	52.704	5.087
		16	-0.3	64	44.639	4.37
		32	0.3	64	38.522	2.429
		64	0.58	64	35.204	0.152
	21	4	-1.78	64	61.718	4.479
		8	-0.89	64	52.012	4.286
		16	-0.09	64	44.65	4.005
		32	0.54	64	38.742	2.617
		64	0.84	64	35.334	0.524

Table 4-40-5

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
7.15 MHz		10.067	0.0125	10.4823	0.002	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.008	1	4	-2.09	64	60.678	15.114
		8	-1.35	64	51.163	9.277
		16	-0.78	64	44.334	4.185
		32	-0.42	64	39.772	1.29
		64	-0.23	64	37.15	-1.158
	5	4	-2.07	64	61.271	13.107
		8	-1.29	64	51.391	8.438
		16	-0.66	64	44.219	4.695
		32	-0.25	64	39.39	1.474
		64	-0.05	64	36.658	-0.904
	9	4	-1.97	64	61.351	11.089
		8	-1.16	64	51.475	7.562
		16	-0.49	64	44.18	4.592
		32	-0.04	64	39.144	1.733
		64	0.18	64	36.305	-0.566
	13	4	-1.81	64	60.995	9.259
		8	-1	64	51.395	6.694
		16	-0.31	64	44.186	4.449
		32	0.18	64	39.029	1.986
		64	0.42	64	36.089	-0.197
	17	4	-1.63	65	60.361	7.721
		8	-0.82	65	51.167	5.9
		16	-0.13	65	44.202	4.258
		32	0.38	65	39.02	2.193
		64	0.64	65	35.987	0.103
	21	4	-1.43	65	59.587	6.467
		8	-0.65	65	50.483	5.218
		16	0.04	65	44.202	4.035
		32	0.57	65	39.078	2.342
		64	0.84	65	35.975	0.382

Table 4-40-6

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
7.15 MHz		10.067	0.0125	10.4823	0.002	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.013	1	4	-1.01	66	56.307	13.009
		8	-0.42	66	49.15	8.38
		16	0.05	66	43.808	4.844
		32	0.39	66	39.938	1.987
		64	0.57	66	37.511	-0.162
	5	4	-1.05	66	56.685	11.968
		8	-0.43	66	49.308	7.866
		16	0.08	66	43.795	4.682
		32	0.44	66	39.781	2.012
		64	0.63	66	37.274	-0.078
	9	4	-1.04	66	56.886	10.899
		8	-0.41	66	49.396	7.338
		16	0.12	66	43.78	4.526
		32	0.51	66	39.652	2.063
		64	0.71	66	37.069	0.039
Good	13	4	-1	66	56.92	9.853
		8	-0.36	66	49.415	6.814
		16	0.19	66	43.766	4.371
		32	0.59	66	39.557	2.127
		64	0.81	66	36.906	0.176
	17	4	-0.94	66	56.811	8.869
		8	-0.29	66	49.374	6.311
		16	0.27	66	43.753	4.217
		32	0.69	66	39.498	2.197
		64	0.92	66	36.785	0.327
	21	4	-0.86	66	56.591	7.97
		8	-0.21	66	49.282	5.84
		16	0.35	66	43.737	4.062
		32	0.79	66	39.469	2.261
		64	1.04	66	36.703	0.478

Table 4-40-7

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
7.15 MHz		10.067	0.0125	10.4823	0.002	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.021	1	4	-0.08	67	52.709	11.1
		8	0.39	67	47.287	7.433
		16	0.78	67	43.124	4.609
		32	1.08	67	39.916	2.313
		64	1.25	67	37.722	0.488
	5	4	-0.12	67	52.939	10.568
		8	0.37	67	47.394	7.144
		16	0.77	67	43.142	4.489
		32	1.08	67	39.859	2.296
		64	1.27	67	37.614	0.513
	9	4	-0.14	67	53.113	10.021
		8	0.36	67	47.476	6.848
		16	0.78	67	43.154	4.369
		32	1.1	67	39.807	2.287
		64	1.29	67	37.515	0.549
	13	4	-0.15	67	53.23	9.467
		8	0.36	67	47.531	6.548
		16	0.79	67	43.161	4.249
		32	1.13	67	39.761	2.282
		64	1.33	67	37.426	0.594
	17	4	-0.14	67	53.292	8.917
		8	0.37	67	47.56	6.249
		16	0.81	67	43.163	4.128
		32	1.16	67	39.723	2.28
		64	1.37	67	37.347	0.644
	21	4	-0.13	67	53.303	8.379
		8	0.39	67	47.566	5.954
		16	0.84	67	43.16	4.008
		32	1.19	67	39.693	2.279
		64	1.41	67	37.281	0.697

Table 4-40-8

Freq.		Mono Len	Mono Rad	Rad. Len	Rad. Rad	
7.15 MHz		10.067	0.0125	10.4823	0.002	
Cond	Perm	Radials	Gain dBi	TO Angle	Resist	React
0.034	1	4	0.72	69	49.742	9.358
		8	1.1	69	45.632	6.477
		16	1.42	69	42.396	4.22
		32	1.67	69	39.783	2.371
		64	1.84	69	37.855	0.855
	5	4	0.69	69	49.875	9.088
		8	1.08	69	45.701	6.319
		16	1.41	69	42.418	4.143
		32	1.67	69	39.767	2.349
		64	1.84	69	37.81	0.86
	9	4	0.67	69	49.991	8.81
		8	1.07	69	45.761	6.157
		16	1.4	69	42.436	4.065
		32	1.67	69	39.751	2.328
		64	1.84	69	37.767	0.868
	13	4	0.66	69	50.088	8.528
		8	1.05	69	45.812	5.993
		16	1.39	69	42.452	3.986
		32	1.67	69	39.736	2.309
		64	1.85	69	37.726	0.879
	17	4	0.65	69	50.168	8.242
		8	1.05	69	45.854	5.827
		16	1.39	69	42.466	3.906
		32	1.67	69	39.723	2.29
		64	1.86	69	37.689	0.892
Vry Good	21	4	0.64	69	50.23	7.955
		8	1.05	69	45.886	5.661
		16	1.39	69	42.476	3.827
		32	1.68	69	39.711	2.273
		64	1.87	69	37.654	0.907

7.15-MHz Notes

The very general trends that we have observed for the 2 lower frequencies repeat themselves at 40 m. For example, the TO angle is almost exclusively a function of the ground conductivity except with very low values of conductivity. For conductivity values below about 0.008 S/m, permittivity plays a role. To a lesser extent, the number of radials also plays a role. Indeed, we might complete the comparative table of TO angles associated with conductivity values.

Cond.	TO Theta Angle Range		
S/m	1.85 MHz	3.6 MHz	7.15 MHz
0.001	62-64	60-64	58-64
0.002	64-65	62-64	60-64
0.003	65-66	63-65	61-64
0.005	67	65	63-64
0.008	69	66-67	64-65
0.013	70	68	66
0.021	72	70	67-68
0.034	73	71	69

The range of values that we encounter at 40 m changes in the same direction as did the change between 160 m and 80 m.

Cond.	Perm.	Radials	Gain dBi	Source Resistance Ω
0.001	1	4	-6.32	88.943*
0.034	21	64	1.87	37.654
	Range of Values		8.19 dB	51.289 Ω
(3.6-MHz Range of Values			7.96 dB	34.669 Ω)
(1.85-MHz Range of Values			6.92 dB	30.244 Ω)

I have starred (*) the source resistance entry for the low end of the scale because it actually occurs with a permittivity of 5. Indeed, one of the more vivid phenomena to occur in the 40-m test models was the large change upward in both resistance and reactance for a conductivity of 0.001 S/m, in the move from a permittivity value of 1 to a value of 5. For a permittivity of 1, the source resistance is

70.656 Ω. Values in the 80-Ω range persist through a permittivity of 9 with 4 radials.

At the extremes of ground quality values, the gain values often elicit the most interest. Therefore, we may compare the maximum and minimum gain values for the 3 bands.

Frequency	Maximum Gain dBi	Minimum Gain dBi
1.85 MHz	3.05	-3.88
3.6	2.52	-5.45
7.15	1.87	-6.32

For the 1.85-MHz and 3.6-MHz data, I noted that the maximum reported gain does not occur with the highest value of permittivity, although it does occur with the highest value of conductivity and the highest number of radials in the survey. At 7.15 MHz, maximum gain does coincide with a permittivity of 21.

In considering the maximum range of all values in the modeled survey, I noted an anomaly related to permittivity in which the highest source resistance does not occur with the lowest permittivity value associated with the lowest conductivity value. Such phenomena suggest that a thorough reading of the tables should occasionally reorganize the data to give permittivity priority over conductivity. We may illustrate the significance of data re-ordering by examining **Table 4-40-9**.

Table 4-40-9						
Freq.	Radials	Mono Len	Mono Rad	Rad. Len	Rad. Rad	
7.15 MHz	64	10.067	0.0125	10.4823	0.002	
Per/Cond	0.001	0.002	0.003	0.005	0.008	0.013
21	1.13	1.01	0.93	0.84	0.84	1.04
17	0.88	0.76	0.67	0.58	0.64	0.92
13	0.6	0.43	0.32	0.26	0.42	0.81
9	0.23	-0.05	-0.17	-0.14	0.18	0.71
5	-0.59	-0.94	-0.95	-0.61	-0.05	0.63
1	-2.93	-2.62	-2.01	-1.08	-0.23	0.57
	|----------------------------Maximum Gain in dBi-------------------------------|					

For the case of 64 radials, the simplified table lists the reported gain values for all permittivity levels and for conductivity values between 0.001 S/m and 0.013 S/m. By reorganizing the data, we can detect an interesting trend. For all but the lowest value of permittivity, the gain actually decreases from its value at a conductivity of 0.001 S/m with the next increment of conductivity improvement. The higher the permittivity value, the higher that the conductivity must be before the gain value begins to rise. The red line on the graph marks the separation that indicates the first rise in gain value.

The sample table is only one of several that you might find useful by reorganizing the data. You may give priority to either the number of radials or to permittivity as the primary category that separates data pages. For each choice of a primary category, you may set out the remaining data giving secondary priority to either of the remaining categories. The samples use 5 levels of radial fields, 6 levels of permittivity, and 8 levels of conductivity. Reading the data in the tables for all of the trends, anomalies, oddities, and inconsistencies requires a versatile scanning method. To this process, of course, add the relevant comparisons between the data collections for each sampled frequency. The notes attached to each data set only skim the most obvious surface features of the data.

For the most part, I have restricted my comments to noting trends and oddities within the data itself. I have not attempted to translate the data into recommendations for construction or interpret the data as a reflection of reality. All of the modeling data emerges from the Sommerfeld-Norton ground calculation system, the basic terms of which we examined in the first chapter. As well, the models themselves are subject to limitations described early in this chapter and elsewhere. Some trends at the extremes of the survey ranges may arouse suspicions about the adequacy of the ground calculation system in those regions. However, finding a way to perform a definitive physical test of the system and its reported results is a daunting task in view of the NEC presumption of homogenous ground beneath the antenna.

The Next Steps

The data in this and the preceding chapter serve the main goal of providing background information on the effects of ground planes and the ground so that you may better appreciate and understanding the range of effects they have on the performance of ground-plane monopole antennas. However, from the perspective of the practical system builder, many questions remain, questions frequently posed to me in private communications. For monopoles, folks ask how tall? How fat? For radials, they inquire how many? How deep? How thick? How long? What materials? Although space does not permit the same extensive and detailed treatment for this vast collection of questions, we can survey them using sample values of ground quality to provide suggestive answers. As with all of the material in this volume, the suggestions will emerge from further modeling.

5. Frequently Asked Questions

The data collections in the preceding 2 chapters comprise a background against which we may develop more reasonable expectations of the performance of ground-plane monopole antennas using a buried radial system. However, they do not address a host of practical questions for the ground-plane monopole builder. The following list distills the basic inquiries, which have appeared in many guises over the years.

1. Does the monopole diameter and material make a significant difference to antenna performance?

2. Does the radial diameter and material make a significant difference to antenna performance?

3. Does it matter whether the radials are bare or insulated?

4. What difference does the length of the monopole make to performance?

5. How many radials must the ground plane use for adequate performance?

6. Does radial length make a significant difference to antenna performance?

7. Does the depth of the radials make a significant difference to antenna performance?

8. Does a ground rod below the monopole feedpoint or a perimeter wire around the radials make a difference to ground-plane monopole performance?

Because the questions are many and varied, we shall not be able to generate any sort of comprehensive data collection. However, we can generate enough samples to show the trends so that you may extrapolate reasonable estimates for any avenue of system improvement. There are 2 keys to the process. First, we must use a relevant set of sample antennas. Second, we must isolate the variable under consideration. Both tasks would be difficult if we had to build physical test antennas, especially for the lower HF range. However, antenna models may provide the level of guidance that we need with far less expense.

Let's be more specific about some of the limits of our exploration.

Frequency: We shall use models at 1.85, 3.6, and 7.15 MHz wherever feasible.

Dimensions: Most monopoles will have a standard diameter of 0.02 m (about 0.7874"), with variations as called for by some questions. The monopole length will rest on the resonant length of the monopole over perfect ground. For tests over real grounds with varying qualities, the monopole lengths for each frequency will remain constant. Except when varied for a specific inquiry, all radials will have a diameter of 0.002 m (2 mm or 0.07874"). The wire size is common in Europe and falls between AWG #14 and AWG #12, both commonly used for buried radial systems by US amateurs. The AM BC industry tends to use AWG #10 wire for its buried radials. The standard ground plane will use 64 radials. We may vary this number to explore one or more questions in our set. The standard radial length will be exactly ¼ λ at the frequency under consideration, except to answer specific inquiries. Except where we need to vary the radial depth in answer to a specific question, the standard burial depth for all frequencies will be 0.1 m or about 3.937".

Model Constraints: All models will use segment lengths as close to 0.024 λ as feasible. For ¼-λ monopoles, we shall use 10 segments, since the monopole lengths will fall under 0.25 λ. Radials will use 11 segments when they are ¼-λ long.

Since all of the models will use buried radial systems, we shall arrange the antenna parts as shown in **Fig. 5-1**. The monopole will extend from the ground up to its height as determined by resonant monopoles over perfect ground. The outer 10 segments of 1/4-λ radials will form wires that are parallel to the ground surface. The innermost segment will slope downward from the monopole base at

Z=0 to join with the inner end of the flat wires. The wire length will be about the same as the segment lengths for the flat portion of the radials.

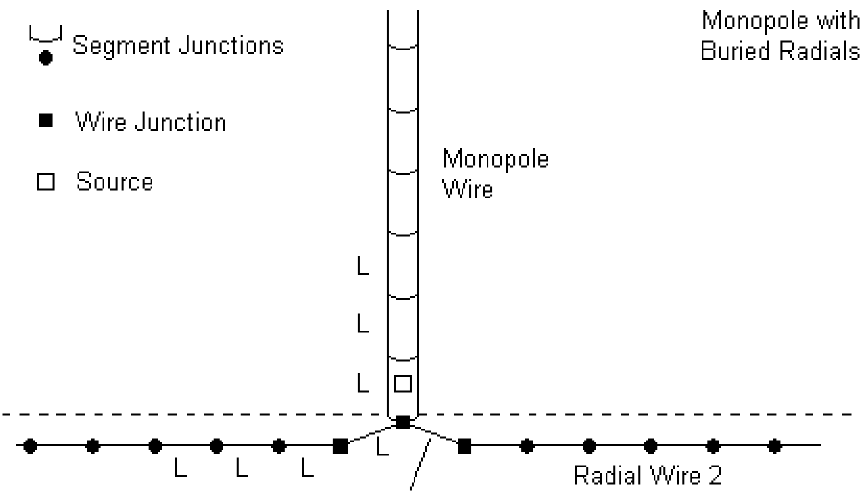


Fig. 5-1

The graphics shows a value L for the physical length of all segments in the model. In virtually all cases, we can closely approximate this ideal. However, in the last chapter, we noted that NEC recalculates the length and the radius of wires in a medium other than a vacuum. Hence, for current calculations, the ground quality will affect the actual segment lengths. As we previously noted, the use of physically identical segment lengths for all parts of the monopole with a buried radial set is not fatal, so long as we use the data for general guidance and not for precision design or analysis efforts. Wherever the NEC recalculation of segment dimensions creates a significant problem, I shall flag the entry.

The individual models will be very similar to those used in past exercises. GW1 is the monopole, and GW2 defines the first radial. As the following sample model shows, the two wires forming the initial radial both have the tag number of

2. This procedure will simplify some of the later additions to the model, such as adding a conductivity value to the radials but not to the monopole. As usual, the following GM command replicates the initial radial by the right number and angular separation to form the desired ground-plane system.

```
CM monopole 1.85 MHz .02 m dia.
CM 64 radials, -.1m, ave ground
CE
GW 1 10 0 0 0 0 0 39.272 .01
GW 2 1 3.65 0 -.1 0 0 0 .001
GW 2 10 40.5125 0 -.1 3.65 0 -.1 .001
GM 0 63 0 0 5.625 0 0 0 2 1 2 11
GE -1 -1 0
GN 2 0 0 0 13 .005
EX 0 1 1 0 1 0
FR 0 1 0 0 1.85 1
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

In order to isolate the variables in which we are interested, all wires will be perfect or lossless except when a question forces us to add a level of material conductivity (LD5). Among the remaining control commands in the model, only the GN entry will change values as we examine certain questions.

The Base-Line Models

Monopole lengths for each radius used in these notes emerge from simple models of 1-wire monopoles resting on perfect ground. The very first question that we shall tackle involves a range of monopole radii, so the first step is to establish the resonant lengths of monopoles for all 3 frequencies, using radii of 0.001 m, 0.01 m, and 0.1 m. The thinnest monopole has the same radius as the radial wires. At the other extreme, we shall consider a monopole with a diameter of 0.2 m or 7.784". This large monopole is a fair representation of the round-wire equivalent of many tower structures pressed into monopole service. For each monopole radius and frequency, I simply varied the length until the monopole was resonant within +/-j0.1 Ω. The following sample model is typical of all of the models in the series.

```
CM monopole 1.85 MHz .02 m dia.
CM perfect ground
CE
GW 1 10 0 0 0 0 0 39.272 .01
GE 1 -1 0
GN 1
EX 0 1 1 0 1 0
FR 0 1 0 0 1.85 1
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

Following the establishment of the monopole length, I then equipped each monopole with 64 buried radials and applied the quality constants for average ground (C 0.005 S/m, P 13). Although these values have some interesting calculation features with respect to developing the complex relative permittivity number used in NEC, they fall about mid-range in the total spread of both conductivity and relative permittivity within the survey. The resulting model is the one shown earlier as a sample.

Table 5-1 provides the complete data for the base-line models for both perfect and average ground. The table provides notes on the meanings of abbreviations used not only in this table, but also in tables to come. Therefore, future tables will only annotate new abbreviations.

The upper half of the table provides the information on the monopoles over perfect ground. Note that as the monopole grows fatter, the length grows shorter, resulting in a natural–although slight–decrease in the resonant feedpoint resistance. Likewise, note the numerical decrease in gain over perfect ground as the monopole radius increases. This feature is also natural, although not at all significant over the 100:1 range of monopole radii. At 1.85 MHz, the total monopole length shrinks just over 2% for the very large change in radii. The shrinkage increases to 3% at 3.6 MHz and to 4% at 7.15 MHz.

If we move the monopole over average ground and add the 64 specified radials, we obtain the performance figures shown in the lower half of **Table 5-1**. Since the radial system is sizable, we do not find very large changes in the reported source impedance. The table contains one anomalous entry: at 7.15

MHz, the largest monopole radius yield gain and source resistance values out of line with the other progressions. I included the AGT scores to confirm that the free-space test cannot indicate the anomaly created by the very large increases in segment length and radius calculated by NEC. As a result, for the 0.1-m radius monopole over ground, the values are not suitable for comparison with other monopoles having smaller radii. However, the values may prove suitable for certain internal comparisons.

Baseline Monopole Antennas								Table 5-1
Lossless Monopole Over Perfect Ground								
Freq MHz	Mn Rd m	Mn Ln m		Gain dBi		Resist	React	Seg Ln wl
1.85	0.001	39.57		5.15		36.307	-0.049	0.02442
	0.01	39.272		5.15		36.207	0.048	0.02423
	0.1	38.645		5.14		36.05	0.027	0.02385
3.6	0.001	20.3		5.15		36.287	0.029	0.02438
	0.01	20.113		5.14		36.16	-0.002	0.02415
	0.1	19.69		5.14		36.007	0.039	0.02364
7.15	0.001	10.199		5.15		36.256	0.034	0.02432
	0.01	10.084		5.14		36.124	0.058	0.02405
	0.1	9.79		5.14		35.997	0.021	0.02335
Lossless Monopole with 64 Lossless Radials with Average Ground (C 0.005 S/m, P 13)								
All radials 1/4-wl long at operating frequency								
Freq MHz	Mn Rd m	Mn Ln m	Rad Ln m	Gain dBi	TO Angle	Resist	React	AGT
1.85	0.001	39.57	40.5125	1.15	67	38.558	1.189	0.98438
	0.01	39.272		1.15	67	38.448	1.266	0.98124
	0.1	38.645		1.16	67	38.251	1.202	0.98355
3.6	0.001	20.3	20.8189	0.5	65	37.651	0.929	0.98323
	0.01	20.113		0.5	65	37.508	0.89	0.97997
	0.1	19.69		0.53	65	37.119	0.989	0.98768
7.15	0.001	10.199	10.4823	0.21	64	36.349	1.312	0.98133
	0.01	10.084		0.21	64	36.199	1.355	0.98108
See text	0.1	9.79		0.35	63	34.879	2.494	0.99677
Notes:	Mn Rd m = Monopole radius in meters							
	Mn Ln m = Monopole length in meters							
	Rad Ln m = Radial Length in meters (all radial use a 0.001-m radius)							
	Seg Ln wl = Monopole segment length in wavelengths							
	Gain dBi = maximum gain in dBi							
	TO Angle = Take-off theta angle (over perfect ground, always 90 degrees)							
	Resist = Source resistance in Ohms							
	React = Source reactance in Ohms							
	AGT = Average gain test score in free space							

1. Does the monopole diameter and material make a significant difference to antenna performance?

Our very first question has received a partial answer as we created the baseline models. For perfect or lossless monopoles–all other things being equal–we find no significant performance difference at any of the frequencies as we move the wire radius over a 100:1 range. However, we obtain a somewhat different picture as we add material loading to the element. Adding material loading consists of assigning the wires in a model with a value of conductivity that corresponds to a desired construction material. We do so by adding a single line to the model.

```
LD 5 1 1 10 1E7 1
```

The LD5 command requires specification of the tag and segment numbers encompassed by the entry. Since we can specify only 1 tag number, you now know why both wires of the radial have the same tag numbers. However, here we are adding a load to the monopole only. The load values consist of a value of conductivity in S/m and a value of permeability. For this exercise, we shall use a permeability of 1 throughout, indicating non-magnetic materials.

As sample values of conductivity, I have selected 3 general values. 1E6 S/m is just below the conductivity of stainless steel and is the lowest value on the list. IE7 S/m falls between bronze and brass, with aluminum having a higher value. However, not even silver reaches 1E8 S/m, the highest value on the list. The spread, therefore, encloses all of the most common antenna materials.

When we add a material load only to the monopole, leaving the radials lossless, we obtain the performance figures in **Table 5-2**. For each frequency and monopole radius, I have listed the performance with the "lossy" monopole and with a perfect monopole for comparison.

Monopole with 64 Perfect Radials with Average Ground (C 0.005 S/m, P 13)						
Material load applied only to monopole; radials remain lossless						
Freq MHz	Mn Rd m	Cond	Gain dBi	TO Angle	Resist	React
1.85	0.001	1E6	0.12	67	49.339	9.197
		1E7	0.83	67	41.592	3.83
		1E8	1.05	67	39.479	2.028
		Lossless	1.15	67	38.558	1.189
	0.01	1E6	1.05	67	39.379	2.093
		1E7	1.12	67	38.737	1.528
		1E8	1.14	67	38.539	1.349
		Lossless	1.15	67	38.448	1.266
	0.1	1E6	1.15	67	38.345	1.282
		1E7	1.15	67	38.281	1.228
		1E8	1.16	67	38.261	1.21
		Lossless	1.16	67	38.251	1.202
3.6	0.001	1E6	-0.25	65	45.089	6.791
		1E7	0.27	65	39.793	2.822
		1E8	0.43	65	38.309	1.529
		Lossless	0.5	65	37.651	0.929
	0.01	1E6	0.43	65	38.174	1.479
		1E7	0.48	65	37.716	1.076
		1E8	0.5	65	37.574	0.949
		Lossless	0.5	65	37.508	0.89
	0.1	1E6	0.52	65	37.186	1.046
		1E7	0.53	65	37.14	1.007
		1E8	0.53	65	37.125	0.995
		Lossless	0.53	65	37.119	0.989
7.15	0.001	1E6	-0.34	63	41.428	5.505
		1E7	0.04	64	37.853	2.653
		1E8	0.15	64	36.815	1.737
		Lossless	0.21	64	36.349	1.312
	0.01	1E6	0.16	63	36.672	1.771
		1E7	0.19	63	36.347	1.487
		1E8	0.2	63	36.246	1.397
		Lossless	0.21	64	36.199	1.355
See text	0.1	1E6	0.34	63	34.928	2.534
		1E7	0.35	63	34.895	2.507
		1E8	0.35	63	34.884	2.498
Table 5-2		Lossless	0.35	63	34.879	2.494

The maximum gain of the ground-plane monopoles varies according to the frequency, as we would expect from the tables in the preceding chapter. As well, when we add the inevitable material loss to the monopole, the gain varies within any one frequency according to the diameter of the monopole. The thinner the monopole, the greater is the loss due to the material load. **Fig. 5-2** shows the curves for 1.85 MHz, although they are similar for all frequencies. The thinnest monopole shows great losses due to material loading with the lowest conductivity. The losses at the middle load value exceed those for the lowest conductivity level for the mid-range radius.

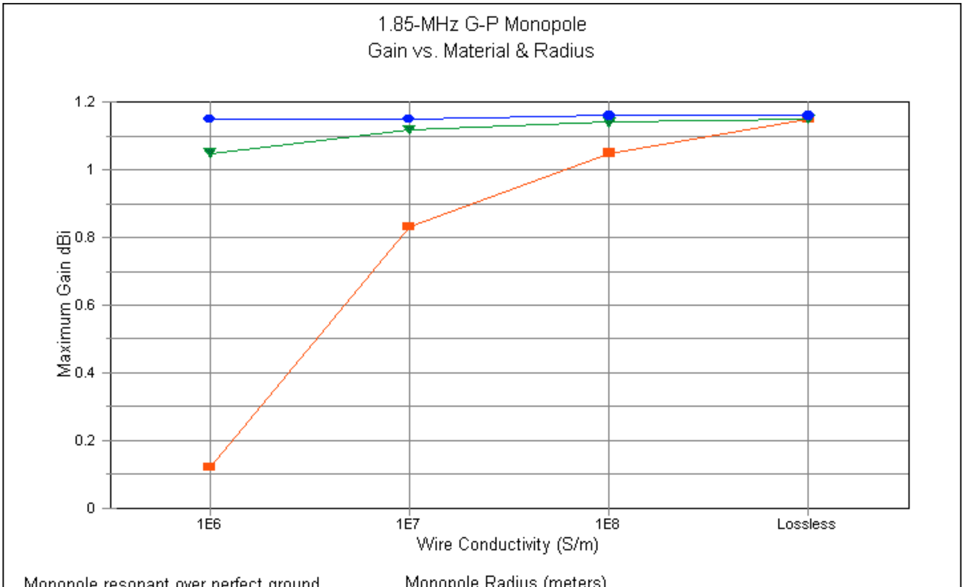


Fig. 5-2

For every level of loading, there is a monopole radius–when measured as a fraction of a wavelength–at which the losses decrease to a completely insignificant level. For the 0.1-m radius at all of the sampled frequencies, even the losses of a conductivity of 1E6 S/m are too low to be noticed.

One more feature of **Table 5-2** is worth notice. For each frequency, skip the entry for lossless wire and compare the performance of the thinner monopole with a conductivity of 1E8 S/m and the performance of the next thicker monopole with a conductivity of 1E6 S/m. Except for the 0.1-m radius monopole at 7.15 MHz, the pairs of performance values are too similar to escape notice. In general, for a constant frequency, a conductivity multiplier of 100 with a constant radius achieves the same performance gain as a radius increase of 10 with a constant conductivity. The tables thus reveal the relationship between element radius and skin effect.

As noted in the construction of the base-line models, the 7.15-MHz monopole that is 0.1-m in radius represents a discontinuity relative to the orderly progression of values in the overall sequence of models. However, within that category, the progressions of values with changing monopole conductivities are orderly and usable for internal comparative purposes. With respect to performance changes with the changing conductivity, the variations in both gain and source impedance follow the patterns of the other categories.

The tables carry all values of conductivity to equal extremes. However, practical antenna work tends to use only a portion of the total range of conductivity values. Since wire monopoles are likely to have a high conductivity, the penalty paid for having a thin element is noticeable but not great. If wire losses become a concern, then a double-wire and spacer–or even a cage-element structure–will likely reduce losses to a negligible level. In contrast, the lower conductivity of tower-style monopole surfaces tends to exact no significant penalty due to the greater effective radius of the element.

2. Does the radial diameter and material make a significant difference to antenna performance?

To answer the second question, we may return the monopole to its original lossless condition. Instead, we may survey various radial wire radii for the 64-radial assembly, using each of the sampling frequencies. Because radials use a narrower range of wire sizes, we may reduce the scope of the survey to the following systematic sizes for the radials.

Radius m	Diameter mm	Diameter inches	Nearest AWG Gauge
0.0005	1	0.03937	#18
0.001	2	0.07874	#12
0.002	4	0.15748	#6

Since the exercise will vary both the radius and the conductivity of the radials, we shall revert to a single (lossless) monopole radius, 0.01 m. You may extrapolate reasonable performance expectations by combining the data for the preceding table and the one containing information about changes in radial size and loading. Other extrapolations will become possible as we add to the data compilation.

Table 5-3 provides the survey data, including the performance information for an "all-lossless" ground-plane monopole. The data include performance figures for the same 3 levels of material loading. Note that all antenna system dimensions, except for the radial radii and their material loading, remain constant throughout the exercise. Perhaps the primary result of the exercise is that reasonable changes in radial size and conductivity create only very small effects on ground-plane monopole performance. Indeed, most wire used in radial systems is copper or a similarly conductive material. Remember, however, that the data apply to a 64-radial system.

The tight data clustering provides the reason that I have transcribed all reported values to the full decimal extent provided by the program. Practical values of source impedance might use integers or perhaps a single decimal place. However, rounding all values to these practical limits would have obscured the numerical progressions within each category. For later extrapolations, it may be useful to know the direction in which the numbers are moving, even if within the present context, the fine shades of differences have no immediate practical value.

To illustrate the tight grouping of values, **Fig. 5-3** provides the tables gain data for the 1.85-MHz monopole. Compare the range of gain values for varying the monopole radius in **Fig. 5-2** with the range of gain values when we vary the radial radius over its smaller span. The gain range for monopole variations was 0.12 to 1.18 dBi. However, the gain range for the radial variations is only 1.07 to 1.18 dBi.

Perfect Monopole with 64 Radials with Average Ground (C 0.005 S/m, P 13)						
Material load applied only to radials; monopole remains lossless						
Freq MHz	Rad Rd m	Cond	Gain dBi	TO Angle	Resist	React
1.85	0.0005	1E6	1.07	67	39.159	1.411
		1E7	1.11	67	38.899	1.562
		1E8	1.12	67	38.82	1.571
		Lossless	1.13	67	38.785	1.573
	0.001	1E6	1.13	67	38.642	1.245
		1E7	1.15	67	38.507	1.264
		1E8	1.15	67	38.467	1.266
		Lossless	1.15	67	38.448	1.266
	0.002	1E6	1.17	67	38.199	0.928
		1E7	1.18	67	38.13	0.931
		1E8	1.18	67	38.109	0.931
		Lossless	1.18	67	38.099	0.931
3.6	0.0005	1E6	0.43	65	38.244	1.211
		1E7	0.46	65	38.016	1.274
		1E8	0.47	65	37.945	1.278
		Lossless	0.47	65	37.913	1.278
	0.001	1E6	0.48	65	37.682	0.833
		1E7	0.5	65	37.561	0.89
		1E8	0.5	65	37.525	0.89
		Lossless	0.5	65	37.508	0.89
	0.002	1E6	0.52	65	37.186	0.471
		1E7	0.53	65	37.125	0.47
		1E8	0.53	65	37.106	0.468
		Lossless	0.54	65	37.097	0.468
7.15	0.0005	1E6	0.14	64	36.952	1.804
		1E7	0.17	63	36.796	1.826
		1E8	0.17	63	36.684	1.826
		Lossless	0.18	63	36.656	1.825
	0.001	1E6	0.19	63	36.348	1.359
		1E7	0.2	63	36.245	1.358
		1E8	0.21	63	36.213	1.356
		Lossless	0.21	64	36.199	1.355
	0.002	1E6	0.23	63	35.821	0.857
		1E7	0.24	64	35.769	0.852
		1E8	0.24	63	35.753	0.85
Table 5-3		Lossless	0.24	63	35.746	0.849

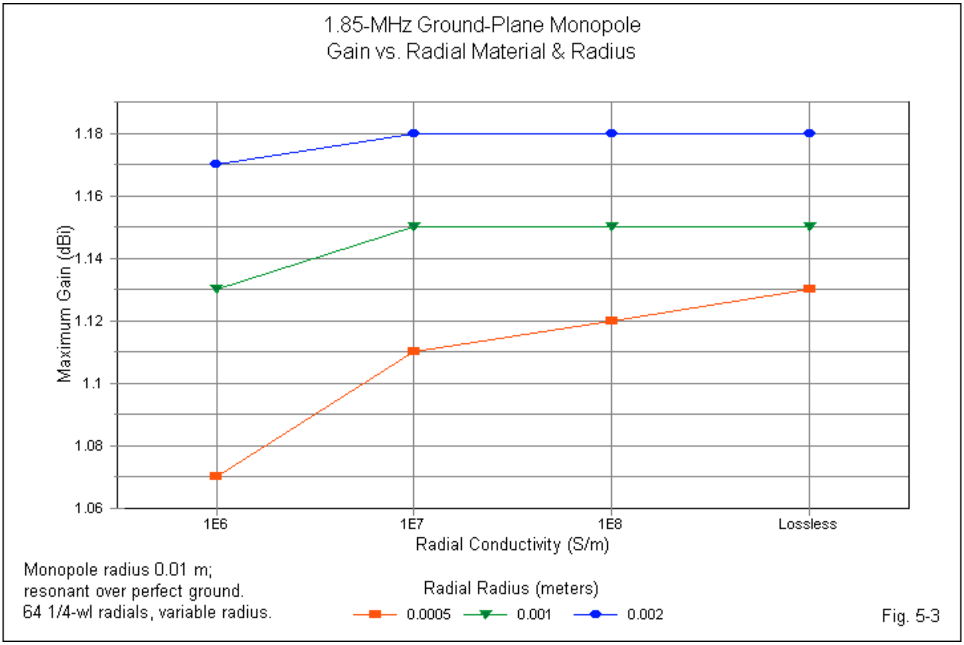


Fig. 5-3

Amateur practice with respect to constructing ground-plane radial systems often operates according to a simple rule: buy as much wire as possible in bulk at bargain prices. Although the practice may not result in radial systems that are as durable as professional AM BC installations, the practice does not create any immediate electrical performance degradation within the limits of the materials and wire sizes within the survey.

3. Does it matter whether the radials are bare or insulated?

Until NEC-4 added the insulated sheath (IS) command to the core, the question of using insulated wire for the buried radial system occasioned considerable guesswork. Since it is not feasible in almost all cases to simply replace an extensive bare-wire radial field with a duplicate using insulated wires, obtaining considered guidance seemed beyond reach. However, using the IS command to insulate the wires of our 64-radial system, we can at least convey what NEC calculates for insulated wires.

To isolate the insulation variable, we shall return to our standard model, using perfect wires for both the monopole and the radials. The monopole radius is 0.01 m, while the radial radius is 0.001 m. These values apply to all 3 sample frequencies. The following sample model with average ground qualities illustrates the application of the IS command to insulate the radials.

```
CM monopole 1.85 MHz .02 m dia.
CM 64 radials, -.1m, ave ground
CE
GW 1 10 0 0 0 0 0 39.272 .01
GW 2 1 3.65 0 -.1 0 0 0 .001
GW 2 10 40.5125 0 -.1 3.65 0 -.1 .001
GM 0 63 0 0 5.625 0 0 0 2 1 2 11
GE -1 -1 0
GN 2 0 0 0 13 .005
IS 0 2 1 704 3 1e-10 .002
EX 0 1 1 0 1 0
FR 0 1 0 0 1.85 1
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

The entries beginning with "2" list the segments to be covered: all 704 segments in the 64 radials bearing tag number 2. The last 3 entries list the permittivity, the conductivity, and the outer radius of the insulation. For our tests, we shall presume a high quality insulation with negligible conductivity, that is 1E-10 Ω/m. Most insulating plastic materials have permittivity values between 2 and 3, with the sample value at the high end of this scale. The command calls for the outer radius of the insulation. Its thickness is simply the listed radius minus the radius of the wire at its center. In this case, with a 0.001-m radial radius, the thickness is 0.001 m (1 mm).

Each test run will have 2 parts. The first part will use a constant permittivity of 2.5 and 3 values of insulation thickness. The second part will use a constant thickness of 1 mm (radius 0.002 m) with 3 values of permittivity within the usual insulation range. **Table 5-4** provides the results.

Monopole and 64 Radials (Perfect) with Average Ground (C 0.005 S/m, P 13)						
Insulation varied by thickness and by permittivity; conductivity 1E-10						
Freq MHz	Variable		Gain dBi	TO Angle	Resist	React
1.85	Thick mm	Radius m	(Pemittivity 2.5)			
	Bare		1.15	67	38.448	1.266
	0.5	0.0015	1.16	67	38.232	1.223
	1	0.002	1.17	67	38.1	1.179
	1.5	0.0025	1.17	67	38.009	1.147
	Permit		(Thickness 1 mm, Radius 0.002 m)			
	Bare		1.15	67	38.448	1.266
	2		1.17	67	38.03	1.15
	2.5		1.17	67	38.1	1.179
	3		1.17	67	38.151	1.2
3.6	Thick mm	Radius m	(Pemittivity 2.5)			
	Bare		0.5	65	37.508	0.89
	0.5	0.0015	0.51	65	37.233	0.816
	1	0.002	0.52	65	37.054	0.739
	1.5	0.0025	0.52	65	36.921	0.678
	Permit		(Thickness 1 mm, Radius 0.002 m)			
	Bare		0.5	65	37.508	0.89
	2		0.52	65	36.951	0.681
	2.5		0.52	65	37.054	0.739
	3		0.52	65	37.124	0.777
7.15	Thick mm	Radius m	(Pemittivity 2.5)			
	Bare		0.21	64	36.199	1.355
	0.5	0.0015	0.22	64	35.886	1.236
	1	0.002	0.22	63	35.676	1.112
	1.5	0.0025	0.22	64	35.522	1.015
	Permit		(Thickness 1 mm, Radius 0.002 m)			
	Bare		0.21	64	36.199	1.355
	2		0.22	64	35.553	1.016
	2.5		0.22	63	35.676	1.112
Table 5-4	3		0.22	64	35.761	1.175

Relative to the bare-wire models, the use of insulated radials produces some numerically visible but operationally insignificant trends. Every use of insulated radials for the 64-radial field yields a gain improvement of 0.01 to 0.02 dB with average ground. As we increase the insulation thickness for any given value of permittivity, the source resistance and reactance decrease. However, for a fixed insulation thickness, increasing the permittivity results in increasing the source resistance and reactance. In both cases, the bare-wire source impedance values appear to function as limiting values. However, the total range of variance is about 0.5%, placing the phenomena among those unlikely to be measured.

For any serious amateur installation, then, the use of insulated vs. bare wire for radials becomes a matter of no electrical concern. This conclusion, of course, presumes the use of relatively high quality wire insulation. The decision on which wire to use for radials rests on other considerations, such as cost.

4. What difference does the length of the monopole make to performance?

So far, the differences in the various facets of a ground-plane monopole installation have been so small that we have used only average ground qualities in arriving at comparative data tables. However, when we raise the question of monopole length, we anticipate that we might see some new kinds of differences, those occurring by virtue of ground quality. Therefore, we shall explore the matter using 3 different soil types: very poor, average, and very good. Even if we do not see significant differences in the performance change with a changing monopole height, that fact alone would still be interesting.

The test models will use bare lossless wire throughout to isolate the effects of monopole height. The 64-radial ground plane will remain in place, with each radial ¼-λ long. However, we shall have to change the way in which we handle the monopole. Using the standard radius of 0.01 m, we shall create a sequence of monopoles ranging from 0.2 λ to 0.6 λ in 0.1-λ increments. To maintain approximately the same segment length as in the base-line model, the number of segments per monopole will range from 8 at the short end to 24 at the high end, with an increment of 4 segments per 0.1-λ change in monopole height.

Due to the volume of data, we shall require separate tables for each of the 3 test frequencies. **Table 5-5** supplies the reported data for 1.85 MHz. The source impedance data simply provides a record to verify the accuracy of the set-up for each model in the sequence. Note that the values do not change very much with changing soil qualities, since we are using a fairly large (64-radial) ground plane.

1.85 MHz Variable-Length Monopole with Lossless 64-Radial Ground Plane						
Monopole length and soil quality as specified.						
Soil	Mn Ln wl	Mn Ln m	Gain dBi	TO Angle	Resist	React
Vry Poor	0.2	32.41	-0.93	61	22.775	-129.318
C 0.001	0.3	48.615	-0.91	64	67.958	172.247
P 5	0.4	64.82	-0.86	67	273.259	633.039
	0.5	81.025	-0.62	70	2480.8	-627.457
	0.6	97.23	-0.04	73	139.411	-577.015
Average	0.2	32.41	1.11	66	24.098	-127.588
C 0.005	0.3	48.615	1.21	64	72.801	176.103
P 13	0.4	64.82	1.33	71	294.414	635.654
	0.5	81.025	1.51	74	2358.21	-620.589
	0.6	97.23	1.5	77	141.362	-579.589
Vry Good	0.2	32.41	2.8	72	24.009	-127.076
C 0.0303	0.3	48.615	3.05	74	73.31	177.054
P 20	0.4	64.82	3.4	76	300.471	638.105
	0.5	81.025	3.91	78	2312.38	-628.241
	0.6	97.23	4.35	80	142.979	-581.115
Notes:	Mn Ln wl = Monopole length in wavelengths					
	Mn Ln m = monopole length in meters					Table 5-5

As we would expect, improving the soil quality by the large amounts in the 3 sampled steps improves the maximum gain value and lowers the TO angle toward the horizon for each monopole length. For each jump in soil quality, the TO angle improves by 3° - 4° or more.

The soil quality plays another role in the results besides increasing or decreasing maximum gain. It also modifies the rates of increase with increasing monopole length. Ideally, we might expect that the sets of gain curves for each soil quality would form parallel curves. However, as shown in **Fig. 5-4**, the curves are not completely parallel. The curves for very poor and very good soil have similar but not identical slopes. The rate of increase between monopole heights of 0.5 λ and 0.6 λ for very good soil is less than the rate for very poor soil. Using average soil, we find no increase in gain in the last increment of increasing monopole length.

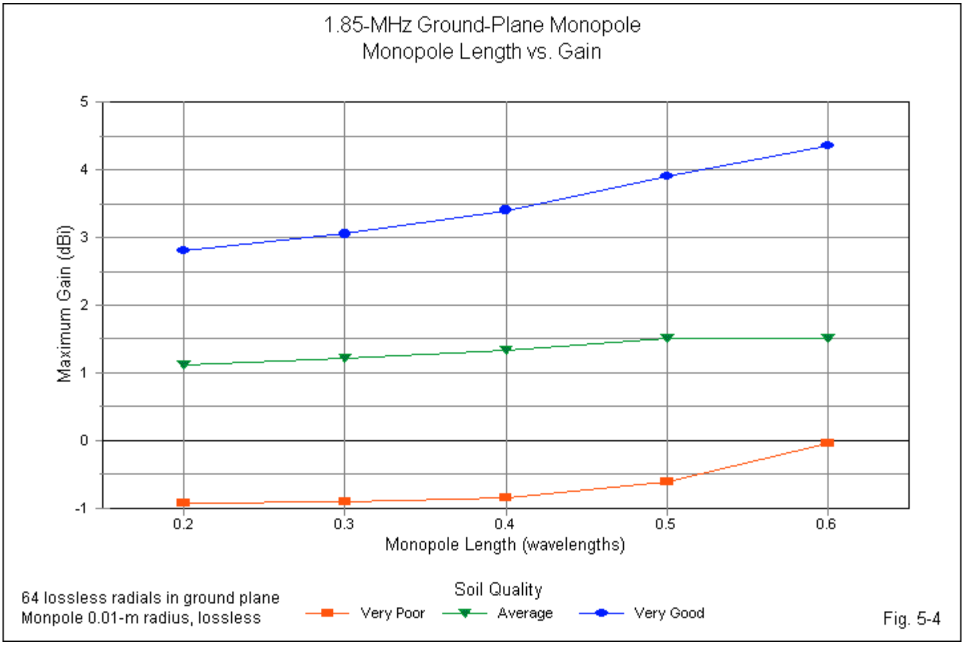


Fig. 5-4

The data for 3.6 MHz appear in **Table 5-6**. As the data compendium in the preceding chapter would lead us to expect, the entire set of gain values is lower than those for 1.85 MHz. As well, the TO angles are about 2° on average higher above the horizon. Despite the performance difference, the source impedance values for both resistance and reactance differ only slightly between the two frequencies.

3.6 MHz Variable-Length Monopole with Lossless 64-Radial Ground Plane						
Monopole length and soil quality as specified.						
Soil	Mn Ln wl	Mn Ln m	Gain dBi	TO Angle	Resist	React
Vry Poor	0.2	16.655	-1.03	60	21.193	-116.14
C 0.001	0.3	24.893	-0.94	62	64.265	159.47
P 5	0.4	33.31	-0.74	66	267.633	586.547
	0.5	41.6379	-0.23	69	2064.31	-699.853
	0.6	49.965	0.79	71	132.068	-511.254
Average	0.2	16.655	0.48	64	23.659	-114.073
C 0.005	0.3	24.893	0.54	67	72.012	163.1
P 13	0.4	33.31	0.62	70	295.429	583.05
	0.5	41.6379	0.78	73	1950.65	-656.264
	0.6	49.965	0.87	76	132.944	-513.927
Vry Good	0.2	16.655	2.27	70	24.281	-113.613
C 0.0303	0.3	24.893	2.47	72	74.482	164.631
P 20	0.4	33.31	2.75	74	307.358	582.358
	0.5	41.6379	3.14	77	1894.09	-644.289
	0.6	49.965	3.39	79	134.513	-515.741
Notes:	Mn Ln wl = Monopole length in wavelengths					
	Mn Ln m = monopole length in meters					Table 5-6

The most striking difference between the maximum gain values for the 2 bands lies in the rates of change with increasing monopole length and improving soil conditions. For the shortest monopole in the sequence (0.2 λ long), the difference in gain between very poor and very good soil is consistent: 3.7 dB at 1.85 MHz and 3.3 dB at 3.6 MHz. However, for the longest (0.6 λ) monopole, we find a 4.4-dB gain difference between the extreme soil qualities, while at 3.6 MHz, the difference shrinks to 2.6 dB.

The curves in **Fig. 5-5** show why the difference shrinks. Over very poor soil, the rate of gain increase is very high between lengths of 0.5 λ and 0.6 λ at 3.6 MHz. Over very good soil, the same increment of length increase yields a smaller gain increase than at 1.85 MHz. The combined effect is to reduce the gain difference between the longest monopoles in the sequence at 3.6 MHz.

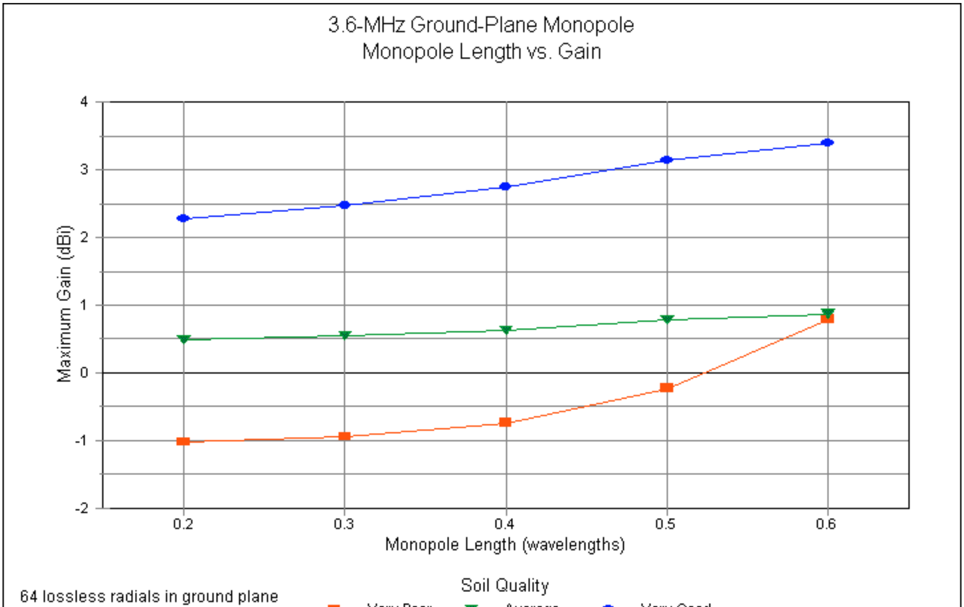


Fig. 5-5

A second notable feature of the curves for 3.6 MHz is the flatness of the curve for maximum gain over average soil. At 1.85 MHz, we noted that the rate of increase in the curve for average soil was lower than for the other soil qualities. At 3.6 MHz, we find only a 0.4-dB rise in gain from the shortest to the longest monopole in the set. One result of the very low rate of gain increase shows up in the relative values for the 0.6-λ monopole: the values for very poor and for average soil are almost identical.

When we turn to the samples for 7.15 MHz, the source impedance data present no surprises. Indeed, the changes among all three monopole series are very small, largely as a function of the relatively large radial field. **Table 5-7** shows the complete data set for the highest frequency in our sample. Perhaps the key question is whether the data show a continuation of the trends that we tentatively uncovered between 1.85 and 3.6 MHz.

7.15 MHz Variable-Length Monopole with Lossless 64-Radial Ground Plane						
Monopole length and soil quality as specified.						
Soil	Mn Ln wl	Mn Ln m	Gain dBi	TO Angle	Resist	React
Vry Poor	0.2	8.386	-0.65	59	19.828	-101.107
C 0.001	0.3	12.579	-0.52	62	61.795	148.694
P 5	0.4	16.772	-0.22	65	269.933	541.549
	0.5	20.965	0.42	68	1628.53	-723.157
	0.6	25.157	1.52	70	123.438	-444.22
Average	0.2	8.386	0.19	63	22.978	-99.483
C 0.005	0.3	12.579	0.25	65	70.949	150.976
P 13	0.4	16.772	0.37	68	299.008	531.46
	0.5	20.965	0.65	71	1550.95	-666.086
	0.6	25.157	1.06	74	123.511	-446.39
Vry Good	0.2	8.386	1.63	68	24.517	-98.718
C 0.0303	0.3	12.579	1.78	70	75.666	152.228
P 20	0.4	16.772	1.97	72	315.298	525.318
	0.5	20.965	2.25	75	1503.21	-632.008
	0.6	25.157	2.34	78	124.581	-448.362
Notes:	Mn Ln wl = Monopole length in wavelengths					
	Mn Ln m = monopole length in meters					Table 5-7

Once more, relative to the preceding tables, the overall trend in maximum gain is downward, with a TO angle that continues to increase above the horizon. The amount of gain improvement that we may attribute to improving soil quality also decreases. For the 0.2-λ monopole, the difference between very poor and very good soil is down to about 2.3 dB, while the difference for the 0.6-λ monopole is a mere 0.8 dB. The performance across the span of monopole lengths for average soil has improved to about 0.9 dB.

The potential trend of greatest note involves the curves for very poor and average soil. As the frequency increased from 1.85 to 3.6 MHz, the curve for very poor soil grew steeper so that at the higher frequency, the maximum gain value for the longest monopole virtually equaled the maximum gain for same monopole over average soil. If that trend should continue, then at 7.15 MHz, we should expect that the maximum gain for a 0.6-λ monopole would exceed the gain of the same monopole over average soil. **Fig. 5-6** informs us that our expectations were correct.

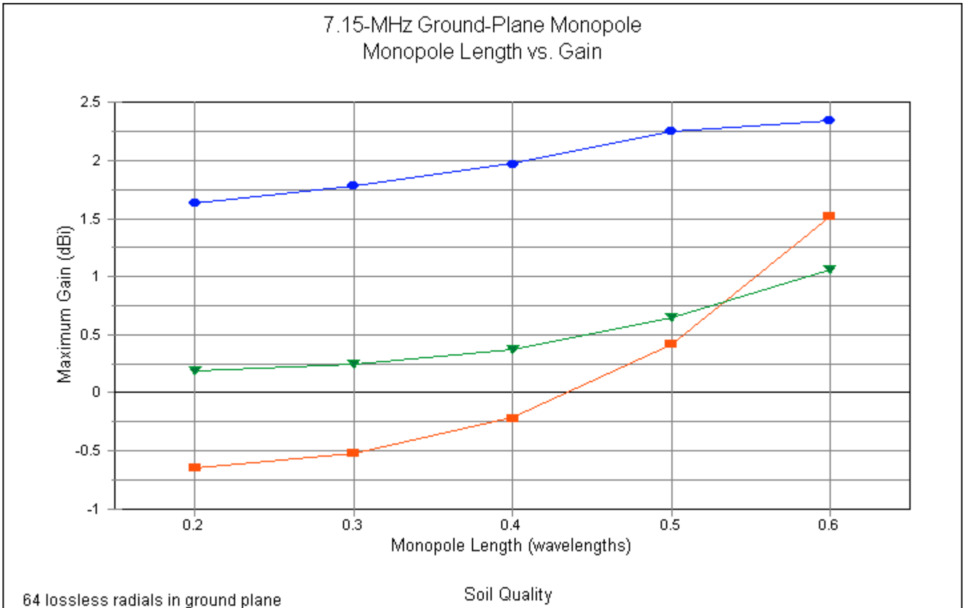


Fig. 5-6

We had also noted in preceding graphs that over very good soil, the maximum-gain curve flattened slightly between monopole lengths of 0.5 λ and 0.6 λ. At 7.15 MHz, the flattening becomes even more evident. In fact, most of the interesting features in the graphs seem to involve the increment of monopole increase between 0.5 λ and 0.6 λ.

Part of the reason for selecting the specific sample monopole length involves the shape of the elevation pattern. Above about 0.625 λ, a monopole shows considerable shrinkage in its lower lobe and the development of a dominant high-angle lobe. Hence, lengths beyond 0.625 λ generally receive poor performance marks, since radio amateurs are most interested in TO angles closer to the horizon. However, the higher-angle secondary lobe in the elevation or theta pattern of a monopole does not appear suddenly in a 5/8-λ monopole. Rather, it emerges definitively for any length above about 0.5 λ. Therefore, our sample 0.6-λ monopoles have well-developed secondary lobes, as shown in the composite of patterns for 1.85 MHz in **Fig. 5-7**.

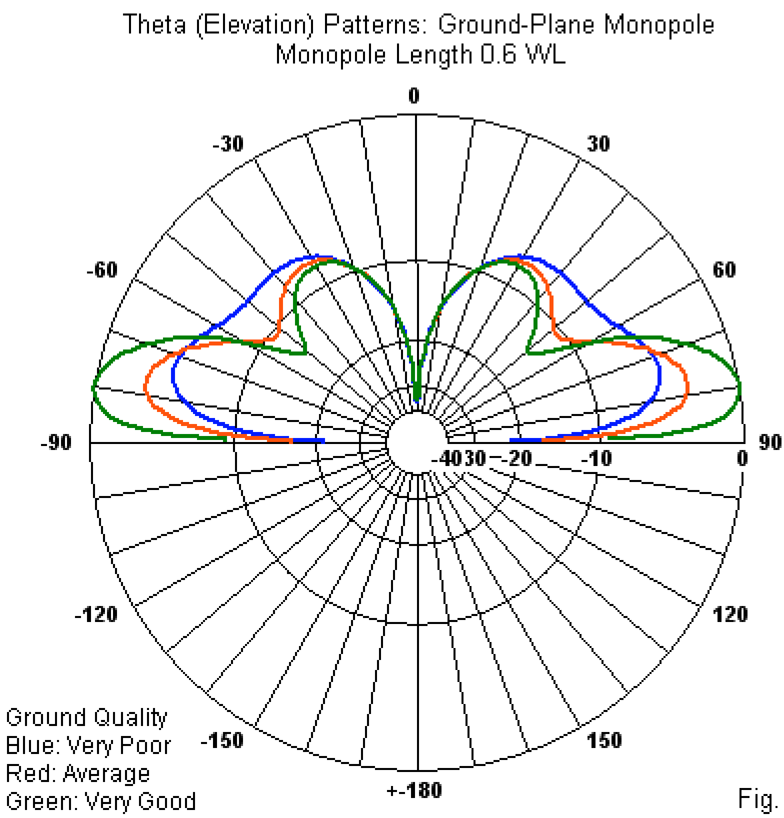


Fig. 5-7

The sample patterns also reveal the differences in pattern formation over the various levels of soil quality used in our survey. The poorer the soil quality, the greater percentage of radiated energy lies in the upper lobe. However, that ratio changes not only with soil quality, but as well with frequency. Let's add one more variable to the mix: the secondary lobe is not merely present when we can detect a definitive lobe, but is also present in the lobe development for shorter monopoles. Given differential rates of development with both soil quality and frequency, the seemingly off behavior of the gain curves becomes much more sensible.

For most amateur installations, ground-plane monopoles longer than 0.25 λ are wholly impractical, excepting perhaps 7.15 MHz. Indeed, most radio amateurs have difficulty achieving a full quarter wavelength on 160 and 80 m. Nevertheless, this particular exercise does provide a feel for the performance of ground-plane monopoles, as the monopole grows longer. More significantly, it may also put a damper on the tendency to transfer uncritically what we learn about the performance at one frequency and soil type to another frequency and soil type.

5. How many radials must the ground plane use for adequate performance?

Of course, we have no definitive answer to perhaps the most asked question of all: how many radials? A proper answer involves mating potential performance curves to the operating goal and specifications for a given installation. Still, we may provide a sample of the relevant data that might go into an answer by sampling radial systems of various sizes. Some of that information appears in the tables for the preceding chapter. Here, we shall concentrate our efforts to produce fewer but perhaps more coherent piles of information.

The sampling frequencies will be the same as always: 1.85, 3.6, and 7.15 MHz. For each test, we shall use the standard 0.1-m radius monopole with a buried set of 0.001-m radius radials 0.1-m below ground. All antenna system elements will use lossless wire in order to isolate as best possible the effects increasing the number of radials. We shall sample using very poor, average, and very good soil quality values. For each model, we shall double the number of radials, beginning with 4 and ending with 128. Because we have several sampling dimensions, we shall divide the work into 3 separate tables, each covering one of the frequencies in the survey. **Table 5-8** holds the data for the 1.85-MHz samples.

1.85-MHz Perfect Monopole with Perfect Radials and Various Soil Qualities						
Monopole length: resonant with perfect ground; radials 1/4 wavelength						
Soil		# Radials	Gain dBi	TO Angle	Resist	React
Very Poor		4	-3.91	62	76.642	17.665
C 0.001, P 5		8	-2.76	62	59.317	11.805
		16	-1.84	62	47.453	6.826
		32	-1.22	62	40.047	2.201
		64	-0.91	62	36.143	-1.256
		128	-0.78	62	33.289	-3.252
Average		4	-0.53	67	56.912	11.657
C 0.005, P 13		8	0.04	67	50.161	8.009
		16	0.5	67	45.2	5.376
		32	0.89	67	41.31	3.205
		64	1.15	67	38.448	1.266
		128	1.29	67	36.696	-0.269
Very Good		4	2.16	73	45.567	6.571
C 0.0303, P 20		8	2.39	73	43.236	4.779
		16	2.58	73	41.406	3.491
		32	2.75	73	39.83	2.425
		64	2.9	73	38.448	1.488
Table 5-8		128	3.01	73	37.347	0.667

If we measure performance in terms of maximum gain, then increasing the number of radials can have only a limited positive effect on performance. The constant TO angle for each level of soil quality reminds us that much of the gain results from ground reflections well beyond the limits of the radial field. Moreover, as suggested by the curves in **Fig. 5-8**, the total gain improvement decreases between 4 and 128 radials as we improve the soil: 3.38 dB for very poor ground, 1.82 dB for average ground, and 0.85 dB for very good ground. As well, the rate of increase for each doubling of the radial field decreases as we enlarge the field.

Fig. 5-9 shows the source resistance curves for the 3 soil types. The fact that at least one source resistance value falls below 36 Ω should suffice overturn a persistent presumption that the source impedance of a ground-plane monopole cannot fall below the value for the same monopole over perfect ground.

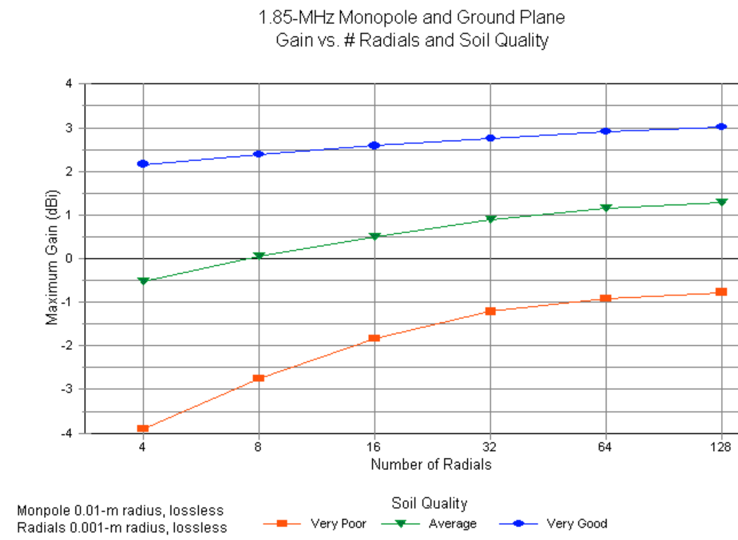

1.85-MHz Monopole and Ground Plane
Gain vs. # Radials and Soil Quality
Maximum Gain (dBi)
4
3
2
1
0
-1
-2
-3
-4
4
8
16
32
64
128
Number of Radials
Monpole 0.01-m radius, lossless
Radials 0.001-m radius, lossless
Soil Quality
Very Poor
Average
Very Good

Fig. 5-8

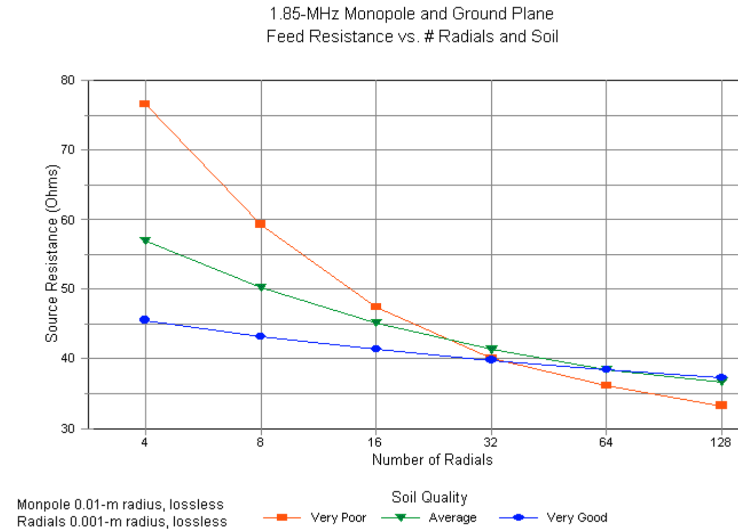

1.85-MHz Monopole and Ground Plane
Feed Resistance vs. # Radials and Soil
Source Resistance (Ohms)
80
70
60
50
40
30
4
8
16
32
64
128
Number of Radials
Monpole 0.01-m radius, lossless
Radials 0.001-m radius, lossless
Soil Quality
Very Poor
Average
Very Good

Fig. 5-9

Table 5-9 shows the data for 3.6 MHz. We find similar curve shapes for gain performance (as shown in **Fig. 5-10**), but at the expected lower values for gain that come with increased frequency. In contrast, the gain improvement with increasing numbers of radials is larger: 3.71 dB for very poor soil, 2.32 dB for average soil, and 1.11 dB for very good soil.

3.6-MHz Perfect Monopole with Perfect Radials and Various Soil Qualities						
Monopole length: resonant with perfect ground; radials 1/4 wavelength						
Soil		# Radials	Gain dBi	TO Angle	Resist	React
Very Poor		4	-4.59	61	85.714	18.334
C 0.001, P 5		8	-3.05	61	60.331	14.096
		16	-1.9	61	44.743	7.675
		32	-1.26	61	36.921	1.803
		64	-0.99	61	33.513	-1.862
		128	-0.88	61	32.045	-3.672
Average		4	-1.69	65	62.155	11.294
C 0.005, P 13		8	-0.93	65	52.811	7.955
		16	-0.29	65	46.008	5.476
		32	0.21	65	40.869	3.139
		64	0.5	65	37.508	0.89
		128	0.63	65	35.747	-0.752
Very Good		4	1.36	71	48.401	7.865
C 0.0303, P 20		8	1.67	71	45.096	5.735
		16	1.94	71	42.537	4.142
		32	2.17	71	40.385	2.853
		64	2.35	71	38.595	1.717
Table 5-9		128	2.47	71	37.298	0.745

The source resistance curves in **Fig. 5-11** show the wider spread of values from 4 to 128 radials, especially with very poor soil. As well, we find more cases in which the source resistance falls below 36 Ω, with instances in both the very poor and the average soil categories. Between the 1.85-MHz and the 3.6-MHz tables, we do find an apparent convergence of source impedance values among soil qualities with 32 radials. At this level, the reactance is low and relatively stable, with a low rate of change for additional radials.

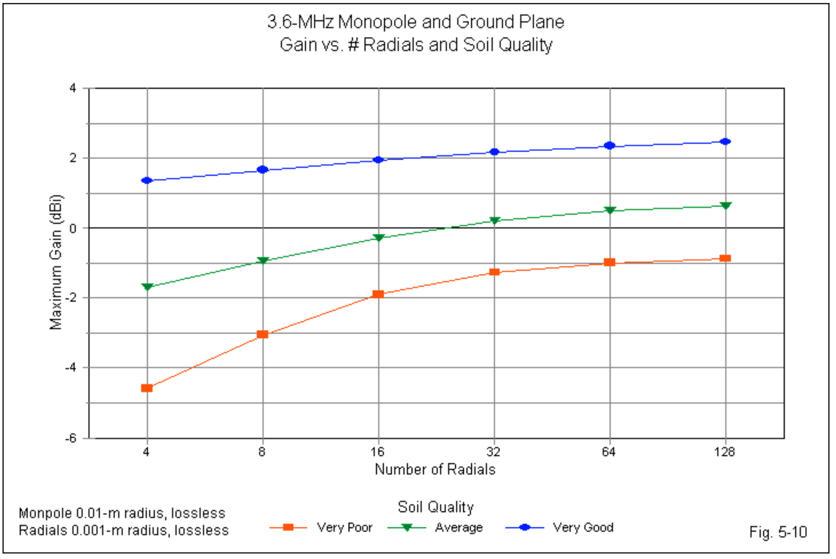


Fig. 5-10

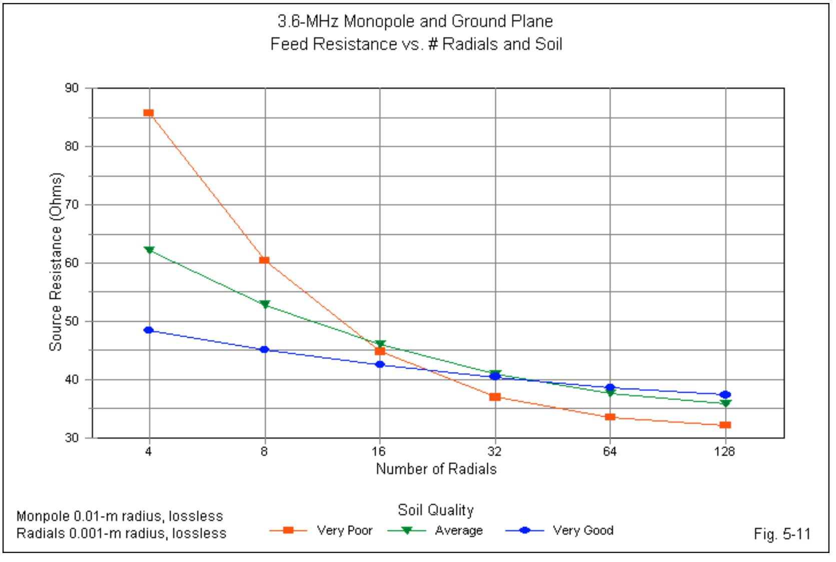


Fig. 5-11

Table 5-9 presents the 7.15-MHz model reports, with essentially the same general patterns of gain information, as shown in **Fig. 5-12**. The spread of gain between 4 and 128 radials continues to increase over each soil type: 4.09 dB for very poor, 2.83 dB for average, and 1.44 dB for very good ground. However, frequency has taken its toll on the potential gain for each level of soil quality.

7.15 Perfect Monopole with Perfect Radials and Various Soil Qualities					
Monopole length: resonant with perfect ground; radials 1/4 wavelength					
Soil	# Radials	Gain dBi	TO Angle	Resist	React
Very Poor	4	-4.63	60	98.337	25.778
C 0.001, P 5	8	-2.59	60	59.252	21.452
	16	-1.31	60	40.65	10.647
	32	-0.79	60	33.803	3.105
	64	-0.61	60	31.355	-0.667
	128	-0.54	60	30.388	-2.277
Average	4	-2.52	64	66.662	8.746
C 0.005, P 13	8	-1.57	63	55.174	7.304
	16	-0.73	63	46.485	6.107
	32	-0.1	63	39.943	3.912
	64	0.2	63	36.346	1.397
	128	0.31	63	34.613	-0.264
Very Good	4	0.36	69	52.12	9.167
C 0.0303, P 20	8	0.79	69	47.419	6.832
	16	1.15	69	43.85	5.117
	32	1.46	69	40.925	3.714
	64	1.69	69	38.654	2.426
Table 5-10	128	1.8	69	37.2	1.338

From 4 to 128 radials, the source resistance shows an increasing total spread, with very poor soil showing the most dramatic curve. See **Fig. 5-13**. Only the curve for very good soil remains wholly above the 36-Ω level, even with 128 radials. The 32-radial level once more appears to mark a threshold of relative performance stability with respect to low source reactance and low rates of change of both gain and source resistance. However, further gain improvement is possible with more radials, although the amount diminishes with frequency.

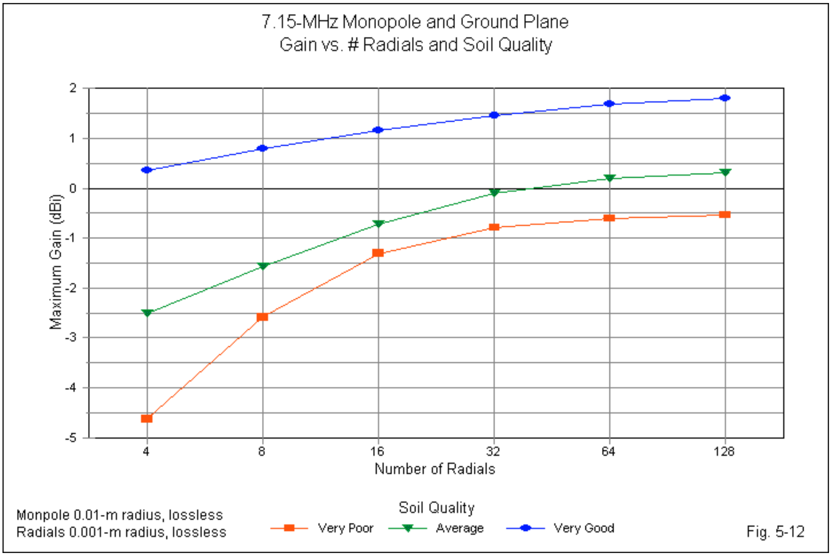


Fig. 5-12

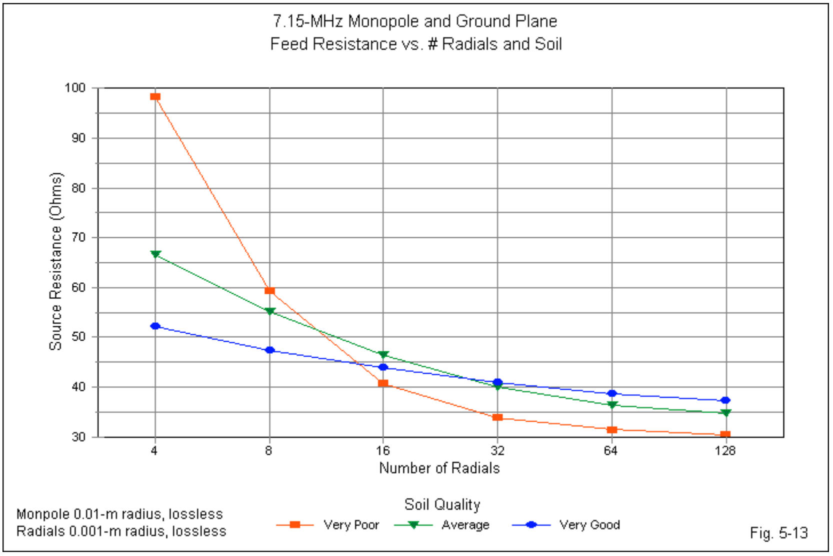


Fig. 5-13

When we compare the tables and graphs for all 3 frequencies, some trends appear. First, as we approach 128 radials at each frequency, the rate of gain improvement decreases. The curve for very poor soil shows the greatest flattening at each frequency. However, in all cases, further gain increase with additional radials is possible. Although radials cannot improve the far-field ground reflections, it can decrease losses in the immediate vicinity of the antenna. We may here note a statement, still taken as gospel within the AM BC industry, that any more than about 113 radials are superfluous relative to ground-plane monopole performance with buried radials. The statement originates from a classic article, "Ground Systems as a Factor in Antenna Efficiency," by G. H. Brown, R. F. Lewis, and J. Epstein (*Proceedings of the Institute of Radio Engineers*, Vol. 25, No. 6, June, 1937). The value of 113 radials comes from the number of radials that Brown, Lewis, and Epstein happened to use in their 3-MHz experiments. The gain curves in the graphs suggest that indeed we may obtain additional gain, although the cost may be too high to make the effort worthwhile. (Indeed, the authors even qualify their remarks by reference to a high but not perfect system efficiency calculation.) Nevertheless, it appears from NEC models that the higher the ground quality–especially its conductivity–the greater the potential benefit of a final doubling of the largest radial field in this survey. We shall shortly check this idea as it applies to radial length, since the curves used here apply only to ¼-λ radials.

At the other end of the scale, a minimal ground-plane field has no precise size. 4 radials will work, with relatively high losses compared to larger numbers of radials. I have noted that for many purposes, 32 radials appear to mark a threshold of performance stability in terms of gain and source impedance. Obviously, standing at a threshold does not place one wholly within a region of stability, and more radials will improve performance and stability. (Stability may also have implications in terms of the minor departures from true symmetry in the field, since all models rest on the symmetry that we can achieve mathematically.) However, above 32 radials, the amount of change per doubling of the number of radials is small per step. Hence, any number of radials from about 40 upward would likely be well within the region. Further radials are not superfluous, but fields below the 30-radial level may prove deficient for serious installations. Again, we note that these conclusions apply to the ¼-λ radials in the models.

6. Does radial length make a significant difference to antenna performance?

The 1937 Brown-Lewis-Epstein conclusions with respect to radial fields involved a relationship among field size and radial length. For large radial fields (113 radials), their experiments and subsequent calculation strongly suggested that radials might beneficially extend to 0.5 λ. However, more scant fields (15 radials) appear not to benefit from radials longer than about 0.1 λ. Since that time, radio amateurs (and others) have suggested alternative radial lengths to the seemingly standard ¼ λ size used by most applications.

In Chapter 4, we saw that NEC expands both the length and radius of buried wire segments (more precisely, any wire segments within a medium other than a vacuum). Hence, the rate of current magnitude decrease along the physical length of a radial is much more rapid than for portions of the antenna above ground. As a result, the effect of radial length upon such antenna properties as resonance is significantly different than the effects of radial length for a ground plane monopole in free space or very high above ground. For this reason alone, we should sample the effects of the length of buried radials on ground-plane monopole performance within the NEC-4 modeling system.

We already have several inter-related variables at work: frequency, soil quality, and the number of radials. Space does not permit simply adding a 4^{th} variable to the collection, since the combinations would quickly overrun the limits of this volume of notes. We have already reduced the number of frequencies to 3, with the same number of sampled soil qualities. We shall explore radial lengths between 0.1 λ and 0.5 λ in increments of 0.005 λ. Therefore, we shall have to reduce the number of field sizes to only 2. To replicate the Brown-Lewis-Epstein experiments within the confines of our models, we shall first look at fields using 16 radials and then at fields using 128 radials. In all cases, we shall use the standard lossless monopoles, with a 0.01-m radius, and employ lossless 0.001-m radius radials. The models will be simple variants of our basic models for each frequency, using the GW2 lines to vary radial length and segmentation (about 0.025 m per segment), and the GM line to vary the number of radials and their angular separation.

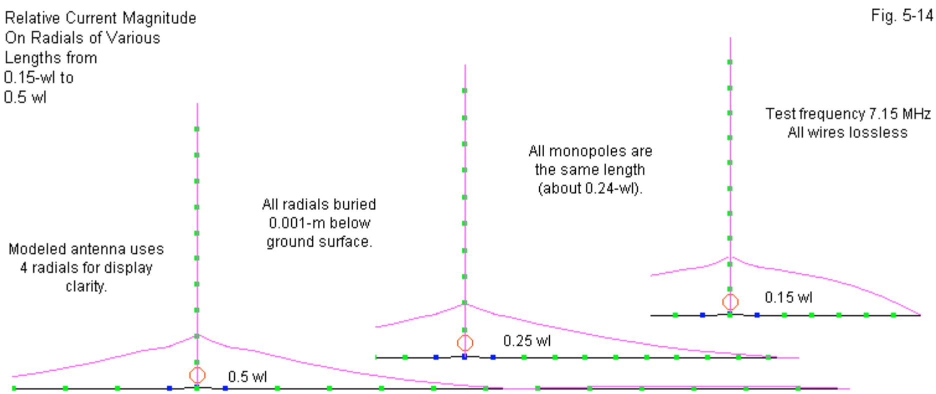


Fig. 5-14 can help us develop the correct expectations from the model results. The 3 partial sketches of monopoles and buried radials all divide the current so that it starts along the radials at about the same magnitude. The monopoles all have the same length and–for clarity of presentation–use only 4 radials. However, the radials are 0.15 λ, 0.25 λ, and 0.5 λ. We are familiar with the rapid decline in the current magnitude along the 0.25-λ radial from our work in Chapter 4. However, note the ogee curve of current magnitude along the 0.15-λ radials. As well, note the rise in current (as small is it may be) between the 0.25-λ and 0.5-λ points along the largest radial of the set. The second current rise peaks about midway between the reference points.

As we change the length of buried radials, the current distribution changes. Therefore, we may also expect performance changes. However, the figure does not take into account any differences occasioned by the soil quality, by the operating frequency, and by the number of radials. The only way to sample the effects of all of the variables is to develop another large series of models.

Table 5-11 provides the 1.85-MHz data for 16-radial ground planes for our sample soil types and range of radial lengths. The comparable data for 128-radial systems appears in **Table 5-12**.

Table 5-11

1.85 MHz Lossless Monopole with Lossless 16-Radial Ground Plane						
Radial length and soil quality as specified.						
Soil		Rd Ln wl	Gain dBi	TO Angle	Resist	React
Very Poor		0.1	-2.93	62	55.185	-8.116
C 0.001, P 5		0.15	-2.31	62	48.145	-1.9
		0.2	-1.99	62	46.439	3.573
		0.25	-1.84	62	47.453	6.826
		0.3	-1.73	62	49.015	8.197
		0.35	-1.63	62	50.368	8.478
		0.4	-1.55	62	51.314	8.161
		0.45	-1.49	61	51.8	7.576
		0.5	-1.46	61	51.864	6.978
Average		0.1	0.28	67	46.605	2.907
C 0.005, P 13		0.15	0.41	67	45.504	4.193
		0.2	0.47	67	45.189	4.899
		0.25	0.5	67	45.2	5.376
		0.3	0.53	67	45.331	5.657
		0.35	0.56	67	45.478	5.776
		0.4	0.57	67	45.638	5.792
		0.45	0.59	67	45.748	5.737
		0.5	0.6	67	45.797	5.654
Very Good		0.1	2.54	73	41.7	3.193
C 0.0303, P 20		0.15	2.56	73	41.499	3.326
		0.2	2.57	73	41.426	3.421
		0.25	2.58	73	41.406	3.425
		0.3	2.59	73	41.413	3.539
		0.35	2.59	73	41.432	3.567
		0.4	2.59	73	41.454	3.577
Table 5-11		0.45	2.59	73	41.473	3.575
		0.5	2.59	73	41.485	3.566
Note	Rd Ln wl = Radial Length in wavelengths; 1 wl = 162.050 m					

Table 5-12

1.85 MHz Lossless Monopole with Lossless 128-Radial Ground Plane						
Radial length and soil quality as specified.						
Soil		Rd Ln wl	Gain dBi	TO Angle	Resist	React
Very Poor		0.1	-2.48	62	49.29	-11.517
C 0.001, P 5		0.15	-1.8	62	41.441	-9.478
		0.2	-1.24	62	36.698	-6.524
		0.25	-0.78	62	34.289	-3.252
		0.3	-0.38	62	33.567	-0.156
		0.35	-0.3	61	34.143	2.448
		0.4	0.29	61	35.685	4.227
		0.45	0.56	60	37.723	4.883
		0.5	0.8	59	39.618	4.339
Average		0.1	0.57	67	43.133	-2.589
C 0.005, P 13		0.15	0.88	67	39.766	-2.392
		0.2	1.11	67	37.74	-1.481
		0.25	1.29	67	36.696	-0.269
		0.3	1.42	67	36.401	0.915
		0.35	1.54	67	36.649	1.849
		0.4	1.63	67	37.244	2.401
		0.45	1.7	67	37.92	2.518
		0.5	1.76	66	38.455	2.274
Very Good		0.1	2.78	73	39.226	0.005
C 0.0303, P 20		0.15	2.89	73	38.104	0.049
		0.2	2.96	73	37.613	0.327
		0.25	3.01	73	37.347	0.667
		0.3	3.04	73	37.295	0.97
		0.35	3.07	73	37.376	1.183
		0.4	3.08	73	37.516	1.289
Table 5-12		0.45	3.09	73	37.656	1.301
		0.5	3.1	73	37.756	1.245
Note	Rd Ln wl = Radial Length in wavelengths; 1 wl = 162.050 m					

To put the 2 tables into comparative perspective, I created a summary in **Table 5-13**. This table catalogs the significant changes. The gain differentials include values for the entire span of radial lengths and for the regions from 0.1 λ to 0.25 λ and from 0.25 λ to 0.5 λ. Source resistance and reactance maximum differentials appear only for the entire range, since maximum and minimum values do not necessarily occur at the radial length extremes.

1.85 MHz Summary: Performance Changes with Radial Length Changes							
		16 Radials-----------------------------|			128 Radials----------------------------|		
Soil	Range	Gain Dif	R Dif	X Dif	Gain Dif	R Dif	X Dif
Vry Poor	.1 - .5	1.47	8.746	16.594	3.28	15.723	16.4
	.25 - .5	0.38			1.58		
	.1 - .25	1.09			1.7		
Average	.1 - .5	0.32	1.416	2.885	1.19	6.732	5.107
	.25 - .5	0.1			0.47		
	.1 - .25	0.22			0.72		
Vry Good	.1 - .5	0.05	0.294	1.152	0.32	1.931	1.296
	.25 - .5	0.01			0.09		
	.1 - .25	0.04			0.23		
	Notes	Range = Range of radial lengths in wavelengths					
		Gain Dif = Gain differential in dB					
		R Dif = Maximum source resistance differential in Ohms					
Table 5-13		X Dif = Maximum source reactance differential in Ohms					

For 1.85 MHz, the tables appear to confirm in a very general way the Brown-Lewis-Epstein conclusion that a scant radial field does not require very long radials to reach most of its potential. The gain differential for the 16-radial field is smaller for every soil type than the total gain differential for the 128-radial field. However, there are subtleties to the behavior of the radial fields that go well beyond the aspects investigated in 1937. The poorer the soil, the wider the range of both resistance and reactance at the source. These values are interesting by virtue of their patterns. Over very good soil, the values fall in such a tight grouping that we might easily think of the changes from one radial length to another as random. However, over very poor soil, past the 0.25-λ mark, we find a rise in resistance and reactance that we might otherwise see in a model wholly above ground. The radials give the appearance of resulting in a total antenna that is too large to be resonant.

The data for 3.6 MHz appears in **Table 5-14** for 16-radial systems and in **Table**

5-15 for 128-radial systems.

Table 5-14

3.6 MHz Lossless Monopole with Lossless 16-Radial Ground Plane						
Radial length and soil quality as specified.						
Soil		Rd Ln wl	Gain dBi	TO Angle	Resist	React
Very Poor		0.1	-3.4	61	52.952	-16.901
C 0.001, P 5		0.15	-2.65	61	44.793	-7.591
		0.2	-2.13	61	42.281	1.213
		0.25	-1.9	61	44.743	7.675
		0.3	-1.79	60	49.084	9.99
		0.35	-1.7	60	52.294	9.383
		0.4	-1.61	60	53.834	7.7
		0.45	-1.56	59	54.001	6.077
		0.5	-1.55	59	53.41	5.052
Average		0.1	-0.68	65	47.863	-0.16
C 0.005, P 13		0.15	-0.44	65	45.871	3.031
		0.2	-0.35	65	45.763	4.629
		0.25	-0.29	65	46.008	5.476
		0.3	-0.24	65	46.414	5.945
		0.35	-0.2	65	46.834	6.089
		0.4	-0.17	65	47.154	6.01
		0.45	-0.15	65	47.324	5.827
		0.5	-0.14	65	47.355	5.635
Very Good		0.1	1.85	71	43.068	3.471
C 0.0303, P 20		0.15	1.9	71	42.683	3.786
		0.2	1.92	71	42.557	3.997
		0.25	1.94	71	42.537	4.142
		0.3	1.95	71	42.556	4.236
		0.35	1.95	71	42.614	4.282
		0.4	1.96	71	42.662	4.294
Table 5-14		0.45	1.96	71	42.698	4.282
		0.5	1.96	71	42.717	4.259
Note	Rd Ln wl = Radial Length in wavelengths; 1 wl = 83.526 m					

Table 5-15

3.6 MHz Lossless Monopole with Lossless 128-Radial Ground Plane						
Radial length and soil quality as specified.						
Soil		Rd Ln wl	Gain dBi	TO Angle	Resist	React
Very Poor		0.1	-2.92	61	47.199	-17.006
C 0.001, P 5		0.15	-2.16	61	39.345	-12.573
		0.2	-1.48	61	34.339	-8.177
		0.25	-0.88	61	32.045	-3.672
		0.3	-0.35	61	31.775	0.417
		0.35	0.09	60	32.981	3.615
		0.4	0.49	59	35.279	5.7
		0.45	0.84	58	38.139	6.283
		0.5	1.12	56	40.702	5.227
Average		0.1	-0.42	65	44.49	-5.218
C 0.005, P 13		0.15	0.04	65	39.778	-4.275
		0.2	0.37	65	37.085	-2.636
		0.25	0.63	65	35.747	-0.752
		0.3	0.85	65	35.451	1.102
		0.35	1.03	65	35.971	2.536
		0.4	1.19	64	36.986	3.356
		0.45	1.32	64	38.122	3.469
		0.5	1.43	64	39.001	2.977
Very Good		0.1	2.11	71	40.327	-0.392
C 0.0303, P 20		0.15	2.27	71	38.681	-0.299
		0.2	2.39	71	37.743	0.166
		0.25	2.47	71	37.298	0.745
		0.3	2.53	71	37.21	1.289
		0.35	2.57	71	37.367	1.671
		0.4	2.61	71	37.634	1.861
Table 5-15		0.45	2.63	71	37.902	1.872
		0.5	2.65	70	38.09	1.755
Note	Rd Ln wl = Radial Length in wavelengths; 1 wl = 83.526 m					

As expected, we find systematically lower gain values and TO theta angle values for the higher frequency, regardless of the number of radials. As well, for very poor soil, note the changing TO-angle value for both radial field sizes. As the radials grow longer, the maximum radiation occurs at a higher angle relative to the horizon, as it also would if we had developed the antenna system above ground and brought it closer to the earth's surface. In addition, we also find another instance where the behavior of the antenna above very poor soil resembles the performance of an antenna above ground as we scan the TO angle and the source impedance values.

3.6 MHz Summary: Performance Changes with Radial Length Changes							
		16 Radials-----------------------------|			128 Radials-----------------------------|		
Soil	Range	Gain Dif	R Dif	X Dif	Gain Dif	R Dif	X Dif
Vry Poor	.1 - .5	1.85	11.72	26.891	4.04	15.424	23.289
	.25 - .5	0.35			2		
	.1 - .25	1.5			2.04		
Average	.1 - .5	0.54	2.1	6.249	1.85	9.039	8.687
	.25 - .5	0.15			0.8		
	.1 - .25	0.39			1.05		
Vry Good	.1 - .5	0.11	0.531	0.823	0.54	3.117	2.264
	.25 - .5	0.02			0.18		
	.1 - .25	0.09			0.36		
	Notes	Range = Range of radial lengths in wavelengths					
		Gain Dif = Gain differential in dB					
		R Dif = Maximum source resistance differential in Ohms					
Table 5-16		X Dif = Maximum source reactance differential in Ohms					

The data summary in **Table 5-16** also reveals that–with only one exception–the range of differentials increases with the higher frequency. As the table indicates, most of the change occurs in the shorter portion of the radial-length range, from 0.1 λ to 0.25 λ. Similar results appear in the 1.85-MHz table. Only with very poor soil do we find an appreciable change of gain with radials between 0.25 λ and 0.5 λ. In all cases, the performance improves more dramatically with increasing numbers of radials than with increases in the length of radials beyond 0.25 λ.

Table 5-17 provides the 16-radial information for 7.15 MHz, while **Table 5-18** supplies counterpart information for 128-radial systems at the higher frequency. We may correctly anticipate further extensions of all of the trends that we have so far observed.

Table 5-17

7.15 MHz Lossless Monopole with Lossless 16-Radial Ground Plane						
Radial length and soil quality as specified.						
Soil		Rd Ln wl	Gain dBi	TO Angle	Resist	React
Very Poor		0.1	-3.01	61	46.957	-21.006
C 0.001, P 5		0.15	-2.3	61	40.532	-10.035
		0.2	-1.67	60	37.249	0.288
		0.25	-1.31	60	40.65	10.647
		0.3	-1.29	59	49.254	14.097
		0.35	-1.3	59	55.188	11.042
		0.4	-1.25	59	56.731	6.623
		0.45	-1.22	58	55.338	3.489
		0.5	-1.3	58	53.057	2.625
Average		0.1	-1.28	64	47.27	-4.47
C 0.005, P 13		0.15	-0.88	64	44.193	1.626
		0.2	-0.79	63	45.215	4.95
		0.25	-0.73	63	46.485	6.107
		0.3	-0.67	63	47.367	6.412
		0.35	-0.62	63	48.09	6.358
		0.4	-0.58	63	48.563	6.022
		0.45	-0.57	63	48.711	5.582
		0.5	-0.56	63	48.596	5.241
Very Good		0.1	1	69	44.62	3.493
C 0.0303, P 20		0.15	1.09	69	43.952	4.288
		0.2	1.13	69	43.778	4.774
		0.25	1.16	69	43.803	5.076
		0.3	1.18	69	43.906	5.243
		0.35	1.19	69	44.025	5.311
		0.4	1.2	68	44.127	5.309
Table 5-17		0.45	1.21	68	44.193	5.266
		0.5	1.21	68	44.219	5.21
Note	Rd Ln wl = Radial Length in wavelengths; 1 wl = 41.929 m					

Table 5-18

7.15 MHz Lossless Monopole with Lossless 128-Radial Ground Plane						
Radial length and soil quality as specified.						
Soil		Rd Ln wl	Gain dBi	TO Angle	Resist	React
Very Poor		0.1	-2.63	61	42.983	-18.678
C 0.001, P 5		0.15	-1.95	61	36.849	-12.722
		0.2	-1.25	61	32.351	-7.725
		0.25	-0.54	60	30.388	-2.277
		0.3	0.04	60	30.794	2.304
		0.35	0.5	59	32.699	5.653
		0.4	0.9	58	35.59	7.703
		0.45	1.25	57	39.045	8.027
		0.5	1.55	55	41.999	6.367
Average		0.1	-1.05	64	44.436	-7.998
C 0.005, P 13		0.15	-0.47	64	38.84	-5.794
		0.2	-0.03	64	35.866	-3.015
		0.25	0.31	63	34.613	-0.264
		0.3	0.62	63	34.539	2.162
		0.35	0.88	63	35.508	4.037
		0.4	1.1	62	37.098	5.031
		0.45	1.28	62	38.794	4.995
		0.5	1.43	61	40.033	4.077
Very Good		0.1	1.25	69	41.754	-0.811
C 0.0303, P 20		0.15	1.5	69	39.369	-0.506
		0.2	1.68	69	37.832	0.318
		0.25	1.8	69	37.2	1.338
		0.3	1.91	68	37.053	2.201
		0.35	1.99	68	37.352	2.861
		0.4	2.06	68	37.851	3.189
Table 5-18		0.45	2.11	68	38.351	3.187
		0.5	2.15	68	38.7	2.945
Note	Rd Ln wl = Radial Length in wavelengths; 1 wl = 41.929 m					

The changing TO angle that we observed at the lower frequencies primarily with very poor soil shows itself for both very poor and average soil at 7.15 MHz. At the lower frequencies, average soil appeared more akin to very good soil in its affect upon antenna performance. As we increase frequency, the average-soil models show changes of TO angle–especially with the 128-radial system–that resemble those associated with very poor soil. Over the specified range of radial lengths, the 128-radial system changes TO angles by 3°. Even with very good soil, we find a systematic 1° change in TO angle as we increase the radial length.

7.15 MHz Summary: Performance Changes with Radial Length Changes							
		16 Radials-----------------------------|			128 Radials----------------------------|		
Soil	Range	Gain Dif	R Dif	X Dif	Gain Dif	R Dif	X Dif
Vry Poor	.1 - .5	1.79	19.482	35.103	4.18	12.6	26.705
	.25 - .5	0.09			2.09		
	.1 - .25	1.7			2.09		
Average	.1 - .5	0.72	4.518	10.882	2.48	8.928	13.029
	.25 - .5	0.17			1.12		
	.1 - .25	0.55			1.36		
Vry Good	.1 - .5	0.21	0.842	1.818	0.9	4.701	4
	.25 - .5	0.05			0.35		
	.1 - .25	0.16			0.55		
	Notes	Range = Range of radial lengths in wavelengths					
		Gain Dif = Gain differential in dB					
		R Dif = Maximum source resistance differential in Ohms					
Table 5-19		X Dif = Maximum source reactance differential in Ohms					

The summary data in **Table 5-19** confirms the trend toward ever-larger value spans between maximum and minimum values in all categories. Of the many table entries, only 3 show smaller spans than appear in the table for 3.6 MHz. Most of the value change occurs with the shorter radial lengths. For the radio amateur contemplating a radial field with a certain maximum length of available wire, there is a choice between fewer longer (0.5-λ) radials and more shorter (0.25-λ) radials. Doubling the number of radials will yield greater performance improvements than extending the radial length. As well, using very short radials may also be questionable for soils from average to very poor, especially as we increase the frequency above 1.85 MHz. Even at the lowest of our sample frequencies, we may lose as much as a full dB of gain by reducing the standard 0.25-λ radial down to 0.1-λ.

7. Does the depth of the radials make a significant difference to antenna performance?

Radio amateurs tend to bury their radials at diverse depths ranging from perhaps a foot below the surface up to the ground level itself. One common question from those planning to lay down a radial field is whether the radial depth makes a significant difference to ground-plane monopole performance. None of the models in this chapter have so far shed any light on this question, since all models use radials buried at 0.1 m below ground, regardless of frequency.

To explore our new question, we shall want a few sample depths. We may continue the modeling practice that follows amateur practice of selecting a physical depth for the radials, usually based upon the available installation equipment. Depths of 0.1 m, 0.2 m, and 0.3 m will give us enough values to detect trends. The following listing shows the depths, their corresponding values in inches, and their values in wavelengths for each of the 3 test frequencies.

Radial Depth m	Radial Depth inches	1.85 MHz Depth λ	3.6 MHz Depth λ	7.15 MHz Depth λ
0.1	3.94	0.000617	0.001197	0.002385
0.2	7.87	0.001234	0.002395	0.004770
0.3	11.81	0.001851	0.003592	0.007155

For each depth, we shall sample radial field sizes using 16 and 64 radials to see if the number of radials makes any significant difference to the results. As well, we shall continue to use very poor, average, and very good soil qualities to discover what difference ground properties make to the performance of buried radials.

To isolate the current set of variables, we shall use our standard 0.01-m radius lossless monopole with 0.001-m radius lossless radial wires. Models will differ only in the depth of the GW2 initial wire segment that angles from the monopole base to the inner end of the flat radial. The tables appear by frequency and include data for both the 16-radial and the 64-radial versions of each antenna at each depth with each soil. As well, each soil-type collection includes a listing of the gain and source impedance differences as we move the radials from 0.1-m deep to 0.3-m deep. The

TO angle undergoes virtually no change as we deepen the radial system.

1.85-MHz Lossless Monopole with Lossless Radials						Table 5-20
Soil quality, number of radials, and radial depth variable.						
# Radials	Soil	Depth m	Gain dBi	TO Angle	Resist	React
16	Vry Poor	0.1	-1.84	62	47.453	6.826
	C 0.001	0.2	-1.85	62	47.776	7.311
	P 5	0.3	-1.86	62	48.058	7.779
Dif			0.02		0.605	0.953
	Average	0.1	0.5	67	45.2	5.376
	C 0.005	0.2	0.49	67	45.399	5.748
	P 13	0.3	0.48	67	45.632	6.126
Dif			0.02		0.432	0.75
	Vry Good	0.1	2.58	73	41.406	3.491
	C 0.0303	0.2	2.56	73	41.599	3.776
	P 20	0.3	2.55	73	41.795	4.042
Dif			0.03		0.389	0.551
128	Vry Poor	0.1	-0.91	62	36.143	-1.256
	C 0.001	0.2	-0.91	62	36.353	-0.672
	P 5	0.3	-0.92	62	36.563	-0.112
Dif			0.01		0.42	1.144
	Average	0.1	1.15	67	38.448	1.266
	C 0.005	0.2	1.14	67	38.686	1.768
	P 13	0.3	1.13	67	38.946	2.297
Dif			0.02		0.498	1.031
	Vry Good	0.1	2.9	73	38.448	1.488
	C 0.0303	0.2	2.88	73	38.696	1.96
	P 20	0.3	2.86	73	38.959	2.42
Dif			0.04		0.511	0.932

Table 5-20 provides data for 1.85 MHz, where the difference between 4" and 12" is a very small fraction of a wavelength. As expected, the changes in gain are always less than 0.05 dB and the changes in the components of the source resistance are under 1 Ω. Although we do find some possible trends, the overall level of the changes is too small to certify them.

3.6-MHz Lossless Monopole with Lossless Radials						Table 5-21
Soil quality, number of radials, and radial depth variable.						
# Radials	Soil	Depth m	Gain dBi	TO Angle	Resist	React
16	Vry Poor	0.1	-1.9	61	44.743	7.675
	C 0.001	0.2	-1.92	61	45.5	8.794
	P 5	0.3	-1.94	61	46.139	9.876
Dif			0.04		1.396	2.201
	Average	0.1	-0.29	65	46.008	5.476
	C 0.005	0.2	-0.32	65	46.503	6.285
	P 13	0.3	-0.35	65	47.201	7.097
Dif			0.06		1.193	1.621
	Vry Good	0.1	1.94	71	42.537	4.142
	C 0.0303	0.2	1.9	71	42.966	4.768
	P 20	0.3	1.86	71	43.406	5.35
Dif			0.08		0.869	1.208
128	Vry Poor	0.1	-0.99	61	33.513	-1.862
	C 0.001	0.2	-1	61	33.928	-0.677
	P 5	0.3	-1	61	34.324	0.49
Dif			0.01		0.811	2.352
	Average	0.1	0.5	65	37.508	0.89
	C 0.005	0.2	0.49	65	37.994	1.957
	P 13	0.3	0.46	65	38.49	3.057
Dif			0.04		0.982	2.167
	Vry Good	0.1	2.35	71	38.595	1.717
	C 0.0303	0.2	2.32	71	39.119	2.711
	P 20	0.3	2.27	71	39.68	3.666
Dif			0.08		1.085	1.949

At 3.6 MHz, as shown in **Table 5-21**, the change per unit of radial depth increases, since each increment of depth is a greater fraction of a wavelength. As well, the soil also shows higher losses for any given set of constants, although we cannot in this exercise separate the two factors contributing to higher rates of change. The possible trends that we saw in **Table 5-20** become more numerically significant. The better the soil quality for either radial system, the greater the gain loss with deeper radials. As well, when we increase the soil quality, the amount of

change in source reactance goes down between the shallowest and deepest radial levels. Both of these trends apply to both the 16- and 64-radial systems. However, as we improve the soil quality, the 16-radial source resistance change becomes higher for increasing radial depth, while the 64-radial source resistance change becomes smaller. **Table 5-21**, with data for 7.15 MHz, will tell us if these trends are general or simply accidental.

7.15-MHz Lossless Monopole with Lossless Radials						Table 5-22
Soil quality, number of radials, and radial depth variable.						
# Radials	Soil	Depth m	Gain dBi	TO Angle	Resist	React
16	Vry Poor	0.1	-1.31	60	40.603	10.605
	C 0.001	0.2	-1.34	60	42.03	13.164
	P 5	0.3	-1.37	60	43.301	15.663
Dif			0.06		2.698	5.058
	Average	0.1	-0.73	63	46.438	6.066
	C 0.005	0.2	-0.8	63	47.629	7.798
	P 13	0.3	-0.88	63	48.881	9.584
Dif			0.15		2.443	3.518
	Vry Good	0.1	1.16	69	43.803	5.076
	C 0.0303	0.2	1.08	69	44.8	6.453
	P 20	0.3	0.99	69	45.845	7.762
Dif			0.17		2.042	2.686
128	Vry Poor	0.1	-0.61	60	31.309	-0.709
	C 0.001	0.2	-0.61	60	32.079	1.702
	P 5	0.3	-0.62	60	32.82	4.143
Dif			0.01		1.511	4.852
	Average	0.1	0.21	64	36.199	1.355
	C 0.005	0.2	0.17	63	37.159	3.608
	P 13	0.3	0.14	63	38.157	5.994
Dif			0.07		1.958	4.639
	Vry Good	0.1	1.69	69	38.607	2.385
	C 0.0303	0.2	1.62	69	39.736	4.483
	P 20	0.3	1.54	69	40.926	6.586
Dif			0.15		2.319	4.201

As expected, the 7.15-MHz data shows the effects of higher ground losses and the increasing radial depth as a function of a wavelength. Gain continues to drop more rapidly with radial depth for better soil qualities. As well the trends in the source impedance factors repeat themselves at the new frequency.

However, the largest change in gain at 7.15 MHz occurs with very good soil and is only 0.17 dB. For lesser soils, the gain change is insignificant, and for very good soil, the change is marginal at most. Source resistance and reactance changes remain well within the range of construction variables for virtually any ground-plane monopole antenna system. For virtually any upper MF or lower HF monopole installation, radial depth is unlikely to be a major concern.

8. Does a ground rod below the monopole feedpoint or a perimeter wire around the radials make a significant difference to ground-plane monopole performance?

Two ideas emerge from time to time as almost natural thoughts to those inexperienced with ground-plane monopole antennas. One involves the use of a ground rod at the base of the monopole. Since such a rod is a reasonable practice in terms of lightning safety (assuming that there is a path across the feedpoint), builders wonder if the rod has an affect on the antenna's performance. Some radial system builders also employ a perimeter wire connecting the outer ends of the radials. The motivations are varied, but the general thought seems to be that the wire might overcome inevitable slight variations from true symmetry in the radial system. The emergent question is whether the perimeter wire affects antenna system performance at a more basic level.

To briefly examine the ground-rod question, we shall return to our standard 0.01-m radius lossless monopole at the 3 test frequencies and 3 soil type. We shall try the monopole with the rod alone. Then, we shall use 4 and 16 radials both with and without the rod. The radials will be lossless, with a radius of 0.001 m, and will be buried 0.1-m deep. The ground rod will be 3 m long (about 9.843'), and will have a radius of 0.01 m. The rod will have the same diameter as the monopole, a little over ¾" in diameter. This value is intermediate between common ground rod diameters and the kinds of pipes very often used to support 40-m vertical monopoles. We shall use 1, 2, and finally 3 segments on the rod as we raise the operating frequency. In this way, the segment lengths will approximate those of the remaining antenna system elements.

1.85-MHz Lossless Monopole with Lossless Radials and Ground Rod						
Number of radials, soil conditions, and presence of rod as indicated.						
Soil	# Radials	Rod ?	Gain dBi	TO Angle	Resist	React
Vry Poor	0	Yes	-10.07	62	291.736	-120.899
C 0.001	4	No	-3.91	62	76.642	17.665
P 5	4	Yes	-3.92	62	76.67	15.993
	16	No	-1.84	62	47.453	6.826
	16	Yes	-1.84	62	47.437	6.731
Average	0	Yes	-3.33	67	107.561	2.432
C 0.005	4	No	-0.53	67	56.192	11.657
P 13	4	Yes	-0.5	67	56.51	10.242
	16	No	0.5	67	45.2	5.376
	16	Yes	0.51	67	45.179	5.288
Vry Good	0	Yes	1.19	73	56.83	14.469
C 0.0303	4	No	2.16	73	45.567	6.571
P 20	4	Yes	2.21	73	45.062	6.091
	16	No	2.58	73	41.406	3.491
Table 5-23	16	Yes	2.59	73	41.366	3.461

Table 5-23 presents the 1.85-MHz data. Clearly, a ground rod is no substitute for even the simplest 4-radial ground-plane system. Equally clear is the fact that the radial systems have virtually no effect on the TO angle, since it remains the same for the given soil types even with no radials. At 1.85 MHz, the largest gain difference between using and not using the rod is 0.05 dB, and occurs with the very small 4-radial ground plane. As we enlarge the radial field, the gain differential shrinks to complete insignificance. The one fact that qualifies this analysis is the length of the rod as a function of a wavelength at 1.85 MHz. Although the rod is close to the standard lengths used for lightning protection in U.S. amateur installations (8' to 10'), it is less than 0.02 λ long. The rod will become proportionally longer as we increase the operating frequency without changing the length of the rod itself.

3.6-MHz Lossless Monopole with Lossless Radials and Ground Rod						
Number of radials, soil conditions, and presence of rod as indicated.						
Soil	# Radials	Rod ?	Gain dBi	TO Angle	Resist	React
Vry Poor	0	Yes	-8.9	61	195.202	-128.585
C 0.001	4	No	-4.59	61	85.714	18.334
P 5	4	Yes	-4.59	61	85.181	13.044
	16	No	-1.9	61	44.743	7.675
	16	Yes	-1.91	61	44.855	7.451
Average	0	Yes	-3.89	65	101.359	4.474
C 0.005	4	No	-1.69	65	62.155	11.294
P 13	4	Yes	-1.54	65	60.105	8.83
	16	No	-0.29	65	46.008	5.476
	16	Yes	-0.28	65	45.911	5.283
Vry Good	0	Yes	0.12	71	64.303	19.518
C 0.0303	4	No	1.36	71	48.401	7.865
P 20	4	Yes	1.43	71	47.616	7.447
	16	No	1.94	71	42.537	4.142
Table 5-24	16	Yes	1.94	71	42.477	4.11

In **Table 5-24**, we find the data for 3.6 MHz, where the rod is about 0.036 λ long. At this frequency, we can see some signs of gain change with the rod present, but only for the 4-radial system and only with average or better ground. With very poor soil, there is no change at all in gain for either size radial system. Nor is there any gain change for better soils when we use at least 16 radials in the buried ground plane. With a 4-radial system, the change is more pronounced with average soil than with very good soil. Nevertheless, the amount of change is small, with a maximum value of 0.15 dB.

The fluctuations in the source resistance and reactance values with and without a rod, especially with few radials and poorer soil, provide some insight into why I classify these notes as useful only for general guidance and not for specific design work. To the degree that the ground rod represents a conductive mounting and support system for the monopole, it has some affect on the source impedance. Actual installation techniques for ground-plane monopoles vary widely, with various amounts of metal below the monopole. Therefore, general models cannot provide strict analyses of the source impedance value found at a given monopole, even by taking great pains to replicate the monopoles and radial systems used in one or more of the models that we have examined.

7.15-MHz Lossless Monopole with Lossless Radials and Ground Rod						
Number of radials, soil conditions, and presence of rod as indicated.						
Soil	# Radials	Rod ?	Gain dBi	TO Angle	Resist	React
Vry Poor	0	Yes	-6.32	61	109.616	-62.365
C 0.001	4	No	-4.63	60	98.289	25.748
P 5	4	Yes	-4.37	60	87.017	5.862
	16	No	-1.31	60	40.603	10.605
	16	Yes	-1.37	60	41.516	9.681
Average	0	Yes	-4.37	64	99.182	25.565
C 0.005	4	No	-2.52	64	66.614	8.705
P 13	4	Yes	-2.19	64	62.052	8.936
	16	No	-0.73	63	46.438	6.066
	16	Yes	-0.69	63	46.067	6.113
Vry Good	0	Yes	-1.24	69	74.834	21.119
C 0.0303	4	No	0.37	69	52.073	9.126
P 20	4	Yes	0.45	69	51.131	8.758
	16	No	1.16	69	43.803	5.076
Table 5-25	16	Yes	1.16	69	43.742	5.055

At 7.15 MHz, as shown by the data in **Table 5-25**, the use of a 16-radial system tends to obscure any affects of the ground rod on system performance. However, with a 4-radial system, we do find gain differences with and without the rod at all levels of soil quality. The gain-change due to the presence or absence of the rod is greatest for average soil, but still significant numerically with very poor soil. Nevertheless, as we enlarge the radial field to sizes more likely to be used by serious operators, that is, well above the 16-radial level, the influence of the ground rod on system performance will wholly disappear.

Testing the influence of a perimeter wire around the outer ends of the radials requires a different technique of modeling. To each GW2 initial radial entry, we must add a wire angled to just meet the next radial when the GM entry creates it.

Indeed, the GM entry will replicate the perimeter segment along with the radial itself, thus closing the out circle of wire. All else within the ground-plane monopole antenna system will remain as is, including the ¼-λ radials. Since we might anticipate that the perimeter wire would have its greatest influence with the fewest radials–just as did the perimeter wire used with top loading hat structures–we may confine our sample once more to 4- and 16-radial systems.

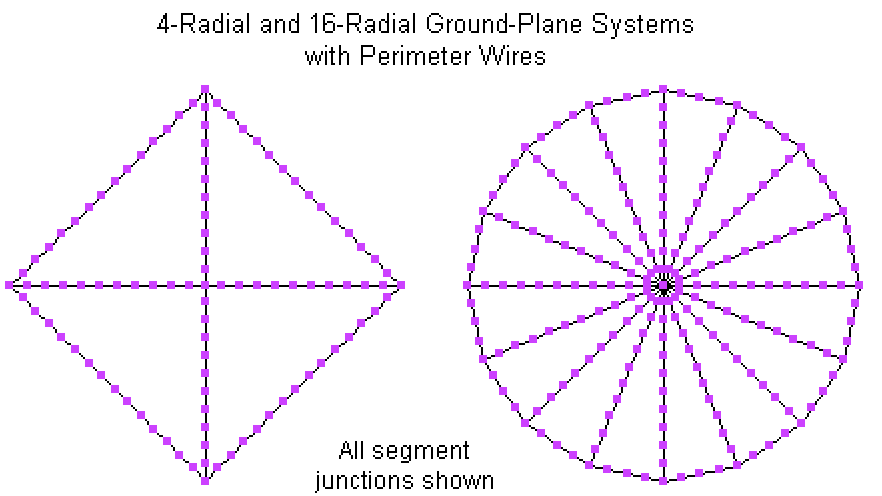


Fig. 5-15

Fig. 5-15 shows the general layout of the radials, the perimeter wire, and the individual segment junctions in the models for 4 and for 16 radials. The following lines sample the 16-radial models, using the 1.85 MHz model as an example. Note that there are now 3 GW2 lines, with the third such entry registering the section of perimeter wire from the initial radial. The first set of coordinates matches the radial end, while the second set of coordinates is calculated to join precisely to the end of the radial created by the GM line. The GM line replicates the sloping wire, the flat radial, and the perimeter section, all rotated by the specified angular separation: 22.5°. Note also that the GM line limit has extended to segment 15, to account for the 4 added segments in the new GW2 entry.

```
GW 1 10 0 0 0 0 0 39.272 .01
GW 2 1 3.65 0 -.1 0 0 0 .001
GW 2 10 40.5125 0 -.1 3.65 0 -.1 .001
GW 2 4 40.5125 0 -.1 37.4286 15.5034 -.1 .001
GM 0 15 0 0 22.5 0 0 0 2 1 2 15
```

1.85-MHz Lossless Monopole and Radials, With and Without Perimeter Wire						
Soil, radials, and presence of perimeter wire as indicated						
# Radials	Soil	Per Wire?	Gain dBi	TO Angle	Resist	React
4	Vry Poor	No	-3.91	62	76.642	17.665
	C 0.001	Yes	-3.87	62	75.008	16.998
	P 5					
	Average	No	-0.53	67	56.192	11.657
	C 0.005	Yes	-0.52	67	58.854	11.745
	P 13					
	Vry Good	No	2.16	73	45.567	6.571
	C 0.0303	Yes	2.16	73	45.556	6.59
	P 20					
16	Vry Poor	No	-1.84	62	47.453	6.826
	C 0.001	Yes	-1.83	62	49.285	7.346
	P 5					
	Average	No	0.5	67	45.2	5.376
	C 0.005	Yes	0.51	67	45.306	5.413
	P 13					
	Vry Good	No	2.58	73	41.406	3.491
	C 0.0303	Yes	2.58	73	41.409	3.495
Table 5-26	P 20					

Table 5-26 provides the modeled data from the 1.85-MHz antennas both without and with the perimeter wire. The model held the radial length constant so that the perimeter wire is in addition to the length of the radial. However, there is no significant difference in any soil category for either radial system. With only 4 radials and very poor soil, we find a very slight numerical gain improvement. It has not practical significance.

As we move upward in frequency to 3.6 MHz, we obtain slightly more noticeable results over very poor soil, as revealed in **Table 5-27**. Gain improves by 0.17 dB with only 4 radials, but the difference disappears as we change to average soil. With very poor soil and 16 radials, the gain with a perimeter wire is actually lower in the modeled result than without the perimeter wire. None of the differences would be operationally measurable.

3.6-MHz Lossless Monopole and Radials, With and Without Perimeter Wire						
Soil, radials, and presence of perimeter wire as indicated						
# Radials	Soil	Per Wire?	Gain dBi	TO Angle	Resist	React
4	Vry Poor	No	-4.59	61	85.714	18.334
	C 0.001	Yes	-4.42	61	77.262	11.429
	P 5					
	Average	No	-1.69	65	62.155	11.294
	C 0.005	Yes	-1.67	65	62.036	11.481
	P 13					
	Vry Good	No	1.36	71	48.401	7.865
	C 0.0303	Yes	1.36	71	48.382	7.902
	P 20					
16	Vry Poor	No	-1.9	61	44.743	7.675
	C 0.001	Yes	-1.98	60	49.979	8.682
	P 5					
	Average	No	-0.29	65	46.008	5.476
	C 0.005	Yes	-0.29	65	46.335	5.497
	P 13					
	Vry Good	No	1.94	71	42.537	4.142
	C 0.0303	Yes	1.94	71	42.549	4.149
Table 5-27	P 20					

At the highest frequency, 7.15 MHz, we find larger numerical differences among the entries in **Table 5-28**. Over very good soil, there are no differences regardless of the radial field size. However, with very poor soil and a 4-radial system, the perimeter wire adds about 0.5-dB gain maximum. As dramatic as is the gain increase (in the present context), when we increase the number of radials to 16, we find an equally dramatic gain drop of nearly 0.3 dB. These values are dramatic only in comparison to the values we obtain at lower frequencies. Operationally, we likely could not detect them, and construction variables would likely override them. Nevertheless, the numerical patterns are both evident and consistent with each other over the span of the modeling tests.

7.15-MHz Lossless Monopole and Radials, With and Without Perimeter Wire						
Soil, radials, and presence of perimeter wire as indicated						
# Radials	Soil	Per Wire?	Gain dBi	TO Angle	Resist	React
4	Vry Poor	No	-4.63	60	98.289	25.748
	C 0.001	Yes	-4.04	60	69.133	2.279
	P 5					
	Average	No	-2.52	64	66.614	8.705
	C 0.005	Yes	-2.5	64	66.61	9.258
	P 13					
	Vry Good	No	0.37	69	52.073	9.126
	C 0.0303	Yes	0.37	69	52.043	9.198
	P 20					
16	Vry Poor	No	-1.31	60	40.603	10.605
	C 0.001	Yes	-1.59	60	51.635	12.302
	P 5					
	Average	No	-0.73	63	46.438	6.066
	C 0.005	Yes	-0.75	63	47.126	5.688
	P 13					
	Vry Good	No	1.16	69	43.803	5.076
	C 0.0303	Yes	1.16	69	43.849	5.081
Table 5-28	P 20					

The data suggest that below ground, perimeter wires do not exert control over the resonance of the antenna system, as they do in top-hat loading schemes. Rather, the ground itself, as an encompassing medium within which we place the radial system–with or without a perimeter wire–constitutes the main controlling factor. As we saw when we looked at various radial lengths, the rapid decline in current along buried radials resulted in only small changes in the source impedance for considerable radial length changes once we passed a length of about 0.2 λ. Therefore, the perimeter wire adds only a small additional path for current compared to the same radial without the perimeter wire.

The slight exception to this general rule occurs with very poor soil with very low conductivity and a low relative permittivity. Under these soil conditions, we find remnants of the sorts of changes that would occur with top hats above ground and with other variations in the radial system. Of course, in a vacuum, the relative permittivity is 1 by definition, and the conductivity is zero. Very poor soil approaches those conditions.

In actual antenna installations, with very poor soil, we find several moderating situations. First, the soil is likely stratified. Therefore, surface measurements that rate the soil as very poor may extend downward to variables depths. If the soil quality changes within the range of radiation penetration, then the results obtained from the models will not obtain. Second, very poor soil may contain materials that ionize when wet, changing the soil character during and after precipitation. Better soil qualities–as defined by high values of conductivity and relative permittivity–are often less susceptible to noticeable changes in quality with changing weather conditions.

Most of the subtle changes in very poor soil disappear as we increase the size of the radial field to 32 or more radials. Over better soils, we find an even closer coincidence of performance reports for fields of 32, 64, and 128 radials. Of course, as the data show, the size of the radial field has only a limited affect on the maximum gain of a ground-plane monopole. The radial field can only limit the losses in the immediate vicinity of the monopole feedpoint. However, it cannot affect significantly the losses incurred beyond the field in the region of reflection for far-field radiation.

The Next Steps

In this chapter, we have surveyed as many practical questions as possible concerning ground-plane monopoles with buried radials. Most of the concerns turned out to have only small effects on the antenna's performance–with one major exception. The number of radials continues to prove itself to be the most influential factor in the performance of a ground-plane monopole with buried radials. While performance characteristics tend to approach stability–that is, a low rate of change–as we pass the 32-radial mark, we saw that even 128 radials did not level the improvement curves. However, with real materials and situations, 64 to 128 radial systems prove to be a practical maximum. With very large radial systems, we saw some advantage in using radials longer than 0.25 λ. However, the benefits were small, and the extra wire might as easily form additional standard-length radials.

Despite the plethora of data, we have not answered every important question concerning ground-plane monopoles. For example, some builders prefer to use elevated radial systems. On the minds of these builders are 2 questions. How high? How many radials? Ground-plane monopoles also have applications in the upper HF range, not to mention their extensive VHF and UHF use. The elevation of the system quickly departs from the ground or near-ground mounting of lower HF monopoles and ranges from a quarter-wavelength to many 10s of wavelengths. These are not the only remaining questions, but they will occupy us for another chapter.

6. Elevated Radials

An alternative to burying ground radials is placing them above ground. Here, we need to distinguish between a NEC-2 modeling work-around and the actual physical placement of radials above ground. Since NEC-2 cannot accept wires below ground, models for a while tried placing radials above but very close to the ground–as close as 1E-5 λ. Although the practice gave some ballpark results, the advent of NEC-4 (actually, NEC-3) allowed for much more precise modeling of buried radial systems.

In this chapter, we are concern with placing radials wholly above ground as a method of ground-plane monopole construction. What sort of construction counts as an elevated radial system depends on the circle of operating interests.

1. *Upper MF and Lower HF*: Low-band operators consider any radial system that is not buried to be elevated. Al Christman, K3LC, has done perhaps the most thorough job of modeling and describing low-band elevated radial systems, the latest installments of his work appearing in a 2-part series of articles in *The National Contest Journal* (January/February and March/April of 2005). The notes within this chapter on the subject are indebted to his efforts.

2. *Upper HF*: On 20 through 10 meters, amateurs–especially those with restricted space for antennas–have used vertical monopoles. Mounting positions have ranged from ground level up to over a wavelength above the surface. Common elevated mounting positions include garages, barns, roofs, and chimneys. Indeed, the amateur marketplace offers many multi-band ground-plane monopoles, although most makers leave the ground-plane elements for the buyer to invent and implement.

3. *VHF and UHF*: Mobile and repeater operations in the amateur VHF and UHF allocations make the simple ground-plane monopole a popular utility antenna. Operators can construct one from available materials with good success. The height of these antennas ranges from 1 to very many wavelengths

above ground, depending on the application.

The answers to many common questions about elevated radial systems are implicit in the survey of monopole that we did in Chapter 3. However, in this chapter, we shall make the implicit explicit, at least so far as NEC-4 modeling may allow. Indeed, the specific questions posed by each frequency range and its typical range on installations will differ as we proceed from MF to UHF. So let's start at the bottom–of the frequency range and of the span of heights above ground.

Upper MF and Lower HF Elevated Radial Systems

When Al Christman suggested some years ago that a small number of elevated radials might do the work of very large fields of buried radials, his work met opposition and disbelief. However, data tend to confirm the suggestion, so long as the antenna meets certain criteria. For example, since the structure will employ fewer radials than a buried system normally uses, special attention to symmetry is necessary.

An individual attracted to such a system usually has a number of questions. How many elevated radials will replicate or even exceed the buried system's performance? How high off the ground must we place the monopole base and the radials for optimal performance? To develop such answers as NEC-4 models may provide, I went through series of models for our test frequencies, 1.85, 3.6, and 7.15 MHz. I used the same monopoles and radials used in the buried radial exercises. The lossless monopoles use a uniform 0.01-m diameter, and the equally lossless radials use a 0.001-m radius. All radials are exactly ¼ λ long at the operating frequency, and each monopole is resonant over perfect ground without radials. The tests involve very poor, average, and very good soil. Therefore, we shall be able to compare directly the results of our elevated-radial tests with those for buried radials. To answer the question of how many radials we need in an elevated system, the tests cover models with 4, 6, and 8 elevated radials.

Because these exercises work in physical measures, the element radii change from band to band when measured as a fraction of a wavelength. For the elevated radial tests, I retained this practice. For each model, I used a series of stepped heights above ground for the monopole base and the radials. The steps range from virtually touching the ground to 3 meters. The following listing provides a reference for converting the metric heights into inches and into fractions of a wavelength.

Frequency MHz				1.85	3.6	7.15
Wavelength meters				162.05	83.276	41.929
Step	meters	inches	feet	Fraction of a Wavelength at Listed Frequency		
1	0.001	0.0394	–-	0.0000062	0.000012	0.0000239
2	0.01	0.3937	–-	0.0000617	0.00012	0.0002385
3	0.1	3.937	0.328	0.000617	0.0012	0.002386
4	1	39.37	3.281	0.00617	0.0120	0.02386
5	2	78.74	6.562	0.01234	0.0240	0.04771
6	3	118.11	9.843	0.01851	0.0360	0.07156

The most logical physical heights range between 1 and 3 meters above ground. Indeed, a 3-meter height (close to 10') provides a physical safety margin for anyone straying into the antenna field. However, the progression of tests from very close to the ground gives us a change to see the transition in performance characteristics as we raise the antenna.

Physical measures correspond most closely to the way in which radio amateurs plan antenna installations. However, they do not give a clean curve of values based on measurements in terms of a wavelength at each frequency. The effects of the ground beneath the antennas vary not only with the ground constants, but also with frequency. So we could not expect congruent curves for the 3 frequencies under any conditions.

The models for the tests are very basic and follow patterns used for earlier tests. The key changes occur in only a few lines. GW1 changes the monopole length: 39.272 m for 1.85 MHz, 20.113 m for 3.6 MHz, and 10.084 m for 7.15 MHz. GW 2 changes the radial length according to frequency: 40.5125 m, 20.8189 m, and 10.4823 m for the 3 listed frequencies. The first GM line that specifies how many radials, changes its angle of separation, and gives the number of additional replications: 90° and 3 for 4 radials, 60° and 5 for 6, and 45° and 7 for 8. The basic model uses a base height of zero to set up the model, and the second GM line elevates the antenna through the steps. Finally, the GN line contains the soil qualities and the FR line gives the operating frequency. The single sample model allows you to identify each variable and its place within the model.

```
CM 3.6-MHz monopole, .01-m radius above ground
CM 4-8 radials, 1/4-wl long, 0.001-m radius
CM vp-vg soil, .001-m - 3 m heights
CE
GW 1 11 0 0 20.113 0 0 0 .01
GW 2 11 0 0 0 20.8189 0 0 .001
GM 0 5 0 0 60 0 0 0 2 1 2 11
GM 0 0 0 0 0 0 0 .001
GE -1 -1 0
GN 2 0 0 0 13 .005
EX 0 1 11 0 1 0
FR 0 1 0 0 3.6 1
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

Initial tests will model the antennas for each step over each soil type for a single frequency. Some results, such as the maximum gain, are amenable to graphing. However, other information must remain in tabular form and summary commentary.

1.85-MHz Data: **Tables 6-1**, **6-2**, and **6-3** list the performance data for the 160-m monopole with 4, 6, and 8 radials, with each table covering the 3 soil types and the 6 height steps.

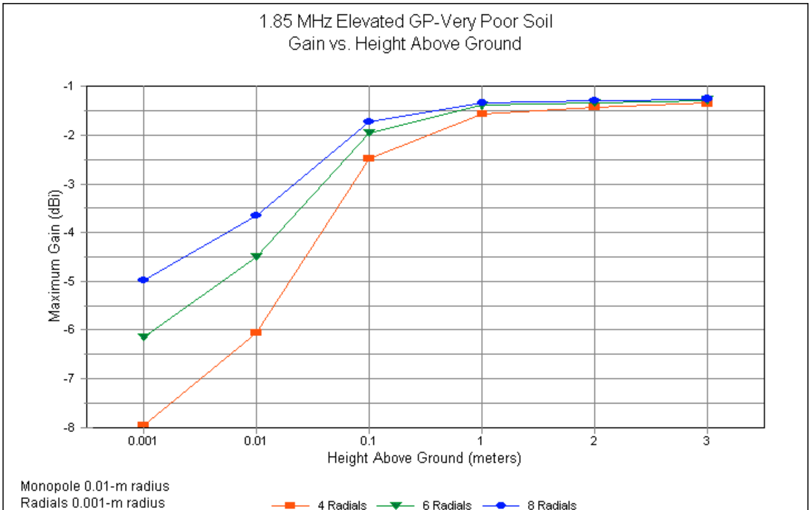
1.85-MHz Lossless Monopole Above Ground						Table 6-1
# Radials	Soil	Height m	Gain dBi	TO Angle	Resist	React
4	Vry Poor	0.001	-7.96	63	207.244	-24.868
	C 0.001	0.01	-6.07	63	117.773	84.137
	P 5	0.1	-2.48	63	47.114	26.714
		1	-1.56	63	37.188	-7.638
		2	-1.43	63	35.381	-13.942
		3	-1.35	64	33.886	-16.962
	Average	0.001	-5.77	67	198.861	-55.525
	C 0.005	0.01	-4.74	67	140.473	196.404
	P 13	0.1	0.33	67	43.437	36.203
		1	0.83	68	38.473	-3.392
		2	0.94	68	36.875	-10.025
		3	1	68	35.657	-13.499
	Vry Good	0.001	-2.38	73	131.899	7.298
	C 0.0303	0.01	-1.16	73	92.392	193.846
	P 20	0.1	2.18	73	43.892	30.915
		1	2.71	73	38.694	-3.605
		2	2.87	73	36.91	-9.953
		3	2.95	73	35.792	-12.66

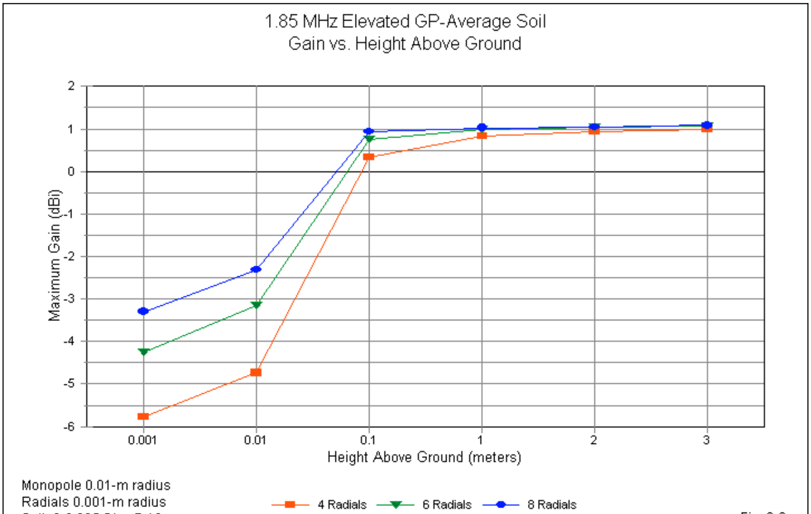
1.85-MHz Lossless Monopole Above Ground						Table 6-2
# Radials	Soil	Height m	Gain dBi	TO Angle	Resist	React
6	Vry Poor	0.001	-6.15	62	134.395	-2.828
	C 0.001	0.01	-4.5	62	80.706	45.803
	P 5	0.1	-1.95	62	41.475	11.506
		1	-1.39	63	35.617	-11.184
		2	-1.33	63	34.322	-15.118
		3	-1.28	64	33.204	-16.944
	Average	0.001	-4.25	67	140.279	-37.65
	C 0.005	0.01	-3.15	67	97.404	119.39
	P 13	0.1	0.76	67	39.325	19.818
		1	0.98	68	37.096	-6.714
		2	1.03	68	36.039	-11
		3	1.06	68	35.095	-13.322
	Vry Good	0.001	-1.22	73	101.165	-1.376
	C 0.0303	0.01	0.13	73	68.793	125.085
	P 20	0.1	2.56	73	40.236	18.16
		1	2.84	73	37.484	-5.542
		2	2.94	73	36.253	-10.063
		3	3	73	35.388	-11.926

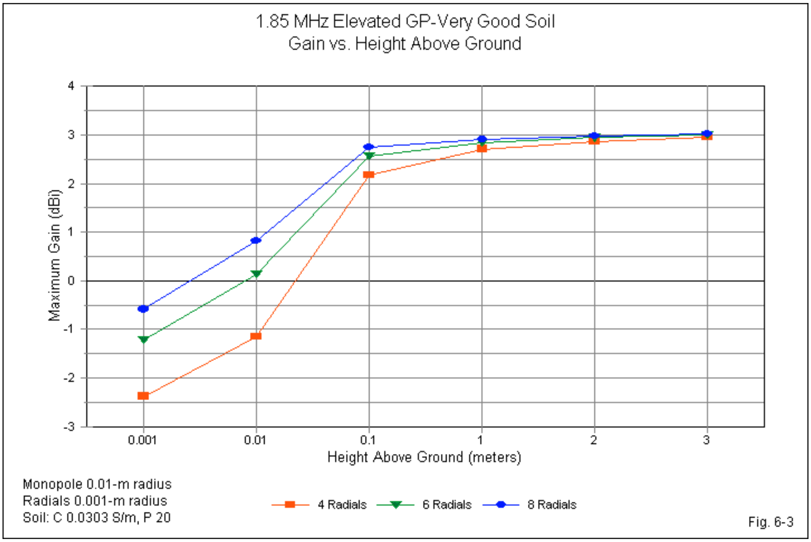
1.85-MHz Lossless Monopole Above Ground						Table 6-3
# Radials	Soil	Height m	Gain dBi	TO Angle	Resist	React
8	Vry Poor	0.001	-4.98	62	100.656	3.44
	C 0.001	0.01	-3.65	62	65.516	28.412
	P 5	0.1	-1.73	62	39.265	4.975
		1	-1.34	63	35.09	-12.239
		2	-1.3	63	34.031	-15.041
		3	-1.26	64	33.005	-16.304
	Average	0.001	-3.3	67	112.714	-29.921
	C 0.005	0.01	-2.31	67	80.386	83.239
	P 13	0.1	0.93	67	37.772	12.363
		1	1.02	68	36.692	-7.843
		2	1.05	68	35.824	-10.942
		3	1.08	68	34.693	-12.693
	Vry Good	0.001	-0.59	73	87.617	-5.176
	C 0.0303	0.01	0.82	73	58.828	93.239
	P 20	0.1	2.74	73	38.627	12.107
		1	2.9	73	37.029	-6.169
		2	2.97	73	36.037	-9.719
		3	3.01	73	35.271	-11.13

Perhaps the most immediate result that we may draw from the tables is that for each soil type, the 3-m results are very close to each other, regardless of the number of radials. As we move the antenna closer to the ground, results vary more radically as we change the number of radials. Second, the table may give the impression that the performance results for a 0.1-m height are usable for an elevated radial system. The gain and source resistance columns appear promising in this regard. However, if we examine the reactance values for height from 1 to 3 m, we find a total difference among them that is less than the difference between 0.1 m and 1m. As well, given the fact that wires stretch with time, maintaining each radial at least 0.1 m above ground would be improbable. The overall stability of the system between 1 and 3 meters above ground appears to be the more promising route to a successful elevated radial monopole.

The tables list the model reports by the number of radials. We may re-arrange the information graphically to show the gain curves for each ground quality level, thus better seeing the differences made by the number of radials. **Fig. 6-1**, **6-2**, and **6-3** fulfill the need.


1.85 MHz Elevated GP-Very Poor Soil
Gain vs. Height Above Ground
Maximum Gain (dBi)
-1
-2
-3
-4
-5
-6
-7
-8
0.001
0.01
0.1
1
2
3
Height Above Ground (meters)
Monopole 0.01-m radius
Radials 0.001-m radius
Soil: C 0.001 S/m, P 5
4 Radials
6 Radials
8 Radials
Fig. 6-1


1.85 MHz Elevated GP-Average Soil
Gain vs. Height Above Ground
Maximum Gain (dBi)
2
1
0
-1
-2
-3
-4
-5
-6
0.001
0.01
0.1
1
2
3
Height Above Ground (meters)
Monopole 0.01-m radius
Radials 0.001-m radius
Soil: C 0.005 S/m, P 13
4 Radials
6 Radials
8 Radials
Fig. 6-2



Except for differences in the non-linear portion of the X-axis, the curves come together as we reach a height of 1 m. With either 6 or 8 radials, the curves between 2 and 3 meters essentially overlap, regardless of soil type. Of course, the differences in soil qualities create differences in the gain levels for each graph. But for any given soil quality, a 6- to 8-radial system suffices to obtain maximum performance from the antenna. As we move above ground, we may also notice that the system is capacitively reactance by an amount that levels out as we raise the base height. Above ground, the antenna acts more and more like the free-space models that we examined in Chapter 3. Indeed, we may even wish to change perspective on the lower gain of the antenna over very poor soil. Instead of looking at the ground as a poor replica of a perfect ground, we may see it as a closer approximation of free space than we obtain from average and very good grounds.

3.6-MHz Data: **Tables 6-4**, **6-5**, and **6-5** list the performance data for the 80-m monopole with 4, 6, and 8 radials, with each table covering the 3 soil types and the 6 height steps.

3.6-MHz Lossless Monopole Above Ground						Table 6-4
# Radials	Soil	Height m	Gain dBi	TO Angle	Resist	React
4	Vry Poor	0.001	-7.5	61	167.755	40.124
	C 0.001	0.01	-4.42	61	69.994	49.848
	P 5	0.1	-2.31	61	40.502	8.981
		1	-1.62	62	33.2	-14.981
		2	-1.44	63	30.847	-19.217
		3	-1.33	63	29.137	-21.087
	Average	0.001	-6.08	65	184.543	-68.231
	C 0.005	0.01	-3.86	65	96.637	118.607
	P 13	0.1	-0.28	65	41.162	20.565
		1	0.15	66	36.225	-10.737
		2	0.26	67	33.969	-16.308
		3	0.33	67	32.185	-19.012
	Vry Good	0.001	-2.91	71	133.446	-31.429
	C 0.0303	0.01	-0.92	71	76.759	139.186
	P 20	0.1	1.78	71	42.114	19.419
		1	2.23	71	37.175	-9.197
		2	2.38	72	35.02	-14.637
		3	2.47	72	33.392	-17.305

3.6-MHz Lossless Monopole Above Ground						Table 6-5
# Radials	Soil	Height m	Gain dBi	TO Angle	Resist	React
6	Vry Poor	0.001	-5.54	61	103.484	29.959
	C 0.001	0.01	-3.27	61	53.003	24.919
	P 5	0.1	-1.92	62	36.822	-0.261
		1	-1.51	63	32.253	-15.869
		2	-1.38	63	30.333	-18.355
		3	-1.29	65	28.829	-19.435
	Average	0.001	-4.59	65	131.401	-36.533
	C 0.005	0.01	-2.47	65	69.654	68.954
	P 13	0.1	0.08	65	37.824	8.679
		1	0.25	66	35.321	-12.012
		2	0.31	67	33.514	-15.624
		3	0.35	67	31.927	-17.453
	Vry Good	0.001	-1.77	71	102.707	-25.924
	C 0.0303	0.01	0.23	71	58.934	88.193
	P 20	0.1	2.1	71	39.134	9.846
		1	2.32	71	36.409	-9.7
		2	2.41	72	34.693	-13.577
		3	2.48	72	33.234	-15.556

3.6-MHz Lossless Monopole Above Ground						Table 6-6
# Radials	Soil	Height m	Gain dBi	TO Angle	Resist	React
8	Vry Poor	0.001	-4.36	61	76.877	20.704
	C 0.001	0.01	-2.71	61	46.163	14.018
	P 5	0.1	-1.75	61	35.313	-4.025
		1	-1.47	62	31.932	-15.647
		2	-1.36	63	30.167	-17.33
		3	-1.28	63	28.732	-18.081
	Average	0.001	-3.65	65	105.249	-21.84
	C 0.005	0.01	-1.79	65	59.449	46.195
	P 13	0.1	0.21	65	36.626	3.411
		1	0.27	66	35.103	-12.038
		2	0.32	67	33.418	-14.717
		3	0.35	67	31.875	-16.168
	Vry Good	0.001	-1.14	71	88.863	-23.154
	C 0.0303	0.01	0.8	71	51.776	64.664
	P 20	0.1	2.24	71	37.884	5.262
		1	2.35	71	36.174	-9.513
		2	2.42	72	34.615	-12.584
		3	2.49	72	33.205	-14.239

The individual numbers for the 3.6-MHz data differ from those of the 1.85-MHz data, but the trends persist. Despite being higher as a fraction of a wavelength, the model at 0.1-m above ground remains outside the range of total system stability, where that idea includes all of the information categories. As we move to 80 meters, we can be concerned not only with the changes in the source reactance, but as well with the TO angle. At base heights between 2 and 3 m, the antenna achieves the smallest angle with respect to the horizon, regardless of soil quality. Perhaps the one additional noticeable feature is the fact that as we add more radials (in the 4 to 8 range), the differences in both resistance and reactance in the 1 to 3 m range go down. However, at 80 meters, we are talking of resistance differences of less than 5 Ω and reactance differences of less than 10 Ω.

For comparative purposes, **Fig. 6-4**, **6-5**, and **6-6** present the gain data, rearranged according to soil type. Within each graph, we can see the effects of having 4, 6, or 8 radials in the elevated system.

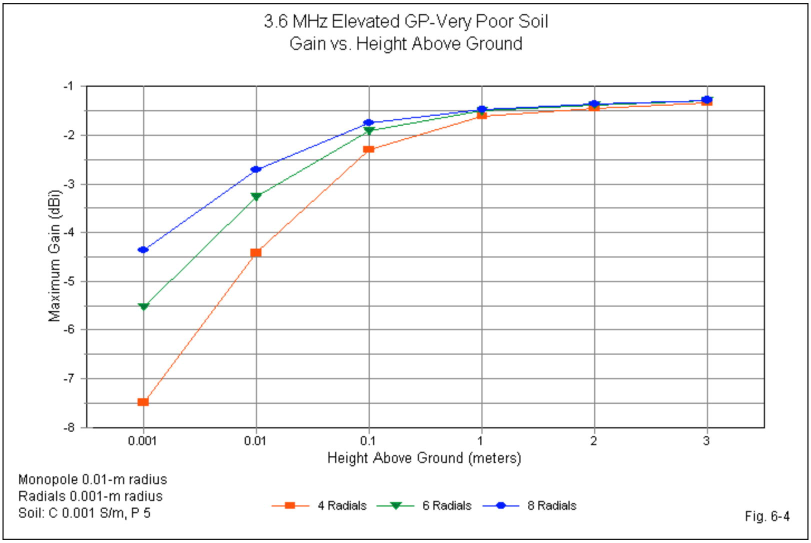

3.6 MHz Elevated GP-Very Poor Soil
Gain vs. Height Above Ground
Maximum Gain (dBi)
-1
-2
-3
-4
-5
-6
-7
-8
0.001
0.01
0.1
1
2
3
Height Above Ground (meters)
Monopole 0.01-m radius
Radials 0.001-m radius
Soil: C 0.001 S/m, P 5
4 Radials
6 Radials
8 Radials

Fig. 6-4

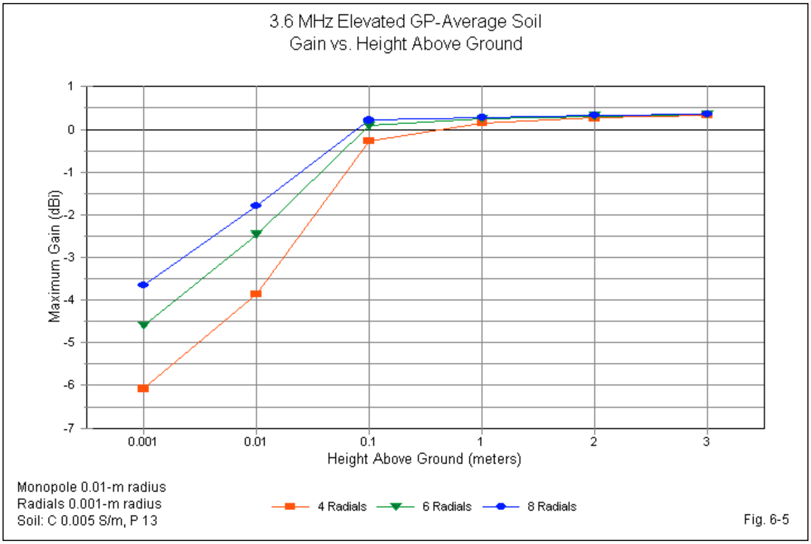
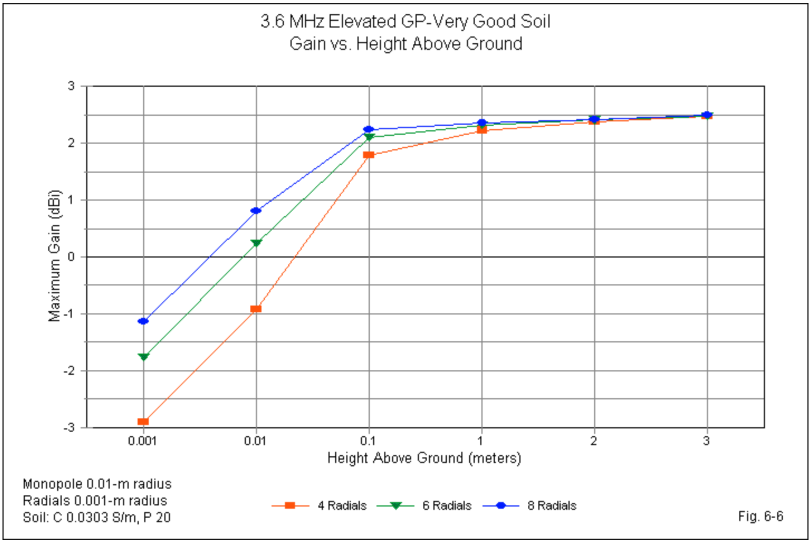

3.6 MHz Elevated GP-Average Soil
Gain vs. Height Above Ground
Maximum Gain (dBi)
1
0
-1
-2
-3
-4
-5
-6
-7
0.001
0.01
0.1
1
2
3
Height Above Ground (meters)
Monopole 0.01-m radius
Radials 0.001-m radius
Soil: C 0.005 S/m, P 13
4 Radials
6 Radials
8 Radials

Fig. 6-5



The curves exhibit the expected odd bends in the non-linear portion to the left. However, the right side of each graph shows the joining of the 3 curves representing different radial field sizes. For heights of 2 and 3 m, all three radial fields produce almost identical results, for any given soil quality level. The improved adequacy of the 4-radial system with respect to gain stems from the fact that the base height is higher than at 1.85 MHz, when we measure the height as a fraction of a wavelength. Even over very poor soil at a base height of 3 m, we find only a 0.05-dB difference in maximum gain as we move from 4 to 8 radials. (However, keep in mind that an 8-radial system may be more forgiving of slight lapses from true symmetry.)

7.15-MHz Data: **Tables 6-7**, **6-8**, and **6-9** list the performance data for the 40-m monopole with 4, 6, and 8 radials, with each table covering the 3 soil types and the 6 height steps.

7.15-MHz Lossless Monopole Above Ground						Table 6-7
# Radials	Soil	Height m	Gain dBi	TO Angle	Resist	React
4	Vry Poor	0.001	-5.72	60	107.265	74.343
	C 0.001	0.01	-2.66	60	45.668	30.13
	P 5	0.1	-1.61	61	34.49	-1.658
		1	-1.1	62	29.306	-18.675
		2	-0.85	63	26.698	-21.227
		3	-0.64	65	24.749	-21.987
	Average	0.001	-6.64	63	197.497	-47.336
	C 0.005	0.01	-2.52	64	62.507	70.239
	P 13	0.1	-0.5	64	37.932	7.136
		1	-0.14	65	32.744	-16.557
		2	0	67	29.606	-20.543
		3	0.1	68	27.142	-22.077
	Vry Good	0.001	-3.56	68	134.828	-57.15
	C 0.0303	0.01	-0.84	69	64.064	92.661
	P 20	0.1	1.21	69	40.424	8.868
		1	1.63	70	34.787	-14.828
		2	1.76	71	31.612	-19.429
		3	1.86	72	29.305	-21.535

7.15-MHz Lossless Monopole Above Ground						Table 6-8
# Radials	Soil	Height m	Gain dBi	TO Angle	Resist	React
6	Vry Poor	0.001	-3.87	60	67.72	40.041
	C 0.001	0.01	-1.99	61	38.788	12.92
	P 5	0.1	-1.4	61	32.705	-7.057
		1	-1.05	62	28.937	-17.68
		2	-0.83	63	26.556	-19.222
		3	-0.63	65	24.69	-19.516
	Average	0.001	-5.03	63	135.936	-12.301
	C 0.005	0.01	-1.48	64	48.763	38.378
	P 13	0.1	-0.24	64	35.599	-0.865
		1	-0.09	65	32.279	-15.968
		2	0.02	67	29.439	-18.572
		3	0.1	68	27.074	-19.668
	Vry Good	0.001	-2.4	68	103.413	-39.437
	C 0.0303	0.01	0.15	69	51.007	56.816
	P 20	0.1	1.47	69	38.053	1.884
		1	1.67	70	34.402	-13.96
		2	1.77	71	31.508	-17.392
		3	1.86	72	29.004	-19.117

7.15-MHz Lossless Monopole Above Ground						Table 6-9
# Radials	Soil	Height m	Gain dBi	TO Angle	Resist	React
8	Vry Poor	0.001	-2.91	60	53.008	24.657
	C 0.001	0.01	-1.7	61	36.053	5.669
	P 5	0.1	-1.31	61	31.98	-8.993
		1	-1.04	62	28.813	-16.596
		2	-0.82	63	26.51	-17.598
		3	-0.62	65	24.672	-17.875
	Average	0.001	-3.93	63	103.514	0.239
	C 0.005	0.01	-1.06	64	44.026	24.371
	P 13	0.1	-0.16	64	34.874	-4.145
		1	-0.08	65	32.185	-15.071
		2	0.02	67	29.404	-17.115
		3	0.1	68	27.057	-18.065
	Vry Good	0.001	-1.74	69	88.664	-30.74
	C 0.0303	0.01	0.59	69	46.063	40.394
	P 20	0.1	1.57	69	37.167	-1.327
		1	1.68	70	34.317	-13.031
		2	1.77	71	31.493	-15.945
		3	1.86	72	28.999	-17.523

As we further increase the operating frequency, ground effects further reduce the maximum gain possible from any given soil quality relative to the lower test frequencies. Nevertheless, most of the trends previously noted remain in effect, with a few oddities that are the likely result of the increasing fraction of a wavelength for each physical height. For example, at the lowest height in the set, the reported gain is higher for very poor soil than for average soil. The numbers here are of academic interest only, since in physical terms, we could not replicate the model. Even the small variations of stones and soil under the radial wire would change the modeled situation, which presumes a smooth flat ground surface. Nevertheless, the very low models do provide a means of showing the elevated radial system's instability until it reaches a certain minimum height above ground.

Fig. 6-7, **6-8**, and **6-9** complete the series of maximum gain graphs separated by soil quality. At heights of 2 and 3 m above ground, note the tightening coincidence among all 3 curves in each graph. At 3 m, the maximum gain difference (with very poor soil) is only 0.02 dB between 4 and 8 radials.

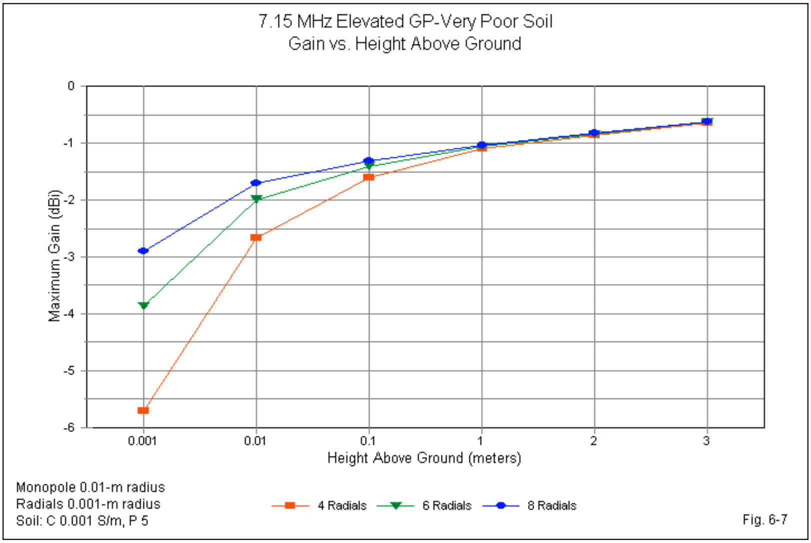

7.15 MHz Elevated GP-Very Poor Soil
Gain vs. Height Above Ground
Maximum Gain (dBi)
0
-1
-2
-3
-4
-5
-6
0.001
0.01
0.1
1
2
3
Height Above Ground (meters)
Monopole 0.01-m radius
Radials 0.001-m radius
Soil: C 0.001 S/m, P 5
4 Radials
6 Radials
8 Radials

Fig. 6-7

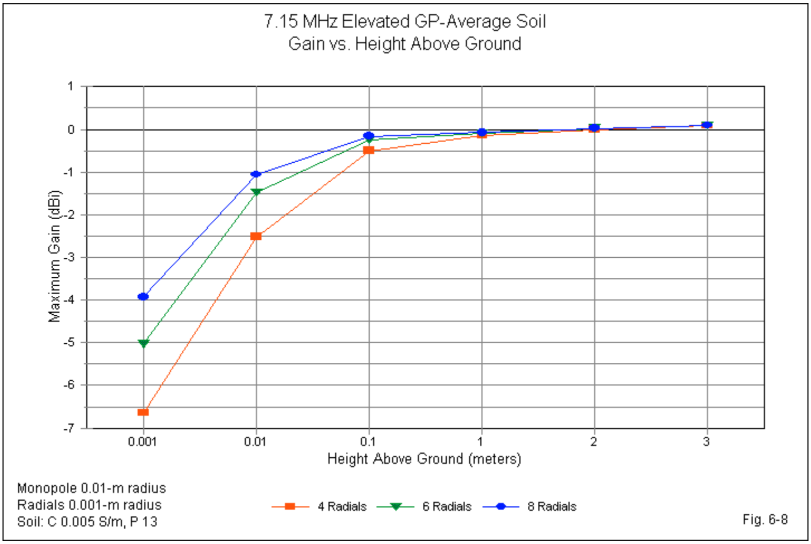
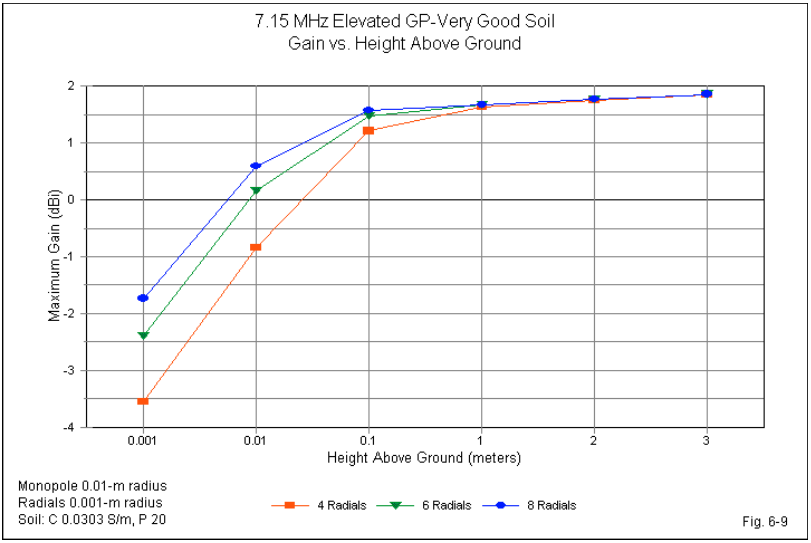

7.15 MHz Elevated GP-Average Soil
Gain vs. Height Above Ground
Maximum Gain (dBi)
1
0
-1
-2
-3
-4
-5
-6
-7
0.001
0.01
0.1
1
2
3
Height Above Ground (meters)
Monopole 0.01-m radius
Radials 0.001-m radius
Soil: C 0.005 S/m, P 13
4 Radials
6 Radials
8 Radials

Fig. 6-8



In practical terms, a lower-HF elevated radial system performs best with radials about 2 to 3 m above ground, regardless of the band (between 160 and 40 meters) and regardless of soil type. The 3-m height becomes slightly more optimal in terms of the TO angle as we increase frequency. From the slopes of the curves, we might guess that additional height might be useful in achieving slight improvements in maximum gain, but heights much above 3 m become impractical for upper MF and lower HF structures. Indeed, even a 3-m elevated system may present construction problems.

The models cannot show a special aspect of elevated radial systems that may compromise their performance. If the user installs a matching network at the base of the monopole, near the feedpoint, it requires a good RF ground return to the energy source. In many buried systems, the ground radials performed this function in addition to their antenna function. Although we may run a ground line and rod from the radials for safety purposes, that measure will not assure a good RF ground return to the energy source. As well, the coax braid for the connecting transmission line may or may not suffice to provide a path with as close to zero

RF voltage drop as may be feasible. As a result, if an elevated radial system fails to give promised performance, the fault might not lie in the radials or their height above ground.

One more basic question remains concerning elevated radial systems: how do they compare with buried radial systems. To provide some sort of answer, we may return to some data presented in the preceding chapter. The antennas will be identical, except that the buried radials will have a downward slope of 0.1 m along the first wire segment. **Table 6-10** presents the data for 1.85 MHz for buried radial systems between 4 and 128 radials.

1.85-MHz Perfect Monopole with Perfect Radials and Various Soil Qualities						
Monopole length: resonant with perfect ground; radials 1/4 wavelength						
Soil		# Radials	Gain dBi	TO Angle	Resist	React
Very Poor		4	-3.91	62	76.642	17.665
C 0.001, P 5		8	-2.76	62	59.317	11.805
		16	-1.84	62	47.453	6.826
		32	-1.22	62	40.047	2.201
		64	-0.91	62	36.143	-1.256
		128	-0.78	62	33.289	-3.252
Average		4	-0.53	67	56.912	11.657
C 0.005, P 13		8	0.04	67	50.161	8.009
		16	0.5	67	45.2	5.376
		32	0.89	67	41.31	3.205
		64	1.15	67	38.448	1.266
		128	1.29	67	36.696	-0.269
Very Good		4	2.16	73	45.567	6.571
C 0.0303, P 20		8	2.39	73	43.236	4.779
		16	2.58	73	41.406	3.491
		32	2.75	73	39.83	2.425
		64	2.9	73	38.448	1.488
Table 6-10		128	3.01	73	37.347	0.667

To see how the buried radial systems compare with the elevated radial system on 160 m, let's use 8 radials at a height of 3 m. **Fig. 6-10** shows the resulting maximum gain curves for each soil type. The level lines represent the elevated radial system, while the curved lines show the buried radial system gain increase as we raise the number of radials.

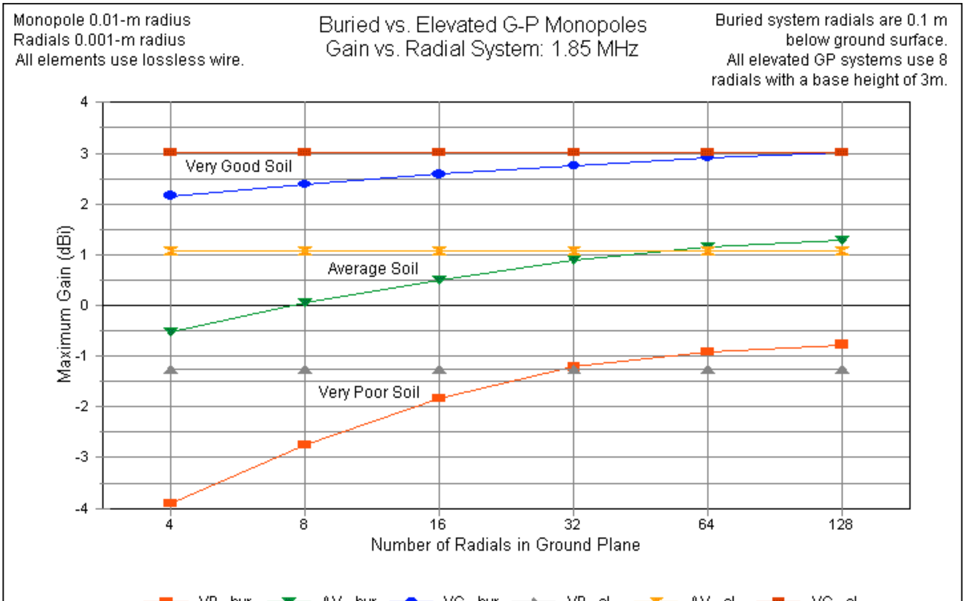


Fig. 6-10

Over very poor soil, a 32-radial buried system begins to outperform the best of the elevated systems. As the soil improves to average, the buried system must have over 40 radials to outperform the elevated system over the same kind of soil. As we move to very good soil, the buried system barely catches up to the elevated system with 128 below ground radials.

As we have seen, curves do not necessarily remain the same as we raise the operating frequency. **Table 6-11** provides the review data for buried radial systems at 3.6 MHz.

3.6-MHz Perfect Monopole with Perfect Radials and Various Soil Qualities						
Monopole length: resonant with perfect ground; radials 1/4 wavelength						
Soil		# Radials	Gain dBi	TO Angle	Resist	React
Very Poor		4	-4.59	61	85.714	18.334
C 0.001, P 5		8	-3.05	61	60.331	14.096
		16	-1.9	61	44.743	7.675
		32	-1.26	61	36.921	1.803
		64	-0.99	61	33.513	-1.862
		128	-0.88	61	32.045	-3.672
Average		4	-1.69	65	62.155	11.294
C 0.005, P 13		8	-0.93	65	52.811	7.955
		16	-0.29	65	46.008	5.476
		32	0.21	65	40.869	3.139
		64	0.5	65	37.508	0.89
		128	0.63	65	35.747	-0.752
Very Good		4	1.36	71	48.401	7.865
C 0.0303, P 20		8	1.67	71	45.096	5.735
		16	1.94	71	42.537	4.142
		32	2.17	71	40.385	2.853
		64	2.35	71	38.595	1.717
Table 6-11		128	2.47	71	37.298	0.745

As we noted in the last chapter, at 64 and 128 radials, the buried radial system shows an impedance that is below the standard perfect-ground value of 36 Ω. Such impedance values provide another reason for thinking of very poor soil more as a less efficient form of free-space below the antenna than as a lossy reflective surface. In free space, the impedance of a resonant monopole system would be around 22-24 Ω.

Nevertheless, our primary interest in the table is using its gain reports to compare with the 8-radial system elevated 3 meters above ground. See **Fig. 6-11**. The crossing points for 3.6 MHz are virtual the same as those for 1.85 MHz. Only the difference in the Y-axis scale confirms that the two graphs are indeed separate records. Besides examining **Fig. 6-11**, compare the values in this table with the values for heights from 1 to 3 meters above ground in **Tables 6-5** through **6-7**.

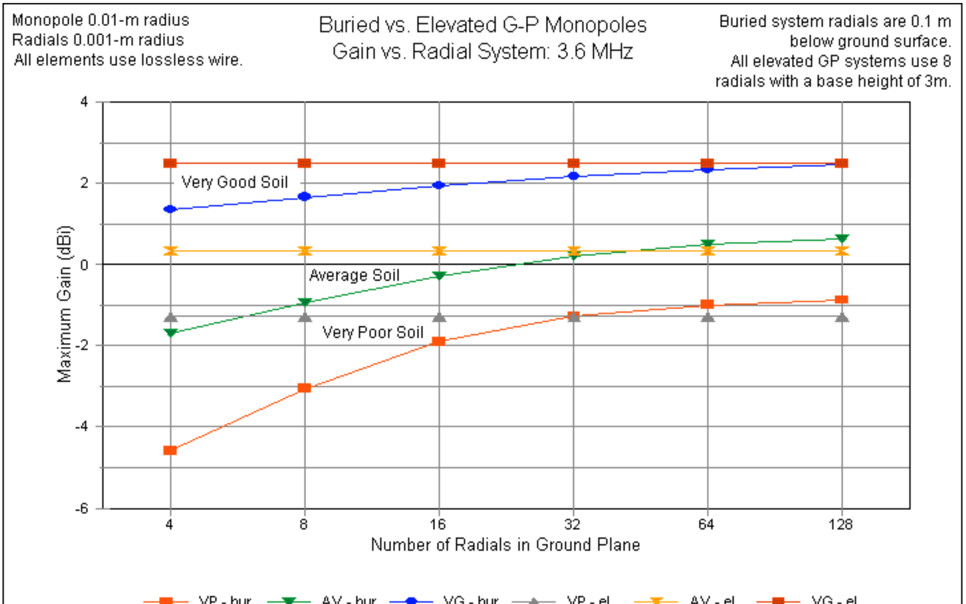


Fig. 6-11

At 7.15 MHz, we begin to see some differences in detail, although not in the general trends. **Table 6-12** provides the data for buried radial system at the highest of our test frequencies. Once more, the numerical values are lower than for either of the lower test frequencies, but the general patterns remain intact. With very poor soil, we encounter source resistance values below 36 Ω from 32 radials onward, and again at 128 radials with average soil. You may also wish to compare the reactance values with those reported from the elevated radial models for the lower three heights in the survey. Virtually all of the tables in all of the chapters contain far more points on interest than we can possibly report on in the commentaries.

7.15 Perfect Monopole with Perfect Radials and Various Soil Qualities						
Monopole length: resonant with perfect ground; radials 1/4 wavelength						
Soil		# Radials	Gain dBi	TO Angle	Resist	React
Very Poor		4	-4.63	60	98.337	25.778
C 0.001, P 5		8	-2.59	60	59.252	21.452
		16	-1.31	60	40.65	10.647
		32	-0.79	60	33.803	3.105
		64	-0.61	60	31.355	-0.667
		128	-0.54	60	30.388	-2.277
Average		4	-2.52	64	66.662	8.746
C 0.005, P 13		8	-1.57	63	55.174	7.304
		16	-0.73	63	46.485	6.107
		32	-0.1	63	39.943	3.912
		64	0.2	63	36.346	1.397
		128	0.31	63	34.613	-0.264
Very Good		4	0.36	69	52.12	9.167
C 0.0303, P 20		8	0.79	69	47.419	6.832
		16	1.15	69	43.85	5.117
		32	1.46	69	40.925	3.714
		64	1.69	69	38.654	2.426
Table 6-12		128	1.8	69	37.2	1.338

When we graph the maximum gain for the buried radials at 7.15 MHz and compare the results to those for an 8-radial 3-m high elevated system, we find some departures from the patterns for 1.85 and 3.6 MHz. **Fig. 6-12** shows the results of the comparison.

Allowing for some compression of lines that might obscure tracking at first sight, the patterns for very good and average soils are essentially the same as in the past graphs. With very good soil, the buried radial system just catches the elevated system at 128 radials. With average soil, the crossing point where the buried radial system shows better gain than the elevated system is still in the vicinity of 40-50 radials. However, with very poor soil, the buried-radial system does not surpass the elevated system until we reach 64 radials.

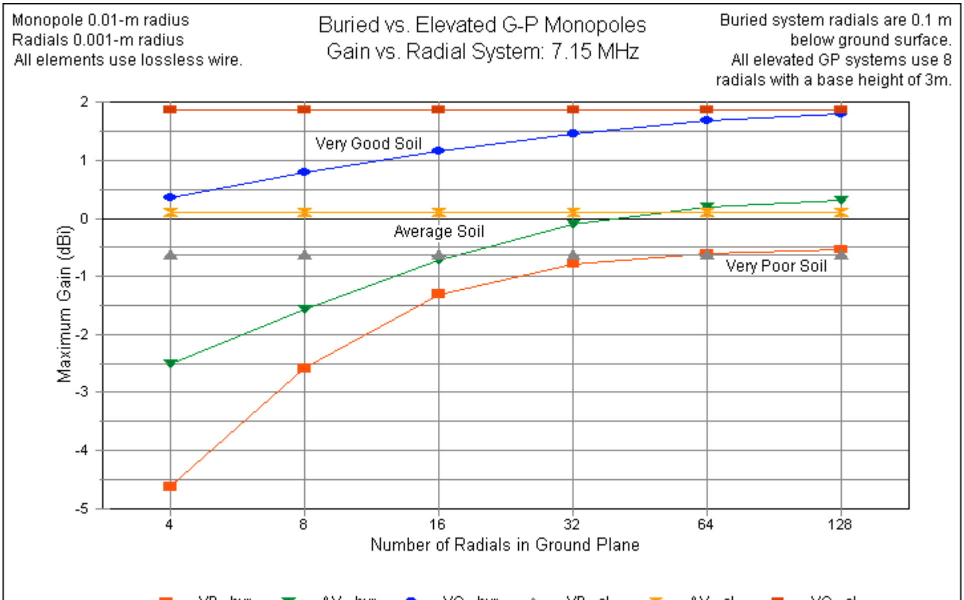
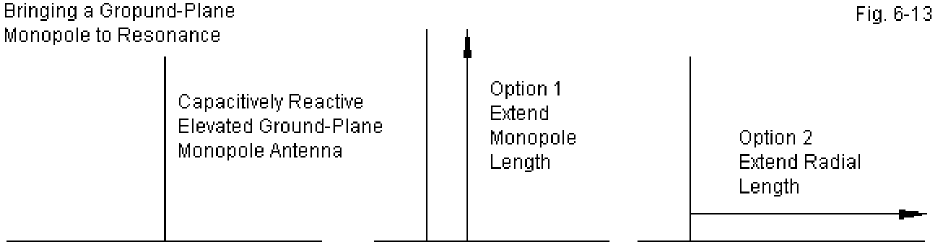


Fig. 6-12

The comparisons suggest that an elevated radial system is capable of equal performance to fairly large buried radial systems and better performance than most smaller buried radial systems. Buried radial systems of considerable size require more wire to establish. However, elevated radial systems present their own construction and maintenance challenges.

Virtually all of the elevated radial systems show a measure of capacitive reactance when we raise the height to the optimal region (1 - 3 m). Since the antenna is not below ground, the current distribution along the radials is normal for any element in a vacuum. Therefore, both the monopole and radial lengths play a role in establishing a resonant system. In order to bring the elevated-radial monopole systems to resonance, we have two options (or a combination of the two). As shown in **Fig. 6-13**, we may extend the length of the monopole or we may extend the length of the radials.



Conventional wisdom (which is not always as wise as it is conventional) would suggest that we might obtain a bit more gain by extending the monopole. To test this idea, I took from the previous tables all of the elevated systems at a 3-m height above ground with 8 radials for all three test frequencies and all three soil types.. Each of these antenna systems showed a capacitive reactance using the original dimensions.

In a 2-part test, I first extended the monopole without altering the radial length until the system showed a resonant feedpoint impedance. Then, I extended the length of the radials without altering the original monopole length until the source impedance was resonant. For the test, resonance is defined as having a reactance of no more than +/-j0.1 Ω.

Table 6-13 provides the results of the test. Among the new headings is the "Version." This heading subdivides into the original dimensions (Orig), the model with the extended monopole and original radials (Mon Ch), and the model with extended radials and original monopole (Rad Ch). The next columns list the monopole length in meters (Mon L m) and the radial length in meters (Rad L m). The columns only list a changed dimension; a blank indicates that there is no change from the original dimensions. The remaining four columns list the performance reports in the usual format.

The models report a consistent pattern that runs exactly contrary to conventional wisdom. The required extension of the monopole to achieve resonance is too small to add any numerically detectable gain to the antenna system. However, extending the radial lengths to bring the system to resonance produces a numerically detectable (although operationally insignificant) improvement in the maximum gain value for each tested system. Note that the amount of improvement increases as the soil quality goes down.

Element Adjustments for Resonance								
All antennas use 8 radials, 3 m above indicated soil								
Freq MHz	Soil	Version	Mon L m	Rad L m	Gain dBi	TO Angle	Resist	React
1.85	Vry Poor	Orig	39.272	40.5125	-1.26	64	33.005	-16.304
		Mon Ch	40.19		-1.27	64	35.178	0.063
		Rad Ch		46.64	-1.03	64	30.604	-0.051
	Average	Orig	39.272	40.5125	1.08	68	34.963	-12.693
		Mon Ch	39.97		1.08	68	36.705	-0.086
		Rad Ch		45.8	1.16	68	33.723	0.078
	Vry Good	Orig	39.272	40.5125	3.01	73	35.271	-11.13
		Mon Ch	39.88		3.02	73	36.8	-0.069
		Rad Ch		45.3	3.04	74	34.809	-0.097
3.6	Vry Poor	Orig	20.113	20.8189	-1.28	63	28.732	-18.081
		Mon Ch	20.685		-1.28	64	31.057	-0.047
		Rad Ch		24.39	-0.97	64	26.87	-0.009
	Average	Orig	20.113	20.8189	0.35	67	31.875	-16.168
		Mon Ch	20.62		0.35	68	34.139	-0.079
		Rad Ch		24.3	0.48	68	30.295	-0.064
	Vry Good	Orig	20.113	20.8189	2.49	72	33.205	-14.239
		Mon Ch	20.56		2.49	72	35.278	0.068
		Rad Ch		24.08	2.55	73	32.387	0.029
7.15	Vry Poor	Orig	10.084	10.4823	-0.62	65	24.672	-17.875
		Mon Ch	10.4		-0.61	65	26.9	-0.028
		Rad Ch		12.331	-0.34	65	23.932	0.062
	Average	Orig	10.084	10.4823	0.1	68	27.057	-18.065
		Mon Ch	10.404		0.1	68	29.503	-0.033
		Rad Ch		12.435	0.23	68	25.954	-0.071
	Vry Good	Orig	10.084	10.4823	1.86	72	28.999	-17.533
		Mon Ch	10.394		1.86	72	31.523	-0.04
Table 6-13		Rad Ch		12.48	1.93	73	27.957	-0.084

One key factor in the increasing gain with radial lengthening is the amount by which we must lengthen the elements to reach resonance for the same capacitively reactive offset. At 1.85 MHz, for example, the required monopole length increase with very poor soil was under 1 m. However, the radials required a 6-m change in length to also achieve resonance. The changes for the other bands are proportional. However, not all changes for any one band are uniform. Compare the nearly equal capacitive reactance for the original 7.15-MHz dimensions with very poor and very good soil. With only limited principles at work, we might expect the radials with very good soil to require slightly less lengthening than those with very poor soil, given the numerical reports of the reactance values. However, just the opposite occurs, with the radials for very good soil requiring more length than those for very poor soil. The elevated radial systems are not so far above ground as to lose all ground influence on the source impedance.

Some antenna builders prefer an alternative strategy for using elevated radial systems. **Fig. 6-14** shows the original layout of an elevated radial system–the one used in all modeling tests so far–and the alternative. Since bringing the monopole base to ground is structurally simpler in most cases than elevating it several meters above ground, some designers start the radials at ground level and elevate them to the full recommended height range at their far ends.

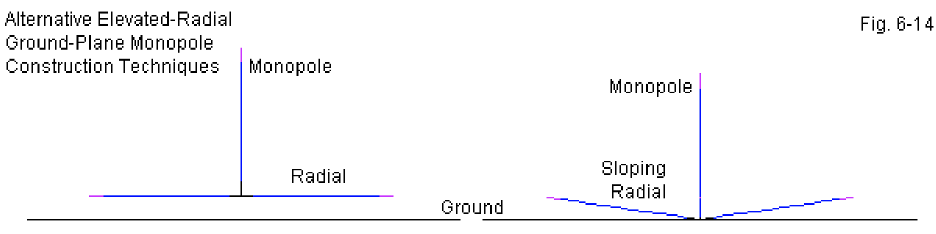


Fig. 6-14

In most cases, these designers wonder what the alternative construction method loses in performance. To provide some guidance toward an answer, I again took all of the 8-radial, 3-m high models for all frequencies and soil types and compared them to sloping-radial equivalents. In each case, the monopole just touches ground, as do the inner ends of the hubs. (This modeling practice does not result in any problematical results, since raising the entire system by a couple of millimeters returns essentially identical results.) The radial outer ends are 3-m high. **Table 6-14** catalogs the test results, along with results for the original models. The data may seem surprising.

Sloping Elevated Radial Systems (From Ground to 3 m)						
All antennas use 8 radials						
Freq MHz	Soil	Version	Gain dBi	TO Angle	Resist	React
1.85	Vry Poor	Orig	-1.26	64	33.005	-16.304
		Sloping	-0.94	63	27.28	-17.895
	Average	Orig	1.08	68	34.963	-12.693
		Sloping	1.49	68	28.589	-16.673
	Vry Good	Orig	3.01	73	35.271	-11.13
		Sloping	3.23	73	29.972	16.082
3.6	Vry Poor	Orig	-1.28	63	28.732	-18.081
		Sloping	-1.17	62	21.644	-22.556
	Average	Orig	0.35	67	31.875	-16.168
		Sloping	0.85	66	22.835	-22.089
	Vry Good	Orig	2.49	72	33.205	-14.239
		Sloping	2.85	71	24.46	-0.02662
7.15	Vry Poor	Orig	-0.62	65	24.672	-17.875
		Sloping	-0.93	63	14.318	-26.129
	Average	Orig	0.1	68	27.057	-18.065
		Sloping	0.21	66	15.42	-26.184
	Vry Good	Orig	1.86	72	28.999	-17.533
Table 6-14		Sloping	2.09	70	16.701	-26.206

For all but one model, the sloping-radial version displays a higher maximum gain value than the level-radial model. The exception is the 7.15-MHz model with very poor ground. Since all models have similar average gain test scores, and since the sloping-radial versions do not change values when raised slightly from contact with the surface, we may take the increments of gain between versions as relatively accurate. With respect to gain, the sloping models are, generally, slightly superior.

The reason why we obtain the added gain is straightforward. The angled radials have not only a horizontally polarized radiation component, but also a vertically polarized component. The vertical components add to form the increased maximum gain level reported by the model. The increase is numerically interesting, but not especially significant operationally. Of equal importance is the raising of the TO angle with respect to the horizon, when compared to the numbers for the level-radial versions.

The sloping radials influence the source impedance in just the opposite way as radials that slope downward. Downward radials tend to raise the impedance relative to those at a 90° angle with respect to the monopole. Upward radials reduce the source impedance. The angle of the slope (in conjunction with the influence of the ground itself) determines the exact reduction in source resistance. The 160-m radials slope upward by about 7.5%, while the 40-m radials slope ward by about 30%. The 40-m assemblies also show the lowest feedpoint resistance values. As well, the amount of upward slope at 40 m is sufficient to actually reduce gain over very poor soil, relative to the level-radial version. The higher values of capacitive reactance for all sloping-radial models suggest a need for greater element extension to bring the antenna to resonance.

The end result is that the sloping-radial alternative to raising the monopole base appears to offer a usable construction method for upper MF and lower HF elevated radial ground-plane monopoles. If one can manage the lower feedpoint resistance values, then the electrical advantages and disadvantages tend to offset each other.

Upper HF Elevated Radial Systems

In the upper HF region–from perhaps 12 MHz upward–the idea of elevated radials means something quite different from the conceptions we bring to the lower HF region. We elevate radials and the entire antenna anywhere from 0.1 λ to 1.0 λ (as a base height). Typically, radio amateurs mount vertical monopoles on decks, garages, barns, houses, and chimneys. A few ground-plane monopoles even appear on towers. A wavelength is close to 70' at 20 meters and 35' at 10 meters, and the ¼-λ elements are also more manageable. Therefore, elevated mounting is almost a rule rather than an exception.

Elevated mounting of ground-plane monopoles holds some advantages that we would be hard pressed to measure. Ground-mounted upper-HF monopoles perform best in the middle of open fields. However, in urban and suburban settings, they fall prey to "RF-eating" trees, shrubbery, and buildings. Elevated mounting offers a path–both incoming and outgoing–that has fewer vertical conductive paths to absorb or reflect energy at the operating frequency.

The coin has a flip side. In the height span from 0.1 λ to 1.0 λ, the theta or elevation pattern of a ground plane monopole undergoes very significant changes in its lobe structure. These changes vary more with the soil quality in the far-field reflection region. As we raise the antenna within the specified range, it very quickly becomes almost (but not quite) independent of the local ground with respect to the source impedance. However, in terms of the operational goals of monopole users, the far-field pattern takes on primary importance, especially for users who wish low angle radiation to match the skip angles for DX communications. As we shall discover, even within the range of heights that are typical of amateur monopole mountings, it is possible to mount a monopole too high for some soil quality values.

To show some of the relevant properties of elevated ground-plane monopoles, I started with free-space dipoles for 14.15 MHz and for 28.3 MHz. These frequencies have an exact 2:1 relationship, so I set the 20-m dipole radius at 0.01 m (about 0.788" diameter), and used ½ that value for the 10-m dipole (about 0.394" diameter). These radii roughly fall in the middle of the elements used in typical amateur antennas for these frequencies. The material is lossless so that we may better isolate the effects attributable to ground. The two antennas had source impedance values of 71.85 + j0.04 Ω with lengths of 10.1376 m at 14.15 MHz and 5.0688 m at 28.3 MHz. The free-space gain was 2.13 dBi, a reflection of the element shortening required by the thicker element. (The standard free-space dipole gain of 2.15 dBi applies to a resonant length of lossless wire with an infinitesimal diameter.)

Since the number of radials becomes unimportant once we elevate an antenna a fairly small way above ground, virtually all elevated upper HF monopoles use only 4 radials. Still in free space, I used exactly half the dipole length and added 4 symmetrical radials. The 20-m radials were 5.948 m, while the 10-m radials were 2.974 m. With lossless elements in free space, both ground-plane monopoles reported a gain of 1.29 dBi with a source impedance of

21.64 - j0.01 Ω. These are the antennas that I used for a series of tests over our standard set of ground qualities: very poor, average, and very good.

For each test run, I elevated the antenna in increments of 0.1 λ, starting at that value and stopping at 1.0 λ above ground. With a 2:1 frequency ratio between antennas, the data should not only show performance differences related to height, but as well it should tell us something about ground effects as we change frequency in the upper HF region. For a given ground quality, we saw significant differences in antenna performance figures as we doubled the frequency from 160 m to 80 meters and again from 80 m to 40 m. What elevated monopoles show as we move from 20 m to 10 m holds some interest.

The following lines show sample models 0.1-wl above ground for both test frequencies. Both samples show average ground in the GN line. The pattern request is for a standard elevation pattern, since the antenna remains omni-directional. However, note that each radial has its own GW entry. This model construction results from shifting from GNEC to EZNEC Pro/4 for these tests. Both NEC-4 cores return the same data. However, EZNEC allows a more compact theta or elevation pattern graphic. Before we set aside these antennas, we shall be very interested in comparing selected elevation patterns. In fact, EZNEC presents its pattern date in terms of elevation. However, for consistency with all other data in this volume, I have converted those TO-angle data back into theta terms.

```
CM 14.15 4-rad gp monopole
CE
GW 1 11 0. 0. 7.187474 0. 0. 2.118674 .01
GW 2 11 0. 0. 2.118674 5.948 0. 2.118674 .004
GW 3 11 0. 0. 2.118674 0. 5.948 2.118674 .004
GW 4 11 0. 0. 2.118674 -5.948 0. 2.118674 .004
GW 5 11 0. 0. 2.118674 0. -5.948 2.118674 .004
GE 1
FR 0 1 0 0 14.15 1
GN 2 0 0 0 13. .005
EX 0 1 11 0  1.00000  0.00000
RP 0 181 1 1000 90. 0. 1.00000 1.00000 0.
EN
CM 28.3 4-rad gp monopole
```

```
CE
GW 1 11 0. 0. 3.593737 0. 0. 1.059337 .005
GW 2 11 0. 0. 1.059337 2.974 0. 1.059337 .002
GW 3 11 0. 0. 1.059337 0. 2.974 1.059337 .002
GW 4 11 0. 0. 1.059337 -2.974 0. 1.059337 .002
GW 5 11 0. 0. 1.059337 0. -2.974 1.059337 .002
GE 1
FR 0 1 0 0 28.3 1
GN 2 0 0 0 13. .005
EX 0 1 11 0  1.00000  0.00000
RP 0 181 1 1000 90 0. 1.00000 1.00000 0.
EN
```

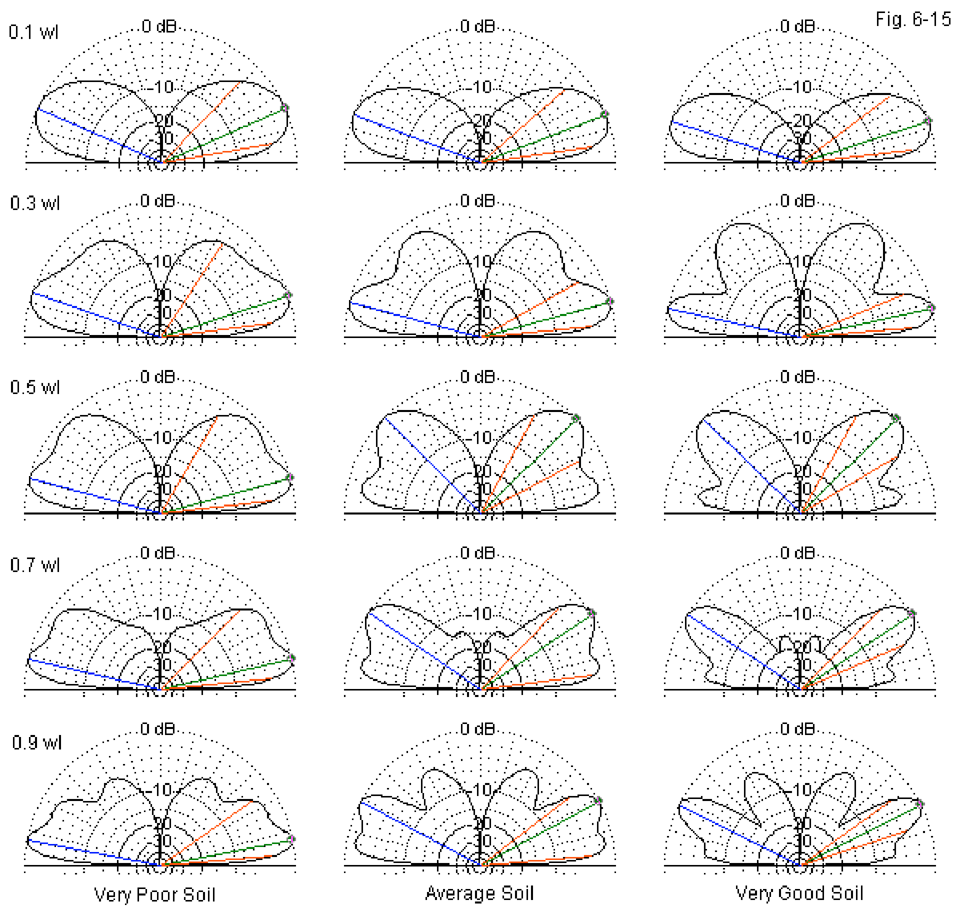
In the models, you will note that each antenna is 0.1-λ above ground (as the starting point). A wavelength at 14.15 MHz is 21.8674 m and 1.059337 m at 28.3 MHz. The values for each 0.1-λ increment of height then become simple arithmetic, although the table lists them for reference. Besides height and soil quality, the tables provide the standard performance figures for maximum gain, TO angle, and source impedance.

The data for 20 m appears in **Table 6-15**. We cannot sensibly graph the values of maximum gain because for 2 of the 3 soil types, the TO angle of maximum radiation changes radically. Over average and very good soil, the second elevation lobe becomes dominant at and above a base height of 0.4 λ (about 29'). All of the gain values for higher base mountings are a function of the second and not the lowest elevation lobe. Only over very poor soil does the lowest elevation lobe remain dominant.

Although the patterns undergo very radical changes as we increase the antenna height, the source impedance does not change much–and hardly at all above 0.3 λ. Even including the lowest height, the source resistance falls within +/-3 Ω of the free-space value. Above 0.3 λ, the range shrinks to about +/-0.75 Ω. Note that these values apply to very good soil, with smaller ranges of variation for soils of worse quality. The general conclusions is that as we raise the base heights of a ground-plane monopole, even with only 4 radials, the local influence of the ground quality rapidly diminishes to an almost negligible level. However, soil quality continues to exert a major influence on the far field.

14.15-MHz 4-Radial Ground-Plane Monopole, Stepped Heights Above Ground						
Soil	Height wl	Height m	Gain dBi	TO Angle	Resist	React
Very Poor	0.1	2.1187	0.08	66	22.9	-3.48
	0.2	4.2374	0.71	69	20.41	-1.66
	0.3	6.356	1.11	72	20.4	0.15
	0.4	8.4747	1.4	73	21.38	0.78
	0.5	10.5934	1.75	75	22.09	0.38
	0.6	12.7121	2.21	76	22.04	-0.21
	0.7	14.8307	2.7	77	21.61	-0.35
	0.8	16.9494	3.1	78	21.38	-0.08
	0.9	19.0681	3.38	79	21.52	0.17
	1	21.1868	3.6	79	21.73	0.14
Average	0.1	2.1187	0.42	69	24.16	-4.57
	0.2	4.2374	0.64	73	20.22	-2.58
	0.3	6.356	0.53	75	19.82	0.01
	0.4	8.4747	1.22	40	21.15	1.1
	0.5	10.5934	2.2	46	22.24	0.62
	0.6	12.7121	2.7	51	22.24	-0.26
	0.7	14.8307	2.99	56	21.63	-0.51
	0.8	16.9494	3.07	59	21.26	-0.14
	0.9	19.0681	2.95	62	21.44	0.24
Very Good	1	21.1868	2.75	65	21.76	0.21
	0.1	2.1187	1.18	72	25.33	-5.54
	0.2	4.2374	1.1	76	20.07	-3.44
	0.3	6.356	0.4	78	19.3	-0.12
	0.4	8.4747	2.39	40	20.93	1.39
	0.5	10.5934	3.39	46	22.38	0.84
	0.6	12.7121	3.97	52	22.43	-0.3
	0.7	14.8307	4.4	56	21.65	-0.66
	0.8	16.9494	4.6	60	21.15	-0.19
	0.9	19.0681	4.58	63	21.37	0.31
Table 6-15	1	21.1868	4.45	66	21.79	0.26

Fig. 6-15 provides a gallery of theta/elevation patterns for all 3 soil types, using the odd values of base height.



Sample Theta/Elevation Pattern: 14.15-MHz 4-Radial Ground-Plane Monopole
at Stepped Heights Above Various Ground Qualities

The gallery of plots has horizontal, vertical, and hybrid dimensions. For each height, we may proceed from left to right (and back again) across the span of soil types. Except for the lowest height–which shows a simple 1-lobe pattern–the plots reveal several significant facts about the effects of soil quality on elevation patterns. For example, the better the conductivity of the soil, the more radically that the lowest lobe diminishes in strength compared to the emergent second lobe. For average and very good soil, the second lobe is dominant at a height of 0.5 λ. However, the first lobe over very good soil at that height is much weaker (comparatively) than the first lobe over average soil.

Vertically, we can watch the development of not only the second elevation lobe, but the third as well. At a height of 0.7 λ, the third lobe shows itself, even though it is only a small bulge in the plot for very poor soil. Elevation lobes do not suddenly appear and disappear. Instead, they emerge and evolve in a continuous manner as we raise the antenna base in very small increments. The plot samples in **Fig. 6-15** should give you enough steps to Gestalt patterns for the intervening heights.

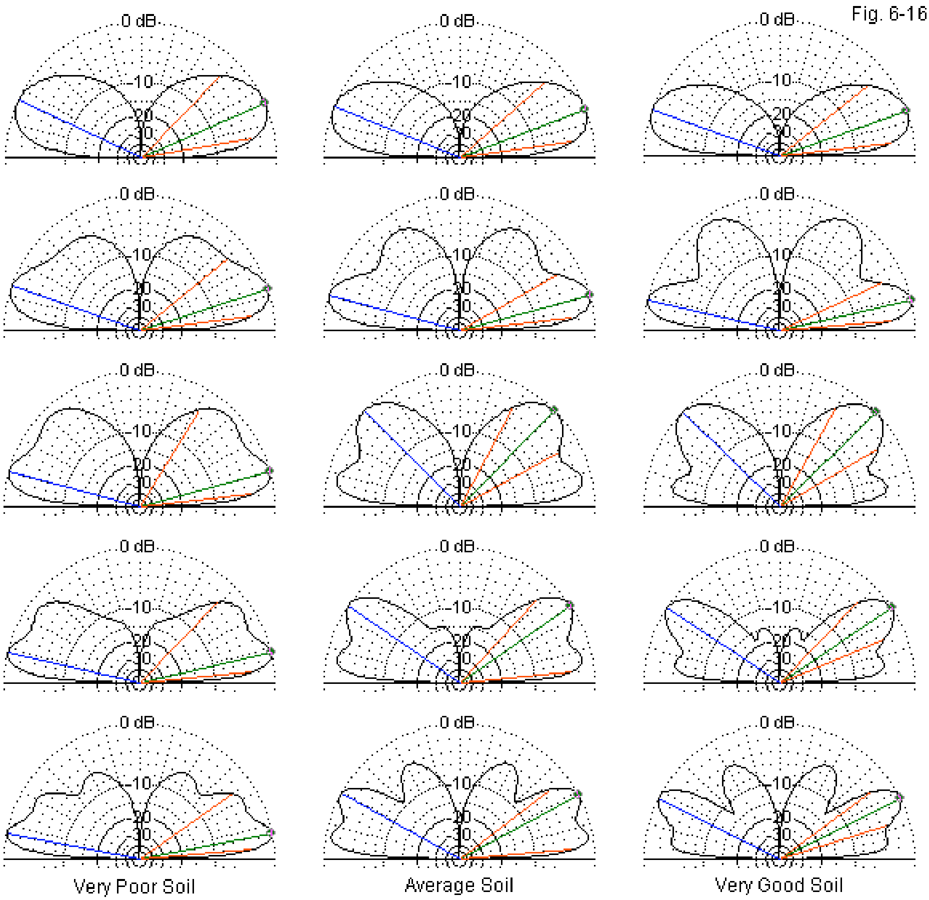
Perhaps the most interesting aspect of the vertical view of the plots is the fact that the secondary lobes over very poor soil never dominate. Rather, the lowest lobe remains dominant throughout the range of heights surveyed. If we adopt our alternative view of very poor soil as the best ground-approximation of free space, then the lack of high-angle reflections becomes a natural phenomenon, rather than an oddity of lossy ground.

The hybrid view requires that we correlate the tabular data with the gallery of patterns. For example, at 1 λ above ground, the monopole over very poor soil shows a higher maximum gain (at a TO angle of 79 °) than over average soil (at 65°). However, these values do not necessarily indicate that the monopole over very poor ground radiates more efficiently in terms of overall energy in the elevation pattern. The second and third lobes of the pattern over very poor soil are considerably weaker than the same lobes over average soil. This example is but one sample of the care we must use in interpreting antenna elevation patterns.

Table 6-16 provides the comparable data for the 28.3-MHz monopole. The heights in meters are ½ the heights for the 14.15-MHz antenna, but are the same height when measured as a fraction of a wavelength.

28.3-MHz 4-Radial Ground-Plane Monopole, Stepped Heights Above Ground						
Soil	Height wl	Height m	Gain dBi	TO Angle	Resist	React
Very Poor	0.1	1.0594	0.26	66	23	-3.3
	0.2	2.1187	0.9	70	20.54	-1.66
	0.3	3.178	1.31	72	20.43	0.09
	0.4	4.2374	1.59	73	21.35	0.74
	0.5	5.2967	1.91	75	22.05	0.39
	0.6	6.3561	2.33	76	22.03	-0.19
	0.7	7.4154	2.8	77	21.62	-0.34
	0.8	8.4747	3.18	78	21.39	-0.09
	0.9	9.5341	3.46	79	21.51	0.16
	1	10.5934	3.66	80	21.71	0.12
Average	0.1	1.0594	0.66	69	24.18	-4.24
	0.2	2.1187	0.97	73	20.38	-2.5
	0.3	3.178	0.96	75	19.91	-0.06
	0.4	4.2374	0.98	39	21.13	1.03
	0.5	5.2967	2.01	45	22.19	0.61
	0.6	6.3561	2.52	50	22.23	-0.22
	0.7	7.4154	2.81	55	21.65	-0.49
	0.8	8.4747	2.9	59	21.28	-0.15
	0.9	9.5341	2.78	62	21.44	0.22
Very Good	1	10.5934	2.59	64	21.74	0.18
	0.1	1.0594	0.81	71	24.85	-5.16
	0.2	2.1187	0.82	75	20.12	-3.1
	0.3	3.178	0.35	77	19.5	-0.07
	0.4	4.2374	1.93	40	21.02	1.28
	0.5	5.2967	2.93	46	22.33	0.75
	0.6	6.3561	3.47	52	22.36	-0.28
	0.7	7.4154	3.84	56	21.64	-0.61
	0.8	8.4747	4	60	21.2	-0.17
	0.9	9.5341	3.93	63	21.4	0.28
Table 6-16	1	10.5934	3.77	65	21.78	0.22

We may reserve comments until we also have **Fig. 6-16** to give us the comparable gallery of elevation patterns.



Sample Theta/Elevation Pattern: 28.3-MHz 4-Radial Ground-Plane Monopole
at Stepped Heights Above Various Ground Qualities

Viewing the plots in any way listed for the 20-m plots, we can hardly detect any differences. Minor differences do exist, for example, in the relative strength of the lowest lobe at the highest surveyed heights. We can obtain a better view of the differences by comparing critical data in **Table 6-17**.

14.15-MHz vs. 28.3-MHz Gain and TO Angle					
Soil	Height wl	20m Gain	20m TO	10m Gain	10m TO
Very Poor	0.1	0.08	66	0.26	66
	0.2	0.71	69	0.9	70
	0.3	1.11	72	1.31	72
	0.4	1.4	73	1.59	73
	0.5	1.75	75	1.91	75
	0.6	2.21	76	2.33	76
	0.7	2.7	77	2.8	77
	0.8	3.1	78	3.18	78
	0.9	3.38	79	3.46	79
	1	3.6	79	3.66	80
Average	0.1	0.42	69	0.66	69
	0.2	0.64	73	0.97	73
	0.3	0.53	75	0.96	75
	0.4	1.22	40	0.98	39
	0.5	2.2	46	2.01	45
	0.6	2.7	51	2.52	50
	0.7	2.99	56	2.81	55
	0.8	3.07	59	2.9	59
	0.9	2.95	62	2.78	62
Very Good	1	2.75	65	2.59	64
	0.1	1.18	72	0.81	71
	0.2	1.1	76	0.82	75
	0.3	0.4	78	0.35	77
	0.4	2.39	40	1.93	40
	0.5	3.39	46	2.93	46
	0.6	3.97	52	3.47	52
	0.7	4.4	56	3.84	56
	0.8	4.6	60	4	60
	0.9	4.58	63	3.93	63
Table 6-17	1	4.45	66	3.77	65

If we first look at the data for the TO angles at both 20 and 10 meters, we see a near identity of values throughout the survey range. However, for all but one case, wherever there is a difference between values, the 10-m TO angle is higher relative to the horizon. The exception is the 10-m antenna at 1 λ above very poor soil.

Interestingly, very poor soil is also the exception to the pattern of gain values. The additional ground losses with increasing frequency show themselves in small but distinct ways over average and very good soil. The 14.15-MHz antenna shows a higher maximum gain, regardless of whether the lowest or the second lobe dominates the pattern. However, over very poor soil, we find quite the opposite pattern: the values of maximum gain for 28.3 MHz are always greater than those for 14.15 MHz. The differences are too small to have operational significance, but the patterns give us further insight into the effects of ground with the elevated ground-plane monopoles in the upper HF range.

These brief notes only sample some of the patterns that the data permits. You may wish to study the table more thoroughly to extract other data patterns. Although the data rest on NEC models of antennas, they may still prove useful in understanding the operation vertical monopoles and making decisions regarding their proper installation.

How high we should mount a ground-plane vertical monopole thus becomes a compromise among several factors: the type of operating that we require or desire, the ground quality in the region of far-field reflections, and the type of antenna that we may be using. The worse the soil, the greater advantage that we accrue from heights up to 1 λ in terms of low-angle radiation for the pursuit of DX stations. Over average and especially over very good soil, we can easily mount the antenna too high to place the greatest quantity of radiation at low elevation angles. At the same time, we may also grapple with problems of local clutter that I earlier characterized as RF-eating trees, shrubbery, and buildings (not to mention vertical metal structures such as towers and light poles). The final element in the puzzle applies to operators using multi-band vertical monopoles. A half-wavelength at 20 meters is a full wavelength at 10 meters. Hence, the best height may involve prioritizing operating frequencies as well as other factors.

Of course, the entire question of vertical monopole heights becomes moot if the installation site has only one available elevated mounting possibility.

VHF and UHF Elevated Radial Systems

To examine the behavior of ground-plane monopoles elevated more than 1 λ, it makes sense to move to the VHF and UHF regions of the radio spectrum. At these frequencies, we find these antennas used at all heights from near ground level on automobiles to tall tower tops. The 2-m and 70-cm amateur bands create good test cases, since we have a 3:1 frequency ratio between 432 and 144 MHz. Therefore, we can once more begin with scaled dipoles in free space.

The 2-m dipole radius will be 4.5 mm (a little less than 3/8" diameter), and the scaled 70-cm version will use a radius of 1.5 mm (just under 1/8" diameter). The scaled lengths are 975.4 mm and 325.134 mm, respectively. Both lossless dipoles in free space produce 2.13 dBi gain and a source impedance of 71.87 + j0.02 Ω. Like past monopoles, we shall take half the dipole length (487.7 mm and 162.567 mm) for the monopole and fit the base with 4 radials. The 2-m radials use a radius of 1.5 mm, while the 70-cm radials have a radius of 0.5 mm, both lossless. To produce overall resonance, the radials are 598 mm and 199.333 mm, respectively. Free-space gain is 1.20 dBi, with a source impedance of 22.08 - j0.06 Ω. Please note this last figure for reference.

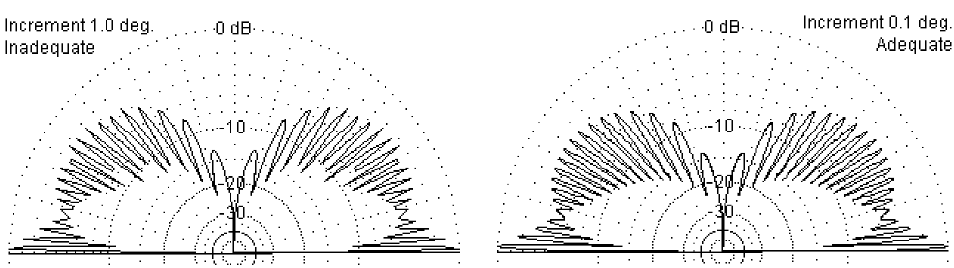
Over ground, the NEC-4 model of the 2-m version looks like this:

```
CM 144-MHz vertical gp-gnd
CE
GW 1 11 0. 0. 4.651484 0. 0. 4.163784 .0045
GW 2 11 0. 0. 4.163784 .598 0. 4.163784 .0015
GW 3 11 0. 0. 4.163784 0. .598 4.163784 .0015
GW 4 11 0. 0. 4.163784 -.598 0. 4.163784 .0015
GW 5 11 0. 0. 4.163784 0. -.598 4.163784 .0015
GE 1
FR 0 1 0 0 144. 1
GN 2 0 0 0 13. .005
EX 0 1 11 0  1.00000  0.00000
RP 0 1801 1 1000 90. 0. 0.10000 1.00000 0.
EN
```

The 70-cm antenna model has a parallel form.

```
CM 432-MHz vertical gp-gnd
CE
GW 1 11 0. 0. 1.550495 0. 0. 1.387928 .0015
GW 2 11 0. 0. 1.387928 .1993333 0. 1.387928 .0005
GW 3 11 0. 0. 1.387928 0. .1993333 1.387928 .0005
GW 4 11 0. 0. 1.387928 -.1993333 0. 1.387928 .0005
GW 5 11 0. 0. 1.387928 0. -.1993333 1.387928 .0005
GE 1
FR 0 1 0 0 432. 1
GN 2,0,0,0,13.,,.005
EX 0 1 11 0  1.00000  0.00000
RP 0 1801 1 1000 90. 0. 0.10000 1.00000 0.
EN
```

In both models, each radial has its own wire line, since we shall once more use EZNEC to produce a small gallery of theta/elevation plots. The TO-angle values listed in the table will be in terms of theta angles. The test base heights will range from 2 λ to 10 λ. Because the antennas will be so high off the ground, we need to reduce the increment of the patterns from 1.0° down to 0.1°. **Fig. 6-17** shows why. With the larger increment between reading, the plot may miss the true angle of one or more lobes. The irregular virtual line connecting the null points between lobes is the crucial evidence. The smooth null-point curves on the right are evidence that the increment is adequately small for a usable plot.



Theta/Elevations Patterns with Adequate and Inadequate Angular Increments
Sample Taken at 10-WL Above Very Good Ground at 144 MHz

Fig. 6-17

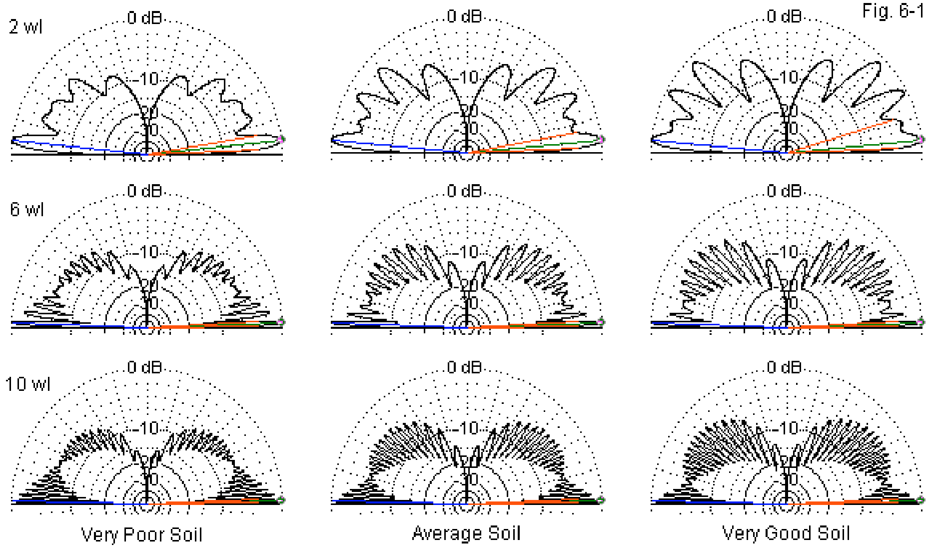
Table 6-18 provides the 144-MHz monopole data.

144-MHz 4-Radial Ground-Plane Monopole, Stepped Heights Above Ground						
Soil	Height wl	Height m	Gain dBi	TO Angle	Resist	React
Very Poor	2	4.164	5.07	84.1	22.1	-0.01
	3	6.246	5.68	85.8	22.08	-0.04
	4	8.328	6.02	86.8	22.08	-0.05
	5	10.409	6.24	87.4	22.08	-0.05
	6	12.491	6.39	87.8	22.08	-0.05
	7	14.573	6.5	88.1	22.08	-0.05
	8	16.655	6.58	88.3	22.08	-0.06
	9	18.737	6.65	88.5	22.08	-0.06
	10	20.819	6.7	88.6	22.08	-0.06
Average	2	4.164	4.22	84.4	22.1	0.01
	3	6.246	5.03	86	22.09	-0.02
	4	8.328	5.5	86.8	22.08	-0.04
	5	10.409	5.8	87.4	22.08	-0.05
	6	12.491	6.01	87.8	22.08	-0.04
	7	14.573	6.17	88.1	22.08	-0.04
	8	16.655	6.29	88.3	22.08	-0.05
	9	18.737	6.38	88.5	22.08	-0.06
	10	20.819	6.46	88.6	22.08	-0.06
Very Good	2	4.164	3.65	84.5	22.11	0.02
	3	6.246	4.6	85.9	22.08	-0.02
	4	8.328	5.15	86.8	22.08	-0.03
	5	10.409	5.5	87.4	22.08	-0.05
	6	12.491	5.76	87.8	22.08	-0.04
	7	14.573	5.94	88.1	22.08	-0.04
	8	16.655	6.09	88.3	22.08	-0.05
	9	18.737	6.2	88.5	22.08	-0.05
Table 6-18	10	20.819	6.29	88.6	22.08	-0.06

Note that the model over very poor soil yields the best maximum gain value, with decreasing values for any given height over improved soils. Above 3 λ base height, the TO angles are the same for all soil qualities. Finally, the source impedance values are too close to the free-space value to need any differentiation.

I have reduced the size of the theta/elevation plot gallery (**Fig. 6-18**) to only 3 heights: 0.2 λ, 0.6 λ, and 1.0 λ. Our goal is not to count elevation lobes for each 0.1-λ increment of increased height, but to see in a general way the growth on the numbers of lobes. More important is the horizontal perspective, which shows why the model over very poor soil has a higher maximum gain in every instance. As we improve the soil quality, the higher-angle lobes increase their relative strength, and the lowest lobe becomes one source for the increased high-angle energy. Although the number of lobes changes at every height, the general relationship between the lowest lobe and the upper lobes remains relatively constant.

Fig. 6-18



Sample Theta/Elevation Patterns: 144-MHz 4-Radial Ground Plane Monopole at Stepped Heights Above Various Ground Qualities

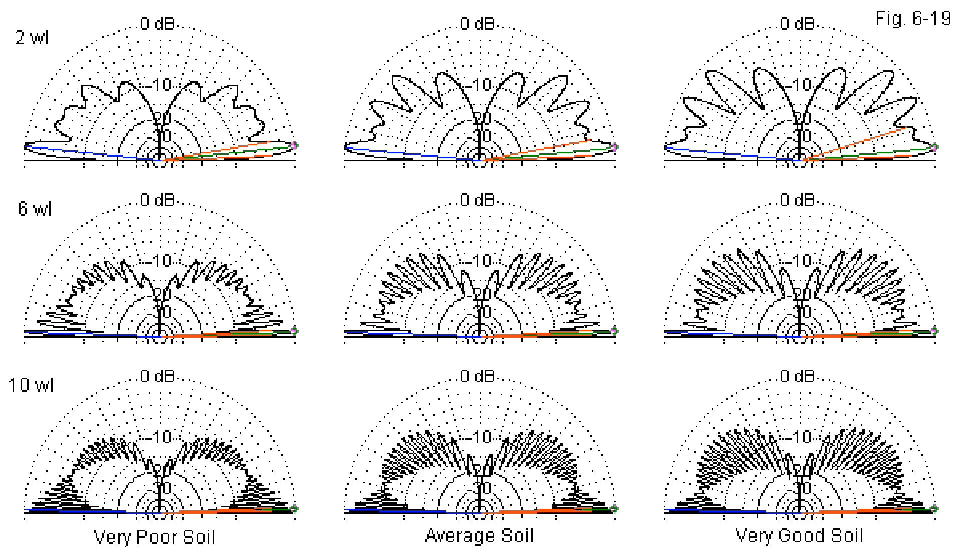
The data in **Table 6-19** result from replicating the 144-MHz tests at 432 MHz. The physical heights are admittedly low for all but mobile and field installations, but the crucial question involves the values at each height increment as a fraction of a wavelength.

432-MHz 4-Radial Ground-Plane Monopole, Stepped Heights Above Ground						
Soil	Height wl	Height m	Gain dBi	TO Angle	Resist	React
Very Poor	2	1.388	5.07	84.1	22.1	-0.01
	3	2.082	5.68	85.8	22.08	-0.04
	4	2.776	6.02	86.8	22.08	-0.05
	5	3.470	6.24	87.4	22.08	-0.05
	6	4.164	6.39	87.8	22.08	-0.05
	7	4.858	6.5	88.1	22.08	-0.05
	8	5.552	6.59	88.3	22.08	-0.06
	9	6.246	6.65	88.5	22.08	-0.06
	10	6.940	6.7	88.6	22.08	-0.06
Average	2	1.388	4.24	84.3	22.1	0.01
	3	2.082	5.04	86	22.08	-0.02
	4	2.776	5.5	86.9	22.08	-0.04
	5	3.470	5.8	87.4	22.08	-0.04
	6	4.164	6.01	87.8	22.08	-0.05
	7	4.858	6.17	88.1	22.08	-0.05
	8	5.552	6.29	88.3	22.08	-0.05
	9	6.246	6.39	88.5	22.08	-0.05
	10	6.940	6.46	88.6	22.08	-0.05
Very Good	2	1.388	3.72	84.6	22.11	0.02
	3	2.082	4.63	86.1	22.09	-0.02
	4	2.776	5.17	86.9	22.08	-0.03
	5	3.470	5.52	87.4	22.08	-0.04
	6	4.164	5.77	87.8	22.08	-0.05
	7	4.858	5.96	88.1	22.08	-0.05
	8	5.552	6.1	88.3	22.08	-0.05
	9	6.246	6.21	88.5	22.08	-0.05
Table 6-19	10	6.940	6.29	88.7	22.08	-0.05

The table virtually replicates the 2-m table in every detail. The largest difference occurs in the gain column at 2 λ above very good soil, a difference of

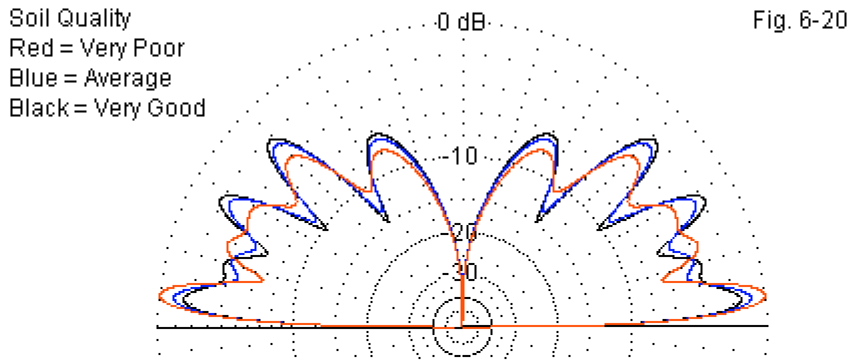
0.05 dB. 90% of the values in the table are identical to those in the table for the lower frequency. Essentially, by the range of heights and frequencies used in the new surveys, frequency no longer make a difference to elevated ground-plane monopole performance. Likewise, the local region beneath the antenna–the region that affected the source impedance of lower frequency monopoles with buried or slightly elevated radials–has lost virtually all influence on the source impedance of our test VHF and UHF monopoles.

If virtually all of the data in the tabular listing is identical between the 2 frequencies with a 3:1 ratio, we should expect the theta/elevation plots also to be nearly identical. **Fig. 6-19** does not disappoint us. We would be hard pressed to find differences between any pattern in this set and its corresponding pattern in the 2-m set.



Sample Theta/Elevation Patterns: 432-MHz 4-Radial Ground Plane Monopole
at Stepped Heights Above Various Ground Qualities

The differences in the patterns among soil types do not only involve the maximum gain of the lowest elevation lobe and the relative amount of energy sent to the higher lobes. **Fig. 6-20** overlays the 2-m patterns at a height of 2 λ above ground. I might have used ant height, but the increasing numbers of lobes and nulls would have obscured the relevant detail. As we move through the 3 sampled soil quality levels, we find some slight differences in the lobe placement as well as lobe strength. Although the lowest lobe and the higher lobes show close to the same angles, note the peak in the second lobe. As we improve the soil quality, the lobe peak assumes a lower angle. Although this detail is unlikely to make a significant operational difference, it is part of the pattern of lobe development from which we develop our understanding and expectations of ground-plane monopole performance.



Overlaid Theta/Elevation Plots at 144 MHz and 2-WL Above Ground
Comparisons for Veryy Poor, Average, and Very Good Soil

At VHF and UHF, we conventionally show the performance of a vertically polarized antenna by comparing it to either a vertical dipole or a ground-plane monopole at the same base height, where the idea of the base height indicates the height of the feedpoint above ground. Also, we conventionally use average ground, since the values reasonably represent a fair middle set of values between those for very poor and very good ground. However, as we bring the antenna closer to ground, say, to 2 λ above ground, we may wish to be more site-specific in choosing the ground, since average ground models at this level approximate very poor ground better than they approach very good ground.

I could have presented the VHF/UHF data in a short series of summary statements. However, that would require one to take on faith the general properties of elevated ground-plane radials. Every student of antennas deserves to see the detailed data. Better yet, every student of antennas should carry out a comparable set of modeling projects to the ones shown throughout this chapter. Hands-on experience, at least at the level of modeling, can go far to naturalizing correct expectations from the ground-plane antennas that we later go on to design or analyze.

In this chapter, we have covered a lot of ground, and covered it with radials at many heights and frequencies, sampling a fair number of soil types along the way. In the upper MF and lower HF range, we were concerned primarily with radial systems very close to the ground. We wondered how many radials to use and at what height to place them. We also wondered how elevated-radial systems stacked up against buried radial system of various sizes. At those frequencies and heights above ground, we saw significant changes in performance with changes in frequency and in soil quality. However, we tended to lose any improvement as we increased the number of elevated radials above 6 or 8 when we placed them, 2 m to 3 m above ground. This same region also saw the stabilization of the source impedance so that minor variations or fluctuations in height made very little difference to performance.

As we increased the frequency into the upper HF range and the heights to a range between 0.1 λ and 1.0 λ, the ground lost much (but not all) of its ability to affect the source impedance. The changes in far-field performance varied less radically among soil types, although differentials remained distinct. By the time we climbed into the VHF and UHF ranges and to heights from 2 λ to 10 λ, the source impedance settled at its free-space value, and frequency differences no longer made a difference to performance data. Even the differences occasioned by soil quality had diminished to relatively small amounts. The remaining differences assumed the role of subtleties.

The Next Steps

Surveying the effects of elevating radials with ground-plane monopoles does not complete our work. There are many vertical antenna designs that require multiple elements. Many other vertical antenna designs do not touch the ground at all. These latter antennas occasion an interesting debate regarding whether they do or do not require or benefit from radial systems. Our task will not be to decide which side of the debate is right and which wrong. Instead, we shall explore with an eye toward seeing in what way (or ways) each side is right.

7. Parasitic and SCV Arrays

Although the chapter title suggests that we shall be examining arrays of vertically polarized antennas, the true purpose is to explore some modeling issues. In the first half of the chapter, we shall look at the best way of modeling complex vertical monopole arrays. In the second half of the chapter, we shall probe some of the relationships between models and physical antenna systems, with special attention to ground-related issues. The antenna designs that we shall use are not necessarily either good or bad designs. Instead, they are illustrations of the principles that we wish to grasp.

Parasitic Arrays and the MININEC Ground

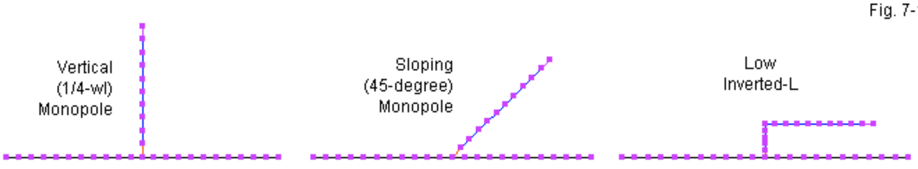
Throughout all of the exercises in this volume, we have used the NEC-4 Sommerfeld-Norton (SN) ground calculation facility. The engineering jury may still be out on the exactitude with which it replicates reality, but it remains the most accurate ground calculation system so far enfolded by an antenna-modeling program. NEC (both -2 and -4) also has a "fast" ground calculating system based on a reflection coefficient approximation (RCA). This system is less accurate than the SN system, and it drifts away from accurate results as wires approach ground with any horizontally polarized component. One major commercial implementation of NEC no longer bothers to make this option available to users. The RCA system arose while computers struggled to obtain any speed at all. The current generation of computers, with CPU speed up to and beyond 4 GHz, handles the SN calculations too rapidly to justify the use of a less accurate ground calculation system.

Both the RCA and SN systems in NEC have a shortcoming. If we place a vertical wire with one end just touching the ground, the reports–especially the source impedance reports–will be wholly unusable. As a result, the modeler who wishes to create trial arrays composed of monopoles with one end at or below ground must also model a radial system. An alternative is to do the initial modeling with a perfect ground, but that options gives the designer no idea of the effects of ground losses or the elevation/theta angles of lobes over real ground.

To answer the demand for simplified monopole array modeling, some programs, such as EZNEC, have grafted the MININEC ground calculation system onto NEC. The MININEC system also uses a reflection coefficient approximation, but not the same way as in the NEC RCA system. As a result, one may place vertical wires with one end touching ground and obtain an approximation of the antenna's performance with a radial system. However, the MININEC method of overcoming the potential problem of unusable source impedance information is always to return the source impedance over a perfect ground.

The simplicity of using a MININEC ground with NEC has led many modelers over the years to place an unwarranted degree of trust in the output reports. The notes that follow are designed to show some of the pitfalls of placing too much trust in modeling arrays with the MININEC ground. As well, it will provide some guidance in knowing to what degree MININEC ground results depart from those of carefully constructed models of buried radial systems. We shall continue to model all buried radial systems within GNEC, since that program gives us some shortcuts in modeling radials systems of different sizes. However, GNEC does not contain the MININEC ground. Therefore, we shall use EZNEC for models using the MININEC ground. In both cases, we shall use NEC-4 as the calculating core, and both programs return the same results for compatible models.

Fig. 7-1



Three Test Antennas Used to Compare the MININEC Ground with the Sommerfeld-Norton Ground

The first step in our progression involves developing some baseline data. Therefore, we shall begin with a series of single-element antennas, as shown in **Fig. 7-1**. We shall begin with a standard ¼ λ monopole and proceed to a similar monopole tilted 45° from vertical. Since the antenna will have both vertical and horizontal components to its total far-field radiation, we shall begin to see to what degree the tilt affects MININEC ground reports. Finally, we shall examine an antenna that is typical of many amateur radio installations, the low inverted-L. All antennas will use 1.85 MHz as the test frequency. Hence, all of the versions of the antenna using buried radials will use 2-mm-diameter lossless wire with 40.5125-m radials. Finally, to isolate ground effects from others, we shall use lossless main elements.

1. *A ¼-λ Vertical Monopole*

A ¼-λ vertical monopole with its base just touching the ground meets the requirements for the most accurate results from using a MININEC ground without adding radials. We may begin with the standard 1.85-MHz monopole used in past chapters. Over perfect ground, the 0.01-m radius antenna is resonant at a length of 39.272 m. The source impedance under these conditions is 36.18 + j0.078 Ω. The section of **Table 7-1** devoted to MININWEC ground results will show this impedance regardless of the soil quality we use as an environment for the antenna. As in many past exercises, we shall use the following soil qualities for all tests.

Soil Quality	Conductivity	Relative Permittivity
Very Poor	0.001 S/m	5
Average	0.005	13
Very Good	0.0303	20

When we develop NEC-4 models, we shall use field sizes of 4, 8, 16, 32, 64, and 128 radials, with the 0.001-m radius lossless wires buried 0.1-m deep. The following geometry lines review the model's wire structure, using a 4-radial system for the buried ground plane.

```
GW 1 10 0 0 0 0 0 39.272 .01
GW 2 1 3.65 0 -.1 0 0 0 .001
GW 2 10 40.5125 0 -.1 3.65 0 -.1 .001
GM 0 3 0 0 90 0 0 0 2 1 2 11
GE -1 -1 0
```

1.85-MHz Perfect Monopole with Perfect Radials and Various Soil Qualities						
Monopole length: resonant with perfect ground; radials 1/4 wavelength						
Soil		# Radials	Gain dBi	TO Angle	Resist	React
Very Poor		4	-3.91	62	76.642	17.665
C 0.001, P 5		8	-2.76	62	59.317	11.805
		16	-1.84	62	47.453	6.826
		32	-1.22	62	40.047	2.201
		64	-0.91	62	36.143	-1.256
		128	-0.78	62	33.289	-3.252
Average		4	-0.53	67	56.912	11.657
C 0.005, P 13		8	0.04	67	50.161	8.009
		16	0.5	67	45.2	5.376
		32	0.89	67	41.31	3.205
		64	1.15	67	38.448	1.266
		128	1.29	67	36.696	-0.269
Very Good		4	2.16	73	45.567	6.571
C 0.0303, P 20		8	2.39	73	43.236	4.779
		16	2.58	73	41.406	3.491
		32	2.75	73	39.83	2.425
		64	2.9	73	38.448	1.488
		128	3.01	73	37.347	0.667
1.85-MHz Perfect Monopole Using MININEC Ground						
Monopole length: resonant with perfect ground; no radials						
Soil			Gain dBi	TO Angle	Resist	React
Very Poor			-1	63	36.18	0.078
Average			1.41	67	36.18	0.078
Very Good			3.16	73	36.18	0.078
	Note:	Mininec ground system always returns the source				
Table 7-1		impedance for a perfect ground.				

Perhaps the only true coincidence between the MININEC data and the NEC-4 data lies in the TO Angle column. **Fig. 7-2** graphs the gain data to show where–for each soil quality, the rising NEC-4 gain line crosses the constant MININEC line. In fact, only over very poor soil does the MININEC result cross the NEC-4 line (at 64 radials). Otherwise, it always exceeds the gain report at 128 NEC-4 buried radials.

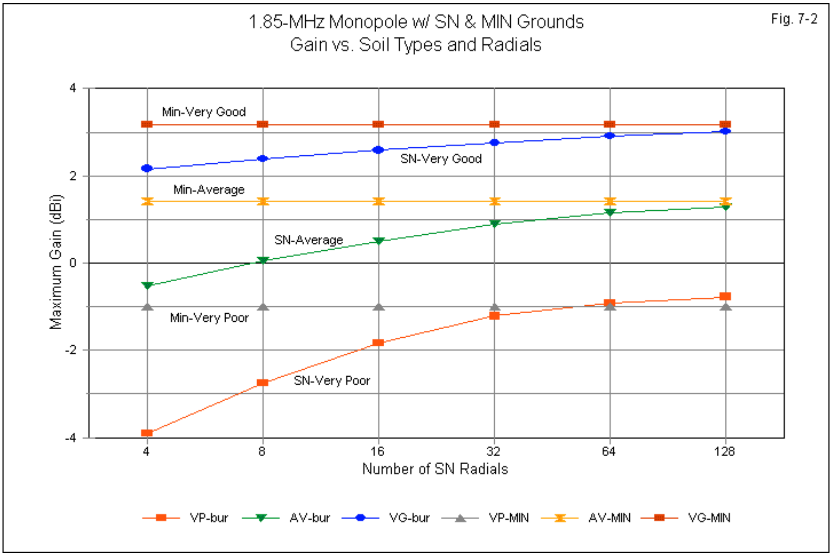

1.85-MHz Monopole w/ SN & MIN Grounds
Gain vs. Soil Types and Radials
Maximum Gain (dBi)
4
2
0
-2
-4
Min-Very Good
SN-Very Good
Min-Average
SN-Average
Min-Very Poor
SN-Very Poor
4
8
16
32
64
128
Number of SN Radials
VP-bur
AV-bur
VG-bur
VP-MIN
AV-MIN
VG-MIN

Fig. 7-2

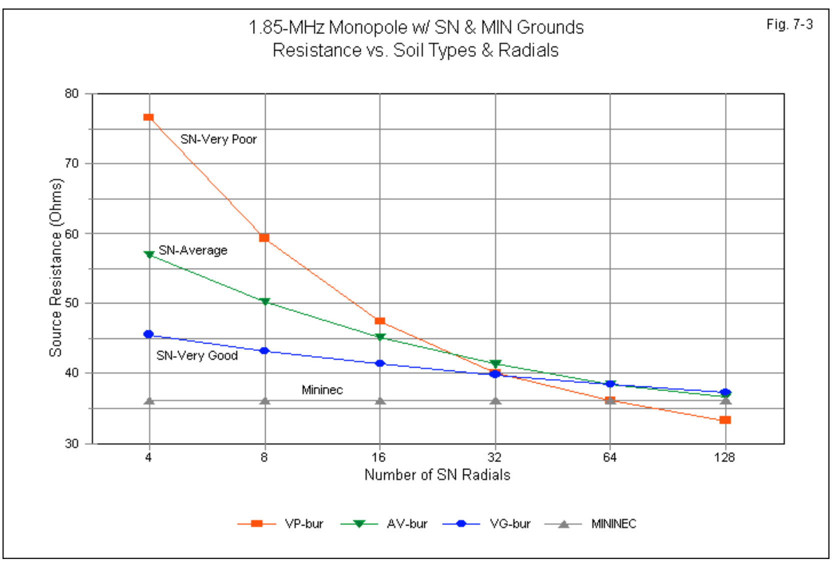

1.85-MHz Monopole w/ SN & MIN Grounds
Resistance vs. Soil Types & Radials
Source Resistance (Ohms)
80
70
60
50
40
30
SN-Very Poor
SN-Average
SN-Very Good
Mininec
4
8
16
32
64
128
Number of SN Radials
VP-bur
AV-bur
VG-bur
MININEC

Fig. 7-3

Fig. 7-3 provides similar data for the source resistance value. In this table, the MININEC report has only one value. Once more, the very poor soil value cross the MININEC value at 64 NEC-4 radials. For better soils, the NEC-4 buried-radial reports never quite reach the MININEC source resistance, even using 128 radials.

For virtually all amateur applications, MININEC ground results over-report the gain and under-report the source resistance, even under the most optimal conditions for using a MININEC ground with a vertical monopole.

2. *A ¼-λ Sloping Monopole*

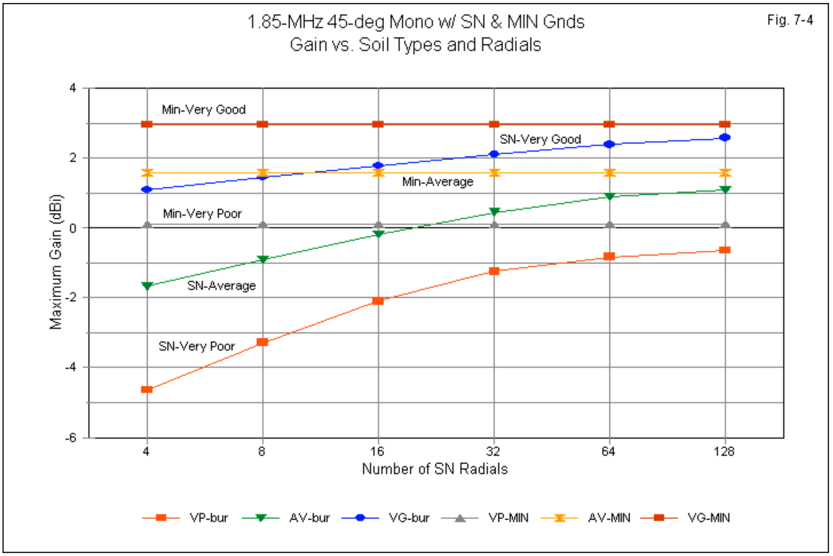
The second case uses a monopole that slants by 45° relative to the ground (and to the vertical). The antenna is not a mere hypothetical test case, since many amateurs use slanting wires for vertical antennas. In the present context, the antenna is a first order test of the sensitivity of the MININEC ground to wires having a horizontal component to the far field radiation. As shown by the coordinates in the same lines from the sample model, the monopole is resonant over a perfect ground with a length of 40.164 m (slightly longer than the truly vertical monopole). The source impedance is 21.18 - j0.056 Ω. The maximum gain over perfect ground is 4.67 dBi, down from the 5.15-dBi figure for the vertical monopole.

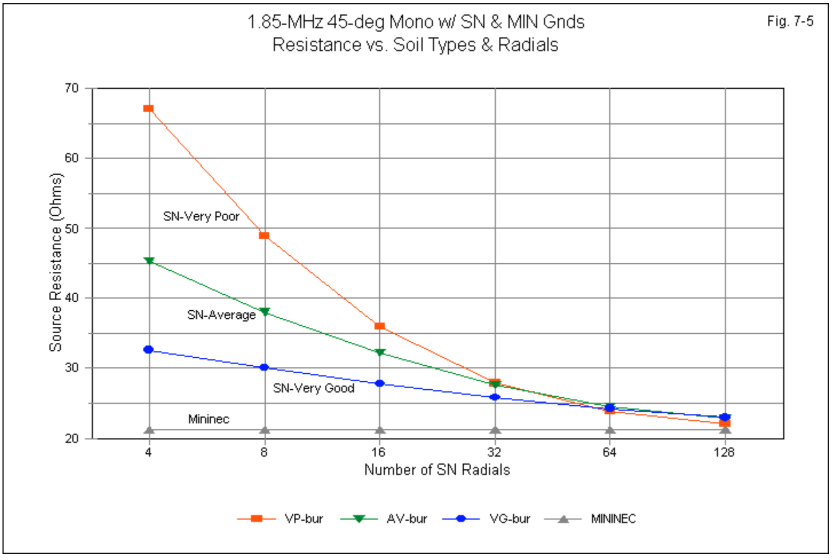
```
GW 1 11 0 0 0 0 28.4 28.4 .01
GW 2 1 3.65 0 -.1 0 0 0 .001
GW 2 10 40.5125 0 -.1 3.65 0 -.1 .001
GM 0 3 0 0 90 0 0 0 2 1 2 11
GE -1 -1 0
```

Table 7-2 provides the tabular information for the MININEC and the buried-radial tests with this slanting monopole. Regardless of the level of soil quality, the MININEC data shows a higher maximum gain value than the corresponding data for 128 buried NEC-4 radials. As well, the MININEC model cannot account for the gradual changes in the TO angle for the buried-radial version of the antenna over very poor soil. At 128 radials, the MININEC reported TO angle is 3-degrees off the NEC-4 report. (As in the last chapter, I have converted EZNEC elevation angles into standard NEC-4 theta angles for consistency within the tables.)

1.85-MHz Perfect Sloping (45-Deg.) Monopole with Perfect Radials						
Monopole length: resonant with perfect ground; radials 1/4 wavelength						
Soil		# Radials	Gain dBi	TO Angle	Resist	React
Very Poor		4	-4.63	55	67.158	27.482
C 0.001, P 5		8	-3.28	55	48.873	20.611
		16	-2.1	56	35.945	13.425
		32	-1.25	56	27.875	6.741
		64	-0.82	57	23.854	1.78
		128	-0.65	57	22.07	-1.098
Average		4	-1.67	63	45.291	18.305
C 0.005, P 13		8	-0.9	63	38.017	14.249
		16	-0.18	63	32.205	10.504
		32	0.45	63	27.663	7.01
		64	0.89	63	24.544	3.884
		128	1.1	64	22.835	1.54
Very Good		4	1.1	70	32.599	10.429
C 0.0303, P 20		8	1.45	70	30.071	8.541
		16	1.79	70	27.816	6.795
		32	2.11	70	25.827	5.136
		64	2.39	70	24.259	3.572
		128	2.58	70	22.949	2.216
1.85-MHz Perfect Sloping (45-Deg.) Monopole Using MININEC Ground						
Monopole length: resonant with perfect ground; no radials						
Soil			Gain dBi	TO Angle	Resist	React
Very Poor			0.1	54	21.18	-0.056
Average			1.58	63	21.18	-0.056
Very Good			2.95	71	21.18	-0.056
	Note:	Mininec ground system always returns the source				
Table 7-2		impedance for a perfect ground.				

Fig. 7-4 shows the increased differential between the MININEC and NEC-4 gain reports. The MININEC over-estimations of gain result from the fact that the sloping wire has a horizontal component to its far field and thus is subject to the effects of the MININEC ground inaccuracy with low horizontal wires.


1.85-MHz 45-deg Mono w/ SN & MIN Gnds
Gain vs. Soil Types and Radials
Fig. 7-4
Maximum Gain (dBi)
4
2
0
-2
-4
-6
Min-Very Good
SN-Very Good
Min-Average
Min-Very Poor
SN-Average
SN-Very Poor
4
8
16
32
64
128
Number of SN Radials
VP-bur
AV-bur
VG-bur
VP-MIN
AV-MIN
VG-MIN


1.85-MHz 45-deg Mono w/ SN & MIN Gnds
Resistance vs. Soil Types & Radials
Fig. 7-5
Source Resistance (Ohms)
70
60
50
40
30
20
SN-Very Poor
SN-Average
SN-Very Good
Mininec
4
8
16
32
64
128
Number of SN Radials
VP-bur
AV-bur
VG-bur
MININEC

In **Fig. 7-5**, we have a comparable picture of the NEC-4 and MININEC source resistance reports. At 128 radials, the 3 NEC-4 resistance values tend to converge, but do not reach the MININEC report value.

3. *A ¼-λ Low Inverted-L*

A common amateur antenna for 160 meters is the inverted-L form of the monopole. In many installations, the absence of high supports limits the antenna height to about 10 m (about 32.8'). The required horizontal section for resonance over perfect ground is 30.69 m. Because the vertical section is so short, the impedance over perfect ground is 6.931 + 0.070 Ω with a maximum gain of 3.96 dBi. As the sample lines from the model show, this model used 0.001-m radius (2-mm diameter) wire throughout to simulate a typical amateur installation.

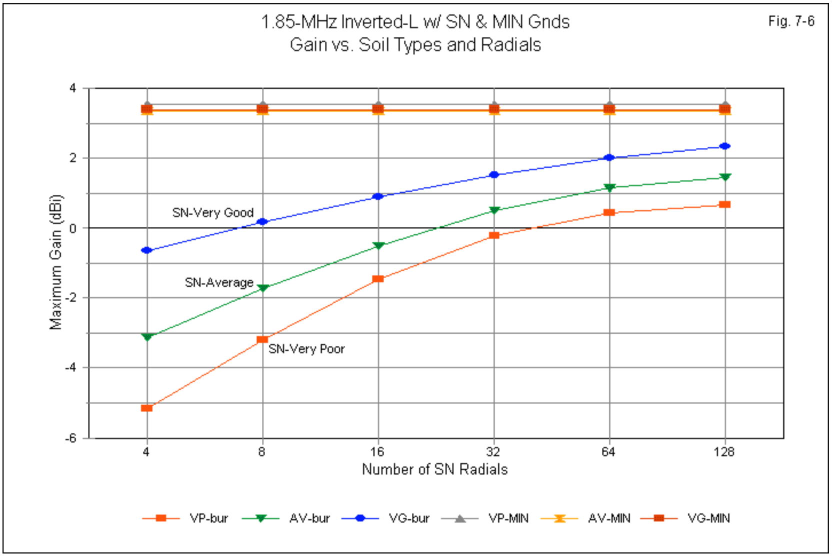
```
GW 1 5 0 0 0 0 0 10 .001
GW 1 10 0 0 10 30.69 0 10 .001
GW 2 1 3.65 0 -.1 0 0 0 .001
GW 2 10 40.5125 0 -.1 3.65 0 -.1 .001
GM 0 3 0 0 90 0 0 0 2 1 2 11
GE -1 -1 0
```

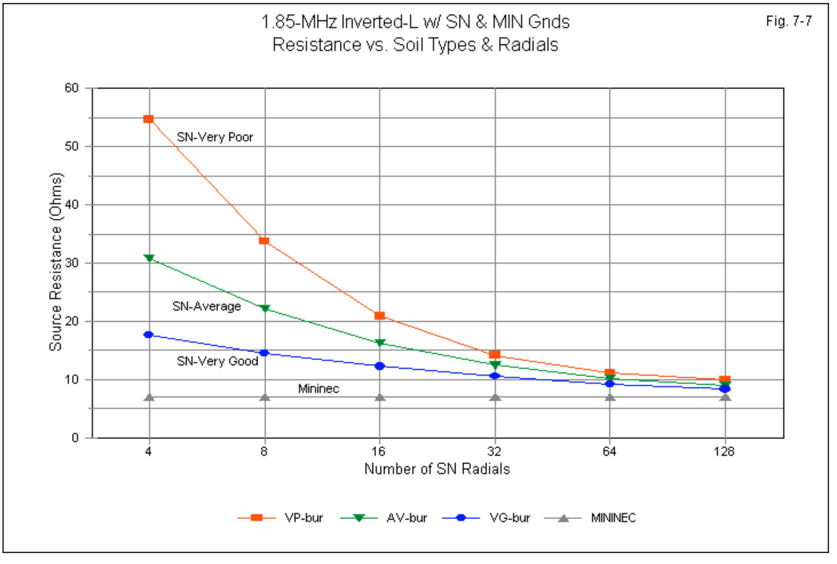
Although the highest current levels occur in the vertical portion of the inverted-L, considerable current remains in the long horizontal wire. That wire is only 0.062 λ above ground, well below the 0.2-λ limit for horizontal wires if the MININEC ground calculation system is to yield accurate results. We would expect that using a MININEC ground (even with the NEC-4 core) would result in further over-estimations of maximum gain, relative to the slanted monopole.

The MININEC-ground section of **Table 7-3** does not disappoint our expectations. Once more, the MININEC ground is unable to trace the variation in the TO angle over very poor soil. However, the biggest surprise in the data may be the relative equality of the 3 maximum gain reports. We find only a 0.2-dB variation in gain among the reports for the three radically different soil types. If we look only at the data for 128 buried radials, we find 1.68-dB differential in gain as we move from the poorest to the best soil quality in the survey. For smaller radial fields, the differential increases as the radial numbers decrease.

1.85-MHz Perfect Inverted-L with Perfect Radials and Various Soil Qualities						
Monopole length: resonant with perfect ground; radials 1/4 wavelength						
Soil		# Radials	Gain dBi	TO Angle	Resist	React
Very Poor		4	-5.16	44	54.663	33.228
C 0.001, P 5		8	-3.2	43	33.705	23.119
		16	-1.45	43	20.866	15.114
		32	-0.21	42	14.116	8.88
		64	0.43	41	11.11	4.784
		128	0.66	41	9.896	2.545
Average		4	-3.12	54	30.715	21.017
C 0.005, P 13		8	-1.73	54	22.1	15.433
		16	-0.51	54	16.269	11.125
		32	0.49	54	12.408	7.614
		64	1.15	53	10.096	4.807
		128	1.45	53	8.964	2.87
Very Good		4	-0.64	64	17.587	11.319
C 0.0303, P 20		8	0.18	64	14.503	8.759
		16	0.9	64	12.202	6.745
		32	1.52	64	10.458	5.059
		64	2.02	64	9.149	3.615
		128	2.34	64	8.29	2.435
1.85-MHz Perfect Inverted-L Using MININEC Ground						
Monopole length: resonant with perfect ground; no radials						
Soil			Gain dBi	TO Angle	Resist	React
Very Poor			3.55	42	6.931	0.07
Average			3.35	54	6.931	0.07
Very Good			3.4	64	6.931	0.07
	Note:	Mininec ground system always returns the source				
Table 7-3		impedance for a perfect ground.				

The dramatic over-estimation of gain becomes visually apparent in the graphed data in **Fig. 7-6**. The MININEC information at the top of the graph forms virtually a single line for all soil qualities. In contrast, the data for the SN buried radials creates a set of normal curves, with each soil quality showing a rising value of maximum gain.


1.85-MHz Inverted-L w/ SN & MIN Gnds
Gain vs. Soil Types and Radials
Fig. 7-6
Maximum Gain (dBi)
4
2
0
-2
-4
-6
SN-Very Good
SN-Average
SN-Very Poor
4
8
16
32
64
128
Number of SN Radials
VP-bur
AV-bur
VG-bur
VP-MIN
AV-MIN
VG-MIN


1.85-MHz Inverted-L w/ SN & MIN Gnds
Resistance vs. Soil Types & Radials
Fig. 7-7
Source Resistance (Ohms)
60
50
40
30
20
10
0
SN-Very Poor
SN-Average
SN-Very Good
Mininec
4
8
16
32
64
128
Number of SN Radials
VP-bur
AV-bur
VG-bur
MININEC

The source resistance information in **Fig. 7-7** shows the same pattern as for the slanted monopole, although the reported values of resistance differ. The values for all SN ground reports are higher than the corresponding reports for the MININEC ground.

The net result of these demonstrations is a simple conclusion. Even with a perfectly vertical monopole, the MININEC ground system over-estimates gain for all but the largest radial systems, regardless of soil type. As well, the use of the source impedance over perfect ground provides an information vacuum except for very large radial systems over better soils.

If the monopole has any horizontal component to its far-field radiation, then the MININEC system departs farther from reality in the direction of reporting unrealistically high gain values. As well, it fails to track deviations in the TO angle. The source resistance reports are largely useless as indicators of reality, where a higher resistance value generally indicates higher losses and lower gain. (This generalization is subject to reservations when soil quality includes very low values of conductivity and the source resistance may easily fall under the value over perfect ground on its way toward–but still distant from–the free-space source resistance for the monopole system.)

In general, then, the MININEC ground system, for all its convenience, is a very poor indicator of monopole array performance. As suggested in early chapters, if the modeled system includes buried radials, one should model those radials as wires below the ground in NEC-4 using the SN ground calculation system.

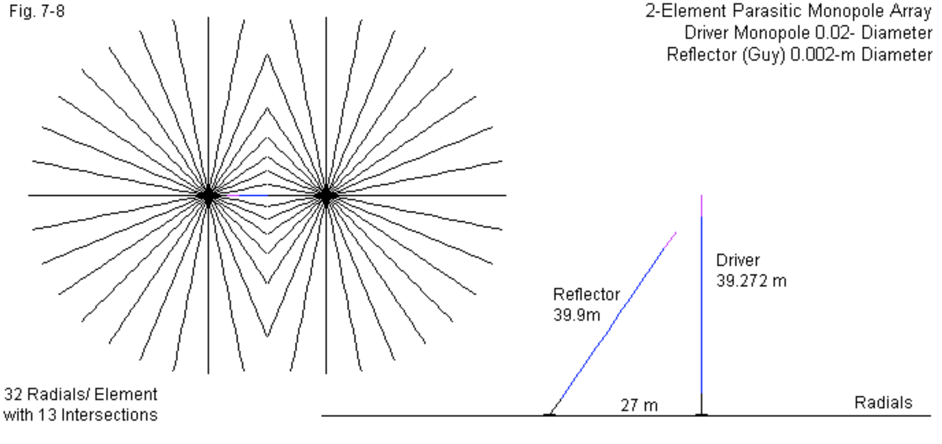
4. *A 2-Element Parasitic Array with a Sloping Guy-Wire Reflector*

There are many reasons why modelers continue to use the MININEC ground in lieu of buried radials. As we move from simple monopoles to more complex arrays, each monopole requires its own radial system. For some designs, the radials may intersect, forcing a decision on the modeler: carefully to mate the intersecting radial ends or to use independent radial systems at different level below ground. Since most modelers employ a radial-making facility in their software, the idea of tracking wires that cross at other than wire or segment junctions is daunting, despite the simple procedure outlined in Chapter 2.

Using radial systems at different levels requires attention to 2 features. First, the shallower radials of one element must not touch any of the wires extending from the other element down to the radial system final depth. Hence, we must use an odd number of radials with sufficient spread between radials to avoid the sloping wires from the radial hub of the other element. Second, the radial fields require a vertical separation to avoid unwanted interactions that attend some multiple systems when the levels are too closely spaced. For most cases, a separation of about 0.001 λ will avoid those interactions, but trial models using at least 2 levels of separation are necessary to test the consistency of the results.

Given the amount of work involved in creating either type of buried system with multiple radial fields, many modelers continue (even in professional circles) to use the MININEC ground system. For some purposes, it may prove adequate. For many others, it fails. To see an example of a failure, let's consider a 2-element monopole array. The driven element will use the standard monopole that is 39.272-m long with a 0.01-m radius. The parasitic reflector will consist of a wire traveling along a non-conductive guy wire to the monopole tip. The wire has a radius of 0.001 m. **Fig. 7-8** outlines the system.

Fig. 7-8



The test design is neither good nor bad, but simply adequate for our use here. The reflector base is 27 m from the driven monopole. I modeled the system over perfect ground to determine the monopole length based on the best front-to-back ratio that I could obtain in that environment. The guy-reflector forms a 55.5° and with the ground and a 34.5° (virtual) angle with the monopole tip. Over perfect ground, the array reports a forward gain of 8.80 dBi with a 180° front to back ratio of 23.31 dB. I took no measures to resonate the system, so the source impedance is 30.82 + 49.0 Ω.

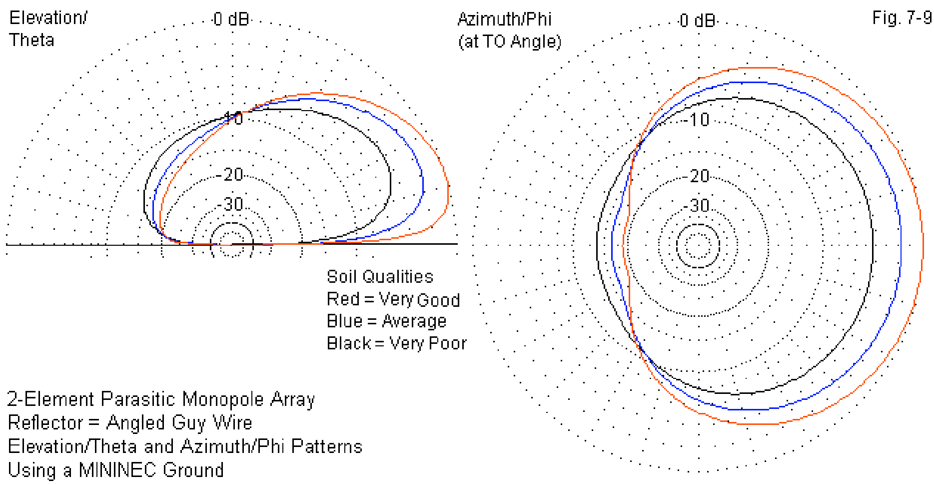


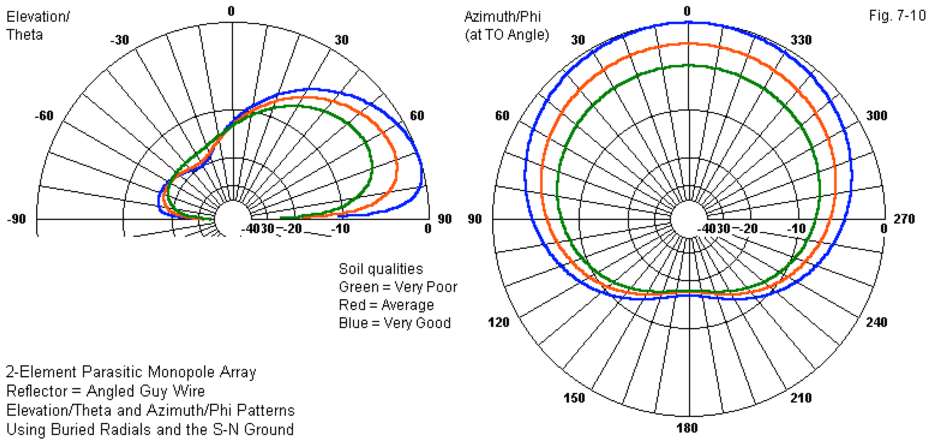
Fig. 7-9, drawn from EZNEC, shows what happens to the azimuth/phi and the elevation/theta patterns as we place these 2 elements over various soil qualities using the MININEC ground. As shown in **Table 7-4**, the front-to-back ratio reports run between 9.37 dB and 18.77 dB. The gain reports range between 2.62 dBi and 6.91 dBi with improving soil quality. Of course, the MININEC report of the source impedance remains constant.

The question that confronts us here concerns the adequacy of these reports when compared to comparable reports with a buried system of radials.

1.85-MHz Perfect 2-El Beam With Perfect Ground						
		Gain dBi		F-B Ratio	Resist	React
		8.8		23.31	30.82	49
1.85-MHz Perfect 2-El Beam with Perfect Radials and Various Soil Qualities						
Monopole length: resonant with perfect ground; 32 radials 1/4 wavelength						
Soil		Gain dBi	TO Angle	F-B Ratio	Resist	React
Very Poor		1.25	60	13	59.771	50.573
Average		3.53	66	15.03	56.74	53.357
Very Good		5.51	72	16.11	52.145	53.757
1.85-MHz Perfect 2-El Beam Using MININEC Ground						
Monopole length: resonant with perfect ground; no radials						
Soil		Gain dBi	TO Angle	F-B Ratio	Resist	React
Very Poor		2.62	60	9.37	30.82	49
Average		5.2	66	14.6	30.82	49
Very Good		6.91	72	18.77	30.82	49
	Note:	Mininec ground system always returns the source				
Table 7-4		impedance for a perfect ground.				

The tabulated data suggests that the MININEC ground reports are far from adequate. However, we must first lay a foundation for the SN reports. As shown in **Fig. 7-8**, the buried radial system consists of a pair of intersecting 32-radial fields. There are 13 intersections of radials that just touch. However, the field does not include wires that connect the intersections. The entire model uses length-tapering techniques in both the monopole and the radials. Since the resulting model contains 80 wires and 1088 segments, I shall not reproduce it here, but include it among the models attached to the volume.

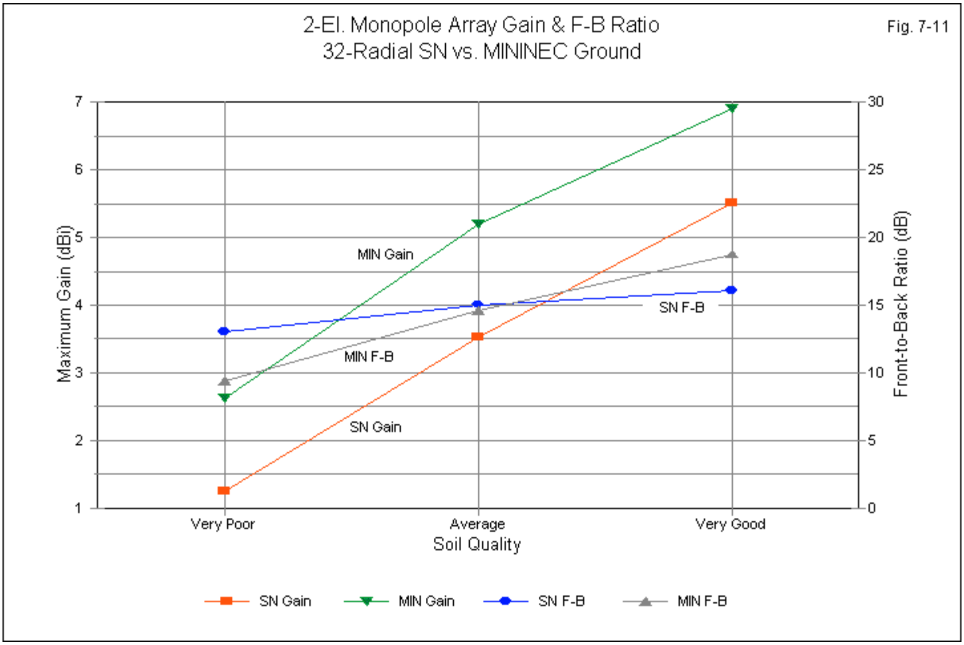
The model yields the data appearing in the upper portion of **Table 7-4**. Note that all reported gain levels are lower than those reported by the use of the MININEC ground. However, the 180° front-to-back ratios vary considerably less across the span of soil qualities than the values for the MININEC ground trials. In fact, the radiation patterns produced with 32 buried radials per element have some interesting differences from those yielded by the MININEC ground models. See the GNEC elevation/theta and azimuth/phi plots in **Fig. 7-10**.



The azimuth/phi lots show a much more distinctly cardioidal shape than the ones in **Fig. 7-9**. The effect is a wider beam width. Over very good soil, the model with buried radials shows a 20° wider beamwidth than the MININEC-ground model.

We also find some interesting differences in the elevation/theta patterns. All of the MININEC-ground models–regardless of soil quality–display egg-shaped patterns. In other words, we find no reduction in gain in the near-vertical region of the pattern, but only a smooth increase of gain as we proceed from the rearward direction to the forward direction. For the models using buried radials, as we progress beyond very poor soil, we see fairly distinct forward and rearward lobes. Once more using the version of the model over very good soil, the buried radial version shows a 3.5-dB decrease in signal strength directly overhead relative to the report from the MININEC-ground model. The differential is far higher than the 1.5-dB difference between models with respect to maximum forward gain.

Fig. 7-11 summarizes the differences for all soil qualities in both the maximum forward gain and the 180° front-to-back ratio levels. Note that the MININEC-ground version of the array has systematically over-estimated forward gain by nearly 1.5 dB, regardless of soil quality, with a slightly higher differential over average soil. We have already noted the differences in front-to-back ratio ranges.



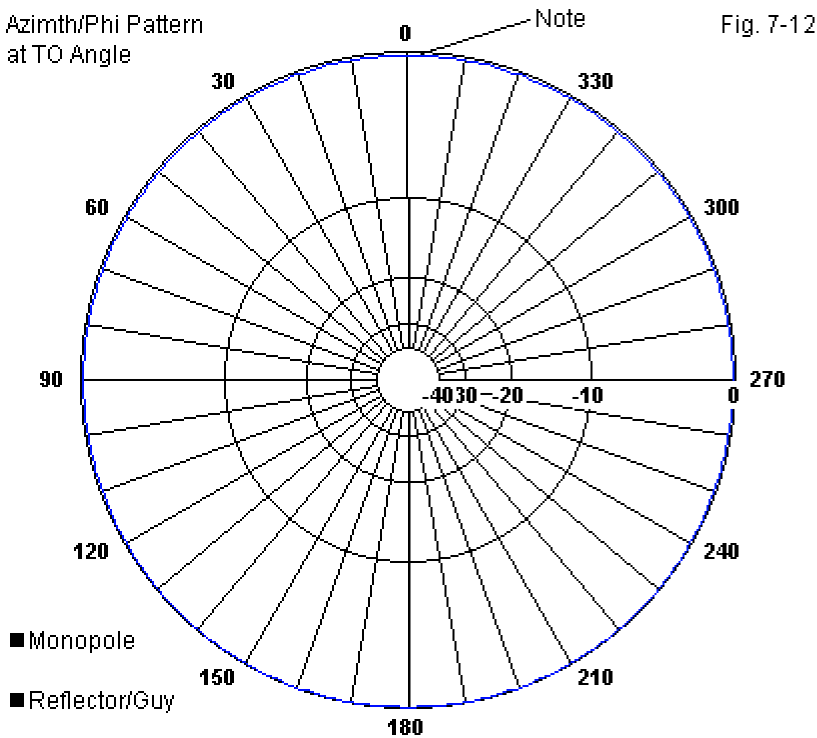
The upshot of the exercise is that even sloping parasitic elements adversely affect the ability of the MININEC ground to present reliable on the performance of a monopole array. Even allowing for the fact that MININEC-ground models approach buried-radial models with fields of about 128 radials, we find too many differences in the reported results to trust the version using a MININEC ground.

Before we depart the 2-element array, let's quickly take up an often-asked question: Do I really need radials for the parasitic element? Can I simply use a wire from ground level up the non-conductive guy and obtain the desired parasitic element effect? The reasoning behind the question is not simply a matter of construction simplicity. The key though is that the parasitic element is over a portion of the monopole radial field.

Unfortunately, the parasitic element (a reflector) requires its own radial field, if for no other reason than to complete the element as one resonant at some lower frequency than the driven element. Without the field, it becomes simply an untuned wire resonant at about twice the operating frequency. As shown in the data in **Table 7-5**, the performance of the array with the radial-less reflector is simply the performance of a single monopole.

Monopole Alone vs. Monopole w/ Reflector Guy					
Monopole alone uses 32 radials.					
Monopole w/ reflector/guy uses 33 radials on only the monopole.					
Soil	Version	Gain dBi	TO Angle	Resist	React
Very Poor	M alone	-1.22	62	44.047	2.201
	M w/refl	-1.11	62	38.275	2.68
Average	M alone	0.89	67	41.31	3.205
	M w/refl	1.02	67	39.616	3.582
Very Good	M alone	2.75	73	39.83	2.425
	M w/refl	2.87	73	38.33	2.799
	Note:	All pattern of the monopole with reflector			
		guy show a 0.1-dB "front-to-back" ratio.			
Table 7-5		Maximum gain is toward the reflector/guy.			

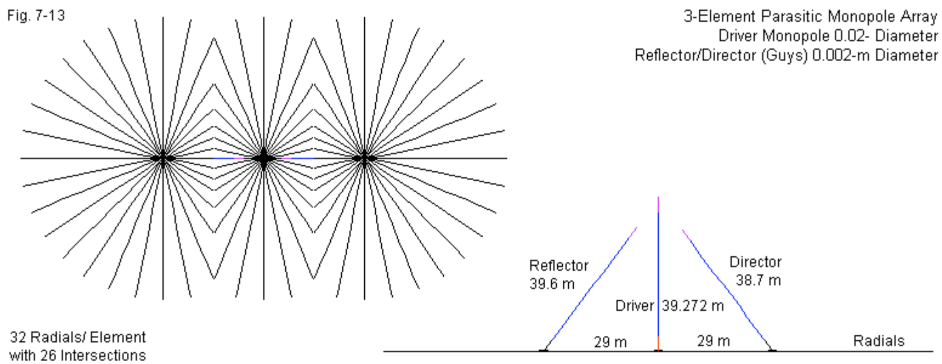
To obtain the tabular data, I removed the intersecting radial fields and gave the monopole a 32-radial system with full-length radials in all directions. Note that the maximum gain report with the reflector in place is about 0.12-dB higher than for the monopole alone, regardless of soil quality. Like any untuned object within the near field of a monopole, the thin reflector wire interacts sufficiently to produce a very small directional characteristic to the otherwise circular pattern. Not surprisingly, the forward-to-rearward differential is just about 0.12 dB. **Fig. 7-12** shows a sample azimuth pattern at the TO angle. However, you may need to peer intently to see the slight reduction in gain. Note that the forward direction with a radial-less parasitic element is toward that element. It has become a faint shadow of a director without its radial system. That fact is unimportant to antenna operation. However, it is a confirmation of the fact that, without the radials, the sloping element has a resonant frequency higher than the operating frequency, which is the required condition for a parasitic director.



2-Element Parasitic Monopole Array: Reflector = Angled Guy Wire
Reflector with No Radials

5. *A 3-Element Parasitic Array with a Sloping Guy-Wire Reflector and Director*

The 2-element sloping-reflector parasitic monopole array may leave the impression that, except for the reported gain, the values reported by MININEC are within some sort of ballpark of being useful. Although I might contend otherwise, we can move the discussion out of the academic into a more realistic arena by looking at one more model. **Fig. 7-13** outlines the basic shape and dimensions of a 3-element array that is similar to the 2-element array. The key difference is the use of sloping guy wires to form both a director and a reflector.

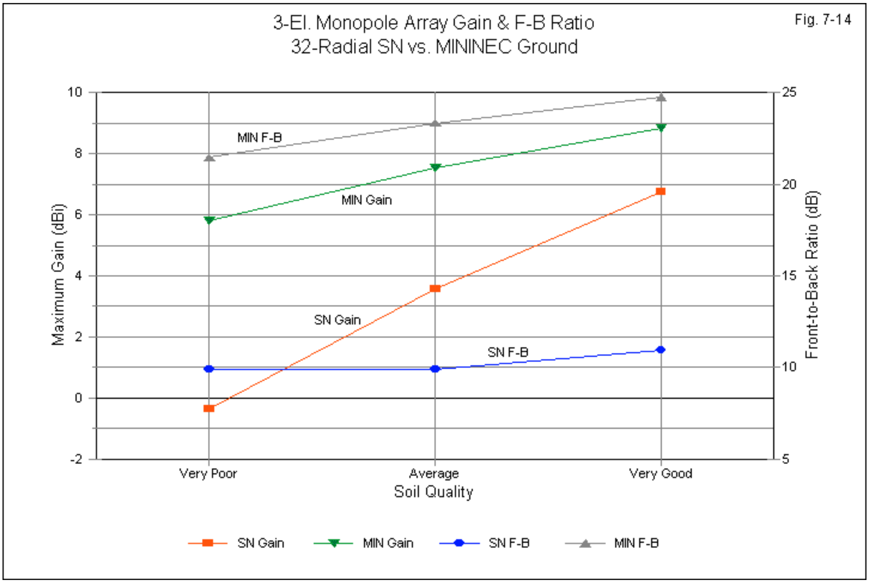


Initially we may focus on the side view, since that much of the sketch will affect the initial modeling over perfect ground and the modeling over a MININEC ground. I have retained the 39.272-m monopole with a radius of 0.01 m, without regard for the resonance of the system. Modeling the array over perfect ground produced a set of dimensions that yielded the highest 180° front-to-back ratio at 1.85 MHz. Since the parasitic elements are each 29 m away from the driver at their bases, the angle with the ground is 53.5° and the virtual angle with the monopole (had they reached it) is 36.5°. The reflector is 39.6-m long, while the director is 38.7-m long. Over perfect ground, the model produces a gain of 10.47 dBi and a 26.59-dB front-to-back ratio.

When we bury the radials, the model uses length-tapered elements in the verticals and the radials. The radial system resembles the earlier 2-element array field, but interlocks 3 32-radial fields with 26 intersections. The resulting model is again too long for reproduction here, since it has 619 wires.

Table 7-6 provides the modeled performance data for both the MININEC ground version and the SN-ground buried-radial version. The critical gain and front-to-back information appear in graphical form in **Fig. 7-14**.

1.85-MHz Perfect 3-El Beam With Perfect Ground						
		Gain dBi		F-B Ratio	Resist	React
		10.47		26.59	8.8	21.03
1.85-MHz Perfect 3-El Beam with Perfect Radials and Various Soil Qualities						
Monopole length: resonant with perfect ground; 32 radials 1/4 wavelength						
Soil		Gain dBi	TO Angle	F-B Ratio	Resist	React
Very Poor		-0.35	62	9.89	12.671	32.148
Average		3.58	68	9.87	8.729	29.973
Very Good		6.75	73	10.92	7.185	25.994
1.85-MHz Perfect 3-El Beam Using MININEC Ground						
Monopole length: resonant with perfect ground; no radials						
Soil		Gain dBi	TO Angle	F-B Ratio	Resist	React
Very Poor		5.82	61	21.46	8.8	21.03
Average		7.52	67	23.34	8.8	21.03
Very Good		8.82	73	24.78	8.8	21.03
	Note:	Mininec ground system always returns the source				
Table 7-6		impedance for a perfect ground.				



In the graph, the reported MININEC-ground values occupy the upper portion of the data area. The gain reports range from 2 dB (very good ground) to 6 dB (very poor ground) higher than the maximum gain reported over the intersection radial system. In the MININEC-ground reports, the front-to-back ratio rises in step with the gain as we improve the ground quality. In fact, the MININEC-ground reports of the front-to-back ratio tend to preserve the value reported by the original design over perfect ground.

In contrast, the SN-ground version with buried radials reports very modest gain values. In fact, over average ground, the gain only equals the 2-element array over the same soil. The 3-element array shows worse gain than the 2-element array over very poor soil. Over very good ground, the 3-element array achieves a little over 1 dB of added gain by adding a director. The front-to-back ratios are all more than 10-dB lower than the MININEC-ground models report.

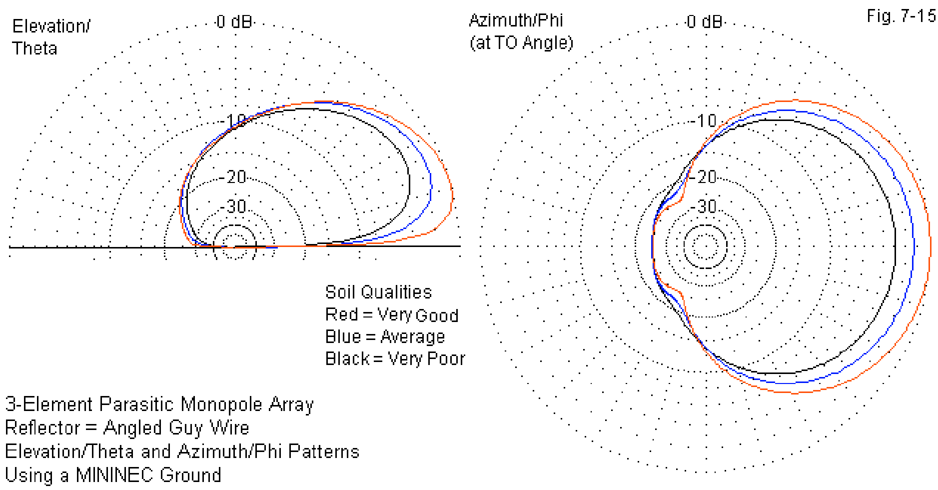
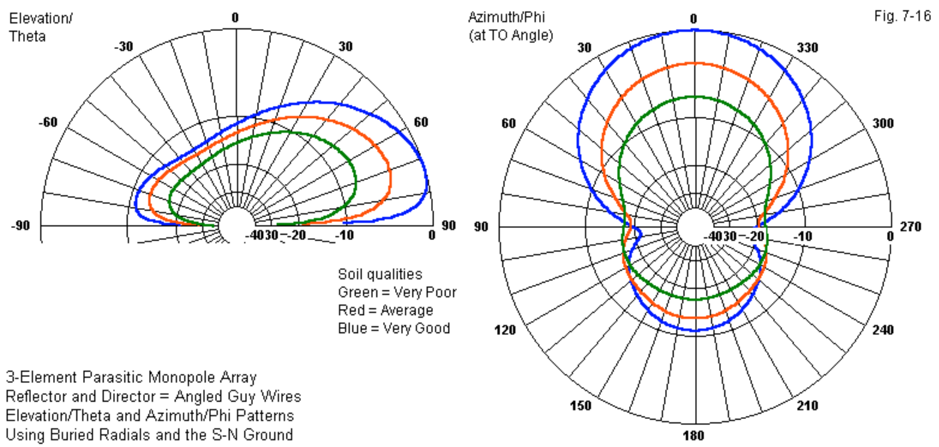


Fig. 7-15 shows the radiation patterns that result from the MININEC-ground models. As we saw in the patterns for the 2-element array, the elevation/theta patterns are simple eggs, differentiated only by the gain differences for the 3 soil

qualities. The azimuth/phi patterns also have a high level of similarity except for maximum gain. As the gain rises with improving soil, the rear lobe just begins to acquire a shape of its own.



The corresponding patterns for the SN-ground models (**Fig. 7-16**) with the buried radial system show quite difference characteristics. Perhaps the most notable effect appears in the azimuth/phi patterns, where the 3-element array develops side nulls as the ground quality improves.

It is clear that the 2 ground calculation systems and the radial field for the SN system yield very different performance portraits of the 3-element array with 2 sloping parasitic elements. The consistency of the results with the corresponding results for the 2-element array that uses only a reflector suggest that the MININEC-ground versions of the models do not provide reasonably accurate guidance for the likely performance of the antenna. However, the model with the intersecting buried radial fields is also limited in the guidance that it can give. The results apply only to the elements as set by the original design activity and by the structure of the buried radial system. For improved performance for a given ground quality, we might have to make several changes. First, the parasitic elements may need re-sizing and possibly even re-angling for better gain and especially for better front-to-back ratio.

Since the reflector and director of a 3-element array interact, the process might prove tedious, although more so on a physical array than on a model.

Equally important is that any difference in the radial field design may have an impact on the performance figures. The intersecting system does not use connecting wires between intersections. If one lays down a set of overlapping radials, more radical performance changes may results, requiring more radical design changes. (Some preliminary tests of overlapping radial systems suggest this direction of re-design, although that step lies outside the scope of this exercise.)

Despite the limitations involved, NEC-4 buried-radial fields and the SN ground calculation system remain the best routes to modeling an array that employs parasitic elements (especially sloping ones) over a physical buried radial set. For best guidance, the model must as fully as circumstance permits reflect all of the relevant electrically active geometric details of the antenna system itself.

SCVs and Radials

A certain category of vertically polarized HF arrays tends to arouse some disagreement with respect to ground planes, that is, systems of radials centered under the vertical radiating elements. In other places, I have referred to the category of antennas as self-contained verticals (SCVs). The total collection includes such classic designs as side-fed deltas, side-fed rectangles (including squares or quad loops), half squares, and bobtail curtains. Of course, there are chained multiples of the basic designs, such as double deltas and double rectangles. Indeed, the bobtail curtain is in fact a double half square, despite the historical sequence that saw the appearance of the bobtail before the emergence of the half square.

The genetic root of the entire class of antennas is the vertical dipole. All of the minimal members of the SCV family use various techniques to produce a pair of vertical dipoles spaced as far apart as feasible–up to ½ λ–using a single wire. The wire is approximately 1λ long. By judicious bending and folding, the goal is to create a pair of vertically polarized dipoles spaced for maximum gain. Two independent vertical dipoles, fed in phase, show maximum gain when they are ½-λ apart. A single wire with a maximum length in the vicinity of 1 λ cannot achieve the desired ½-λ spacing without the disappearance of the dipole as a physically vertical element. However, the SCV goal is to find a shape that balances the spacing and vertical length requirements for maximum performance. In the lower HF range, users also consider the ability of a design to fit the antenna space available.

The basic question that we may pose to the SCV antennas is whether they need or might benefit significantly from providing a radial system beneath each vertical element. We shall construe the idea of the vertical elements to be the portions of the antenna with the highest current. Given the constraints of the designs, some parts of what we might otherwise call the vertical dipole will inevitably be horizontal or slanted.

We cannot survey all of the members of the SCV family, but we can look at a few representatives. For reference, we shall begin with the vertical dipole. Then we shall turn to the half square and the bobtail curtain. Both of these family members have open-end vertical elements. Hence, we may know easily just where to place a radial system.

1. *A ½-λ Vertical Dipole*

Unlike a vertical monopole, the vertical dipole always has an elevated feedpoint relative to the ground. About the closest feedpoint or base height that we can use for a vertical dipole is ¼ λ, if we wish to avoid contact between the dipole end and ground. (In the next chapter, we shall in fact look at the ½-λ antenna touching ground.) Vertical dipoles tend to show higher gain and a TO angle closer to the horizon as we raise the antenna. At some base height, the second elevation lobe comes to dominate the far-field radiation pattern, reducing the utility of the antenna for low-angle DX communications. The height varies with the soil quality, just as it did for elevated monopoles. For very poor soil, the height at which the second lobe becomes stronger than the lower lobe is much greater than for average soils and better.

The left side of **Fig. 7-17** shows the parameters of our exercise. First, we shall establish a resonant free-space dipole using our standard 0.01-m radius lossless wire. Then we shall place it at various heights above ground as determined by the distance from the ground to the feedpoint. We shall use height of 0.25, 0.35, 0.45, and 0.55 λ above ground to check the range of performance. The data tables will show the corresponding. heights in meters for each of our standard test frequencies (1.85, 3.6, and 7.15 MHz).

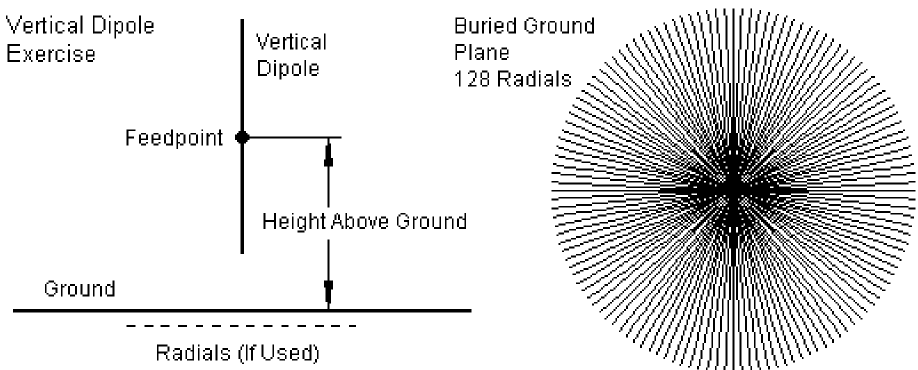


Fig. 7-17

Each survey will have 2 components. The first runs, over each of the standard soil qualities and heights, will use no radials. The second part of the exercise will add a 128-radial system of 1/4-λ wires buried the standard 0.1-m below ground. For simplicity, the models for the radials use a numerical Green's file, such as the following sample.

```
GW 1 11 0 0 -.1 40.5125 0 -.1 .001
GR 0 128
GE -1 -1 0
FR 0 1 0 0 1.85 1
GN 2 0 0 0 13 .005
WG r128-ave-160.ngf
EN
```

The actual test files call on the listed .ngf file, as shown by the following model lines. Changing radial systems for different soils becomes a simple matter of altering the file name in the GF line of the model.

```
GF 0 r128-ave-160.ngf
GW 2 21 0 0 -39.279 0 0 39.279 .01
GM 0 0 0 0 0 0 0 40.5125 2 1 2 21
GE -1 -1 0
EX 0 2 11 0 1 0
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

For the initial run, we can combine the required commands in a single file, since we have a simple 21-segment vertical wire. The GM line in the initial file and in the version using the .ngf file allows easy setting of the dipole height.

```
GW 2 21 0 0 -39.279 0 0 39.279 .01
GM 0 0 0 0 0 0 0 40.5125 2 1 2 21
GE -1 -1 0
EX 0 2 11 0 1 0
FR 0 1 0 0 1.85 1
GN 2 0 0 0 13 .005
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

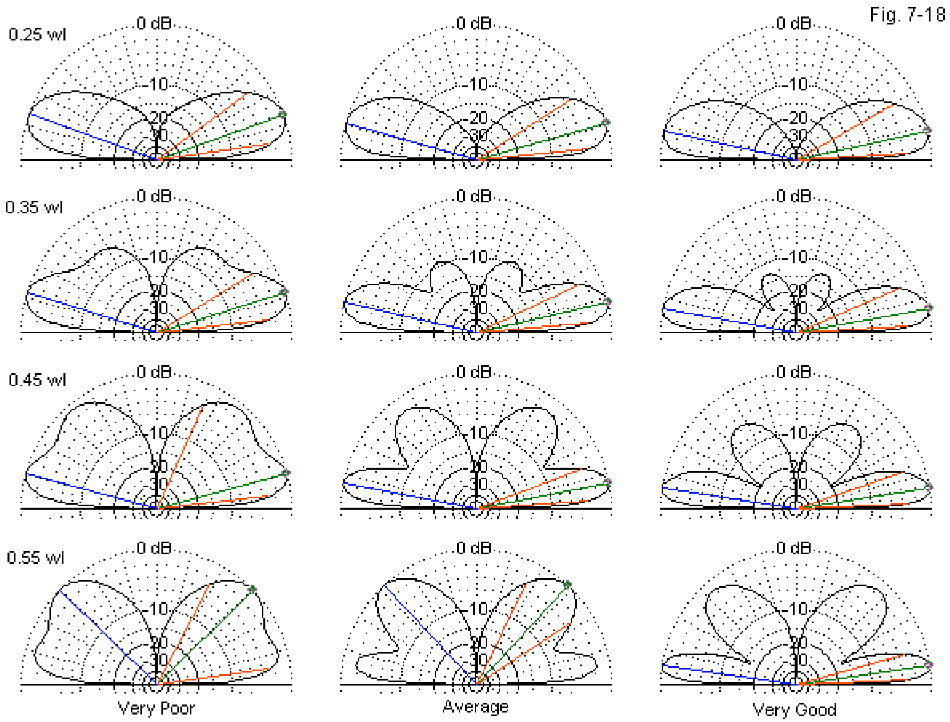
Both file samples show average soil values in the GN line and a height of ¼ λ at 1.85 MHz. The sample files shown are typical of all of the models used in this sequence of tests.

The data for 1.85 MHz appear in **Table 7-7**. Note that the gain does not always rise with increase height, even when the elevation lobe closest to the horizon dominates. As we saw in the case of elevated ground-plane monopoles in the preceding chapter, secondary lobes emerge and grow. As they grow, the energy in the lowest lobe may diminish, even though the lowest lobe remains stronger than the higher lobe.

Also notable is the fact that when we place the dipole feedpoint 0.55 λ above ground, the second elevation lobe dominates over both average and very poor soil. The indicator for this situation is the lower TO (theta) angle value that denotes a main lobe at a higher angle above the horizon.

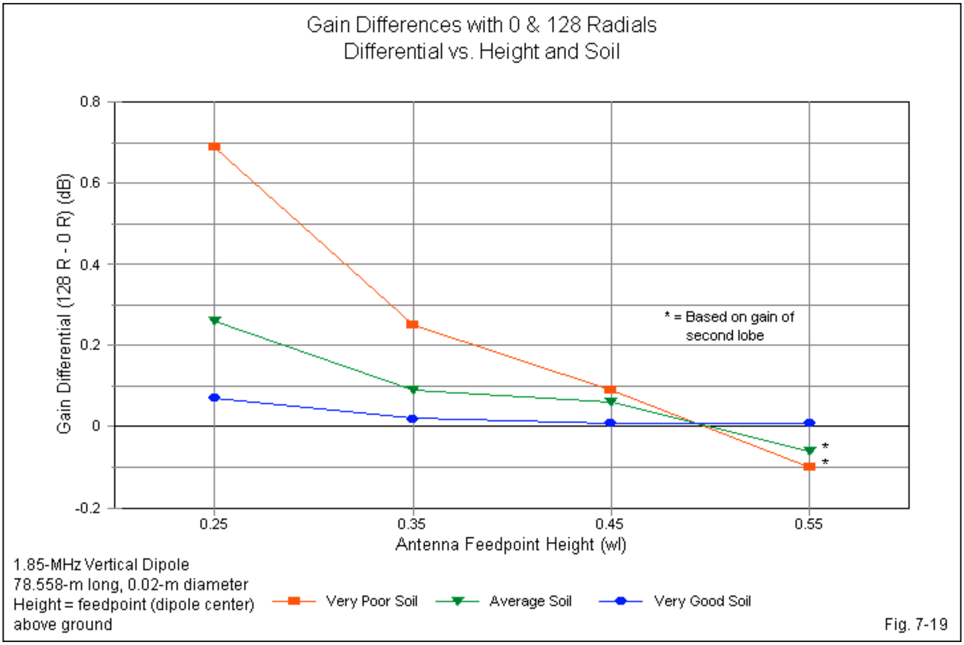
1.85-MHz Vertical Dipole at Various Height Above Various Grounds							
Performance with either no radials or 128 buried radials							
Base height indicates height of feedpoint (center) above ground							
Height wl	Height m	Soil	# Radials	Gain dBi	TO Angle	Resist	React
0.25	40.5125	Very Poor	0	-1.57	71	92.282	3.49
			128	-0.88	70	91.675	13.1
		Average	0	1.16	74	100.92	9.292
			128	1.42	74	97.605	13.07
		Very Good	0	3.76	78	101.381	12.455
			128	3.83	78	100.353	13.619
0.35	56.7125	Very Poor	0	-0.92	73	71.469	-6.841
			128	-0.67	73	71.992	-4.524
		Average	0	1.32	77	73.322	-8.118
			128	1.41	77	73.579	-7.02
		Very Good	0	4.3	80	74.569	-8.384
			128	4.32	80	74.568	-8.048
0.45	72.9225	Very Poor	0	-0.39	75	63.233	0.98
			128	-0.3	75	63.994	1.267
		Average	0	1.09	79	62.164	-0.819
			128	1.15	79	62.524	-0.696
		Very Good	0	4.48	81	62.077	-1.734
			128	4.49	81	62.196	-1.708
0.55	89.1275	Very Poor	0	1.18	46	65.343	3.901
			128	1.08	46	65.582	3.705
		Average	0	1.99	43	63.864	3.389
			128	1.93	43	63.977	3.279
		Very Good	0	3.79	82	63.297	3.079
Table 7			128	3.8	82	63.329	3.038

To acquaint you with the emergence and development of the elevation lobes for vertical dipoles over various ground qualities, **Fig. 7-18** provides a small gallery of selected elevation/theta patterns. The patterns do not compare radiation strength among plots, but only show the relative strength of lobes within each pattern. The green line indicates the strongest lobe, while the red lines provide a visual indication of the vertical beamwidth. You may wish to compare these patterns to similar galleries for ground-plane monopoles in earlier chapters. One feature that both sets of galleries share is that lobes become sharper–with deeper and more distinctive nulls–as we improve the soil quality.



A Gallery of Elevation/Theta Plots: Vertical Dipole
Listed Height Indicates Distance from Ground to Center Feedpoint

Our main question was whether the presence of a set of radials beneath the vertical dipole enhances performance. The data in **Table 7-7** provide the answer, but we may get a better view of the patterns in the data by graphing the differentials between the no-radial and the 128-radial tests. **Fig. 7-19** graphs the data for the 3 levels of ground quality and for each height in the test sequence.



Two general trends emerge from the data. First, the higher that the vertical dipole is above ground level, the less that a radial system adds to the antenna gain. Second, the better the soil quality is beneath the antenna, the less that a radial system adds to the performance. The maximum gain benefit occurs with very poor soil at a height of 0.25λ. This height places the end of the antenna only a meter above ground. In this case, the gain increase is under 0.7 dB. Note that we obtain this increase with 128 radials. Increases will be smaller with sparser radial systems. Whether the potential gain increase justifies the work and cost of installing 128 radials is a user judgment.

I repeated the test at 3.6 MHz, again beginning with a 0.01-m radius vertical dipole that is resonant in free space. At ¼ λ feedpoint height, the dipole tip is just over ½ m above ground. **Table 7-8** provides the data for the test runs for each height and each soil type, using no radials and a system of 128 ¼-λ radials buried

0.1 m below ground level.

3.6-MHz Vertical Dipole at Various Height Above Various Grounds							
Performance with either no radials or 128 buried radials							
Base height indicates height of feedpoint (center) above ground							
Height wl	Height m	Soil	# Radials	Gain dBi	TO Angle	Resist	React
0.25	20.8189	Very Poor	0	-1.36	69	94.821	1.791
			128	-0.56	69	89.346	14.698
		Average	0	0.23	73	99.936	7.255
			128	0.62	73	95.951	13.167
		Very Good	0	2.94	76	101.516	11.115
			128	3.06	76	99.939	13.053
0.35	29.1465	Very Poor	0	-0.26	72	71.544	-5.733
			128	-0.01	72	72.485	-3.046
		Average	0	0.44	76	73.085	-7.556
			128	0.58	76	73.564	-6.047
		Very Good	0	3.31	79	74.546	-8.271
			128	3.35	79	74.725	-7.727
0.45	37.4741	Very Poor	0	0.62	73	64.357	1.334
			128	0.7	73	65.238	1.614
		Average	0	0.39	78	62.452	-0.21
			128	0.47	78	62.964	-0.069
		Very Good	0	3.34	80	61.98	-1.384
			128	3.36	80	62.172	-1.341
0.55	45.8016	Very Poor	0	1.14	74	66.251	3.699
			128	1.15	74	66.528	3.447
		Average	0	1.59	43	64.281	3.566
			128	1.51	43	64.43	3.406
		Very Good	0	2.51	82	63.4	3.294
Table 8			128	2.53	82	63.452	3.229

Perhaps the only significant variation between the 1.85-MHz and the 3.6-MHz data is the fact that, at a height of 0.55 λ, the second lobe dominates only for average soil. This phenomenon is consistent with the slight variations in lobe emergence and growth as a function of frequency. However, we still see the reduction of gain over average soil as we move the vertical dipole upward from 0.35 λ to 0.45 λ. In fact, the lobe patterns of emergence and growth are too similar to those for 1.85 MHz to justify another gallery of elevation/theta plots.

7.15-MHz Vertical Dipole at Various Height Above Various Grounds							
Performance with either no radials or 128 buried radials							
Base height indicates height of feedpoint (center) above ground							
Height wl	Height m	Soil	# Radials	Gain dBi	TO Angle	Resist	React
0.25	10.4823	Very Poor	0	-0.74	69	91.766	1.933
			128	0.05	68	88.455	16.44
		Average	0	-0.1	72	98.089	5.574
			128	0.41	71	94.614	13.872
		Very Good	0	1.95	75	101.358	9.201
			128	2.15	75	99.222	12.417
0.35	14.6752	Very Poor	0	0.47	71	71.659	-4.976
			128	0.72	71	72.99	-2.13
		Average	0	0.38	75	72.605	-6.906
			128	0.56	74	73.474	-5.097
		Very Good	0	2.18	78	73.879	-8.206
			128	2.25	78	74.205	-7.383
0.45	18.8681	Very Poor	0	1.39	73	65.209	0.955
			128	1.47	73	66.228	1.202
		Average	0	0.67	76	63.001	0.095
			128	0.74	76	63.671	0.197
		Very Good	0	2.07	79	61.937	-1.002
			128	2.11	79	62.236	-0.949
0.55	23.061	Very Poor	0	1.89	74	66.766	3.043
			128	1.91	74	67.071	2.736
		Average	0	1.04	43	64.762	3.428
			128	0.94	43	64.931	3.205
		Very Good	0	2.12	43	63.584	3.44
Table 9			128	2.07	43	63.661	3.339

Table 7-9 shows the test results for 7.15 MHz, using the same parameters. As we increase frequency further, we may note a general compression of the range of gain increase with height. Because the second lobe begins to dominate at the 0.55-λ feedpoint height, we cannot be exact, but roughly–from 1.85 MHz to 7.15 MHz–we find over 2.5-dB reduction in the range of values from the very worst to the very best.

Note also that at 7.15 MHz, the dominance of the 2nd lobe occurs over average and very good soil, but not over very poor soil. The 2nd-lobe dominance cases appear as starred entries in **Table 7-10**. With the exception of lobe dominance at the highest feedpoint level, the lobe emergence patterns as very close to those for the other test frequencies.

Gain Differentials With 0 and 128 Radials						Table 10
1.85 MHz						
Soil	Height wl	0.25	0.35	0.45	0.55	
VP		0.69	0.25	0.09	-0.1	*
Av		0.26	0.09	0.06	-0.06	*
VG		0.07	0.02	0.01	0.01	
3.6 MHz						
Soil	Height wl	0.25	0.35	0.45	0.55	
VP		0.8	0.25	0.08	0.01	
Av		0.39	0.14	0.08	-0.08	*
VG		0.12	0.04	0.02	0.02	
7.15 MHz						
Soil	Height wl	0.25	0.35	0.45	0.55	
VP		0.79	0.25	0.08	0.02	
Av		0.51	0.18	0.07	-0.1	*
VG		0.2	0.07	0.04	-0.05	*
Starred entries at 0.55 wl show maximum gain on the 2nd elevation lobe.						

Another similarity among all of the test frequencies is the pattern of gain differentials between no radials and 128 radials. The function of **Table 7-10** is to summarize the gain advantage offered by adding a 128-radial field beneath the vertical dipoles. (Starred entries actually indicate inappropriate heights for the dipole.) In general, only over very poor soil is a 128-radial field significant, and then only marginally so. Anything less than 128 radials in the field, and the margin becomes virtually invisible, even in numerical terms, let alone operationally.

As noted at the beginning of this set of test runs, we shall look more closely at the ½-λ vertical element with a base feed in the next chapter. The notes here apply only to center-fed dipoles.

2. *A Half-Square Array*

Although the half-square array appeared after its larger cousin, the bobtail curtain, it is the more fundamental of the two antennas. **Fig. 7-20** provides an outline of the half square, along with some of the terms that will apply to our modeling tests.

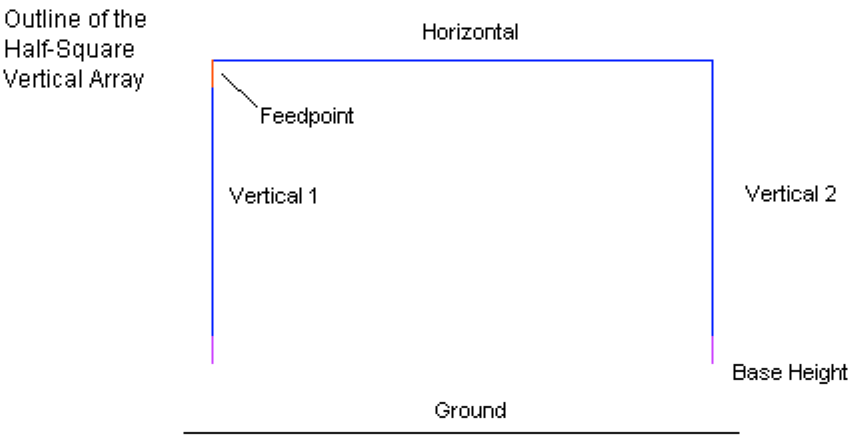
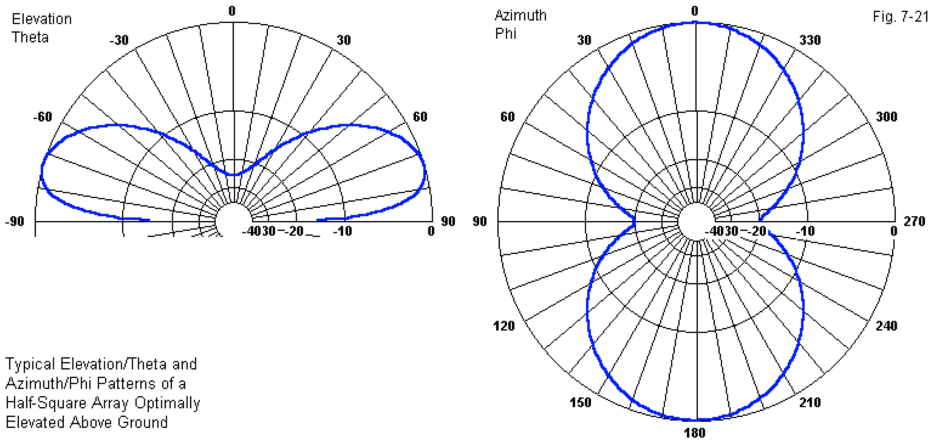


Fig. 7-20

The half-square consists of 2 vertical monopoles having their regions of highest current at the top. Each monopole forms a dipole with half of the horizontal wire between them. However, the current phasing along the horizontal wire results in the virtual (although not quite perfectly complete) cancellation of radiation from that portion of the antenna. The line acts as a phasing line so that the second vertical is in phase with the first. Since the two vertical elements are about ½ λ apart, we obtain a very useful bi-directional pattern of vertically polarized radiation at relatively low TO angles relative to the horizon. **Fig. 7-21** shows a representative pair of azimuth/phi and elevation/theta patterns from the half-square over average ground. The pattern shapes do not change significantly as we move to better and poorer soils.



Typical Elevation/Theta and Azimuth/Phi Patterns of a Half-Square Array Optimally Elevated Above Ground

The standard low-impedance feedpoint for a half square is at one of the 2 upper corners, at the junction of the vertical and horizontal wires. Before we close the chapter, we shall look at alternative feed systems for the half square (and the bobtail curtain). All of the test runs in this section use the corner feedpoint.

The half square has two peculiarities that affect its performance. First, for that best performance, the proportions between the horizontal and vertical wires are not 2:1. Rather, they are closer to a ratio of 8:5. The models in the test runs were resonated in a free-space environment and then carried unchanged to the ground. Second, at each test frequency, the array shows maximum gain at a different height above ground, and that height is not a single fraction of a wavelength. The range of heights for maximum gain is fairly broad, so the selection of a working height for each frequency is somewhat arbitrary. At 1.85 MHz, the lowest reach of the verticals is 10 m off the ground. At 3.6 MHz, the base height is 5 m, but at 7.15 MHz, the height is 4 m.

The heights use average ground as a determining factor. The ideal heights depend in part on soil quality. For example, over very poor soil, gain continues to increase with height for a considerable distance above the heights chosen for average soil. However, our goal in these test runs is to compare the performance of the half square with and without radials beneath the vertical elements. Therefore, the compromise height above ground will not impede the tests.

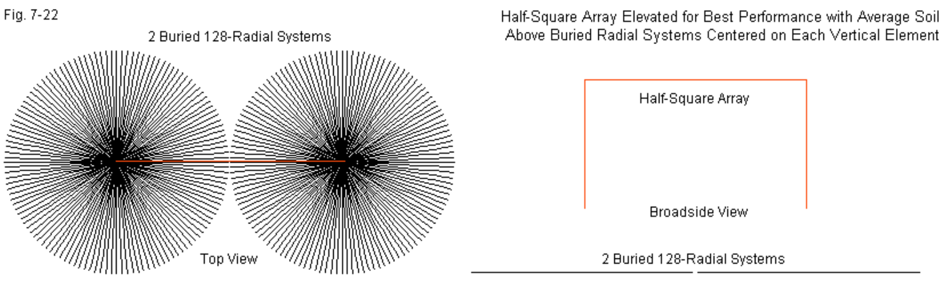


Fig. 22 shows the model used to implement a 128-radial system buried 0.1 m for the half-square tests. The generation of the radials uses a different technique than we used for a single set of radials.

```
GW 11 11 0 0 -.1 36.95 0 -.1 .001
GR 0 128
GM 0 0 0 0 0 0 37 0
GX 1 010
GE -1 -1 0
FR 0 1 0 0 1.85 1
GN 2 0 0 0 5 .001
WG r128x2-vp-160.ngf
EN
```

The Green's file model sets up a single radial. The GR command replicates it for a full field. However, because we have subsequent geometry commands, GR does not implement symmetry. The GM command moves the radials to a point under one of the verticals in the half square. Since the antenna will be centered over the X-axis, the GX command replicates the first radial field using symmetry. The model that calls the .ngf file into play contains the wires of the half-square array. As well it uses a GM command to set the height of the array above ground. For versions with no radials, the model simply includes the FR and GN commands that are part of the

.ngf file-generating model.

```
GF r128x2-vp-160.ngf
GW 1 21 0 -37 45.5 0 37 45.5 .001
GW 2 11 0 -37 45.5 0 -37 0 .001
GW 3 11 0 37 45.5 0 37 0 .001
GM 0 0 0 0 0 0 0 10
GE -1 -1 0
EX 0 2 1 0 1 0
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

Table 7-11 contains all of the data from the half-square runs. Because we are using a single height for the antenna, the amount of data to absorb is considerably less. Perhaps the most notable column is "Gain Add," the amount of added gain that we obtain from the addition of 256 radials split into 2 fields for the pair of verticals. The pattern of gain additions is comparable to those we encountered with the vertical dipole. The range is marginal to insignificant for all bands and all soils.

Half-Square Array with and without Radials								Table 11
Freq MHz	Height m	Soil	# Radials	Gain dBi	Gain Add	TO Angle	Resist	React
1.85	10	Very Poor	0	2.26		70	63.331	0.674
			128	2.68	0.42	69	60.704	2.96
		Average	0	4.95		73	64.351	1.427
			128	5.1	0.15	73	63.255	2.212
		Very Good	0	7.43		77	64.703	1.624
			128	7.47	0.04	77	64.396	1.86
3.6	5	Very Poor	0	2.32		68	63.96	4.557
			128	2.81	0.49	68	61.285	8.14
		Average	0	4.02		72	65.401	5.371
			128	4.22	0.2	70	63.303	8.135
		Very Good	0	6.64		76	65.906	5.546
			128	6.72	0.08	76	65.395	5.956
7.15	4	Very Poor	0	3.05		69	60.882	-1.47
			128	3.36	0.31	68	60.114	1.002
		Average	0	3.63		72	61.617	-2.276
			128	3.85	0.22	72	61.073	-1.07
		Very Good	0	5.65		75	62.16	-3.015
			128	5.74	0.09	75	61.912	-2.614
Note	Gain Add = Added gain (dB) with 128 radials below each vertical element.							

3. *A Bobtail Curtain Array*

The bobtail curtain–outlined in **Fig. 7-23**–shares many properties with its smaller cousin, the half square. The basic principle involves three vertical monopoles fed in phase. Independent monopoles would show a 1-2-1 pattern of maximum current magnitudes among the monopoles moving from one end of the array to the other. As in the half square, the horizontal lines form the completion of dipoles for each vertical element. However, the horizontal wire length results in the nearly complete cancellation of horizontally polarized radiation leaving the array vertically polarized.

Outline of the Bobtail Curtain Vertical Array

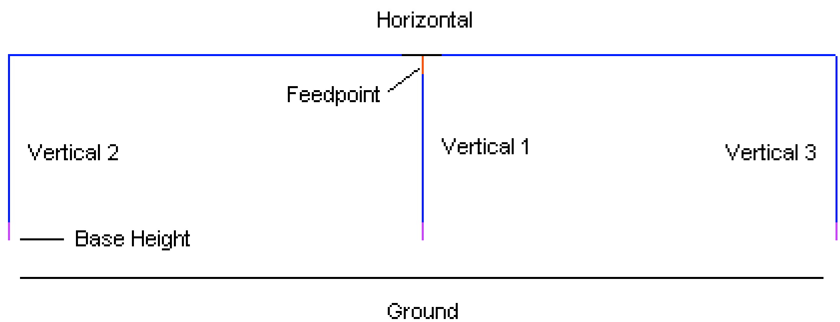
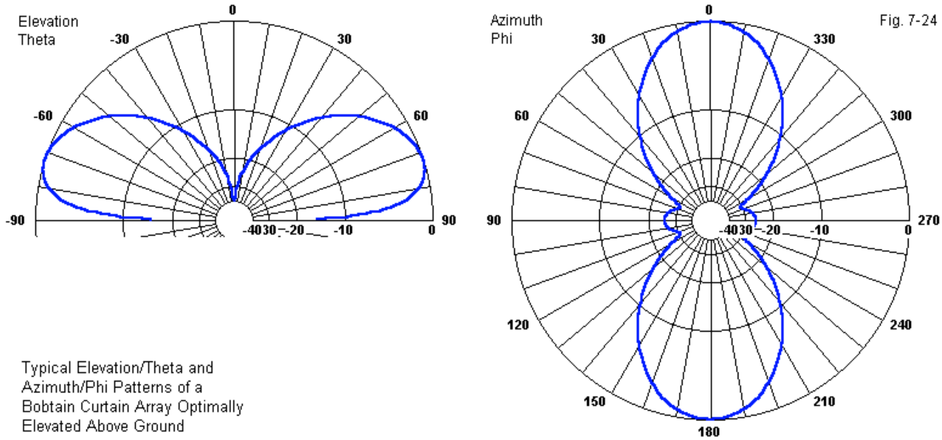


Fig. 7-23

Like the half-square, the bobtail curtain does not answer a theoretical 2:1 ratio of horizontal wire to vertical wire. The ratio is closer to 2.25:1, a more extreme ratio than we find in the half square. Modeling has largely confirmed the basic shape worked out many years ago by SM5CAN. As well the bobtail curtain also exhibits best performance when raised above ground level. The optimal height for the vertical tips above ground varies with soil quality and is quite broad. For the tests that we shall perform, I selected heights of 8, 5, and 3.5 meters for the 3 test frequencies. At these heights, all 3 soil types yield patterns similar to those shown in **Fig. 7-24**. The side bulges in the azimuth/phi pattern result from the excess spacing between vertical element needed to obtain maximum gain from the array.



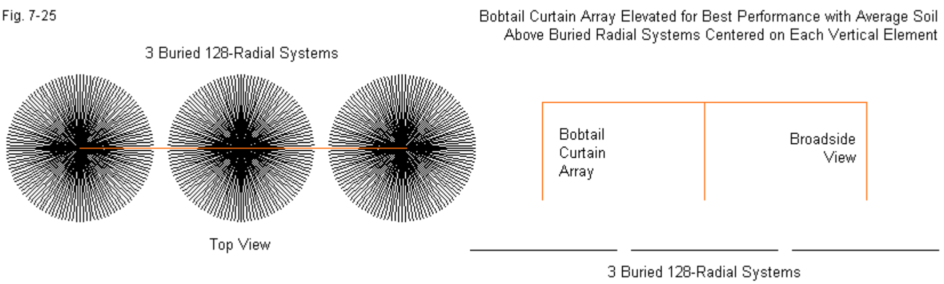
Typical Elevation/Theta and Azimuth/Phi Patterns of a Bobtain Curtain Array Optimally Elevated Above Ground

To obtain three 128-radial systems–one beneath each vertical–I set aside the .ngf files, since symmetry would not be feasible for these models. Instead, I used single models containing the radials and the bobtail wires.

```
GW 1 11 0 0 -.1 40.5125 0 -.1 .001
GR 0 128
GM 1 1 0 0 0 0 -88 0
GM 1 1 0 0 0 0 88 0 1 1 1 1408
GW 11 11 0 0 0 0 0 39.4 .002
GW 12 11 0 -88 0 0 -88 39.4 .002
GW 13 11 0 88 0 0 88 39.4 .002
GW 14 40 0 -88 39.4 0 88 39.4 .002
GM 0 0 0 0 0 0 0 8 11 1 14 40
GE -1 -1 0
EX 0 11 11 0 1 0
FR 0 1 0 0 1.85 1
GN 2 0 0 0 20 .0303
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

The lines up to GW 11 show the radials, with GW 1 setting up the first radial of the center field. Unlike the half-square array, which required radials slightly less than a full quarter wavelength to avoid intersections, the bobtail radials can reach full size. The GR line creates the full radial set but does not invoke symmetry. The first GM line creates a second radial field under an end vertical, and the second GM line creates the final set at the other end of the array. The actual bobtail wires wear tag numbers 11 through 14. The final GM line sets the height above ground for the tips of the verticals. **Fig. 7-15** shows an outline of the full array and radial fields.

Fig. 7-25



The more complex an array, the more difficult it is to arrive at precise dimensions for semi-scaled versions. All three versions of the bobtail curtain are resonant in free space, but the proportions vary slightly. The variations are due to at least 3 factors. First, the wire radius (0.001 m) remains constant, a factor that defeats direct scaling. Second, the proportions are only approximately the same from one frequency to the next, although the free-space gain varies by only 0.02 dB across the frequencies (6.72 to 6.74 dBi). Finally, the heights above ground within the range of maximum gain are rounded approximations. As always, the array and radial wires are lossless. Note that for all models of the bobtail curtain, the source or feedpoint is on the highest segment of the center vertical elements at the junction with the horizontal wires. We shall shortly deal with alternative feedpoint placements and methods.

Table 7-12 provides the modeled performance data with and without radial fields. Unlike the tables for the vertical dipole and the half square, the bobtail 40-meter data shows a wider gain improvement range than the 80-meter data.

Nevertheless, the patterns developed for the other antennas tend to hold true for the bobtail curtain. The higher the frequency or the better the soil, the less improvement we obtain from the addition of radial fields.

Bobtail Curtain Array with and without Radials								Table 12
Freq MHz	Height m	Soil	# Radials	Gain dBi	Gain Add	TO Angle	Resist	React
1.85	10	Very Poor	0	3.82		68	31.382	9.627
			128	4.62	0.8	68	27.816	11.827
		Average	0	6.62		72	31.014	11.285
			128	6.93	0.31	72	29.407	11.942
		Very Good	0	9.03		76	30.388	11.738
			128	9.12	0.09	76	29.899	11.938
3.6	5	Very Poor	0	3.81		67	30.122	6.905
			128	3.92	0.11	67	29.718	7.199
		Average	0	5.65		71	30.701	8.62
			128	5.72	0.07	71	30.342	8.629
		Very Good	0	8.3		75	30.178	9.242
			128	8.28	-0.02	75	30.277	6.35
7.15	4	Very Poor	0	4.47		67	27.238	5.251
			128	5.05	0.58	67	26.017	7.966
		Average	0	5.26		71	28.189	6.09
			128	5.68	0.42	70	26.984	7.492
		Very Good	0	7.35		74	28.154	6.611
			128	7.51	0.16	74	27.597	7.084
Note	Gain Add = Added gain (dB) with 128 radials below each vertical element.							

Since the bobtail curtain requires 384 ¼-λ radials (or 96 wavelengths of wire) to obtain the small gain improvements suggested by the tables, adding radials beneath a bobtail curtain becomes a dubious enterprise for amateur installations, even over the worst of soil qualities. As well, adding fewer radials will result in lower values of improved (numerical) performance. Hence, adding a scant radial field may be mostly a waste of wire.

In all of the exercises, the addition of a radial field with very poor soil results in a noticeable drop in the source impedance. Since we are feeding the bobtail curtain on the center vertical of the array, perhaps we may obtain all of the improvement with a single set of radials under only that element. Since .ngf files already exist for the vertical dipole, we can simply use them in connection with the bobtail curtain. The 1.85-MHz results for no radials, for a single set of 128 radials, and for all 3 sets of radials appear in **Table 7-13**. With only a single set of radials we obtain about 50-55% of the gain improvement for 3 sets of radials. As well, the source resistance drops by about 50-55% of the amount for 3 radial sets. This value is not arbitrary, since the maximum center vertical current magnitude is about twice the level on the end vertical elements. Nevertheless, the maximum gain improvement is well under a half dB and is achievable only at the lowest frequency and worst soil in the set of trials. As well, the amount of wire needed even for a single complete radial set at 1.85 MHz is about 5,186 m or a little over 17,000'.

1.85- MHz Bobtail Curtain Array with 0, 1, and 3 Radial Sets						
Height m	Soil	Rad Sets	Gain dBi	TO Angle	Resist	React
10	Very Poor	0	3.82	68	31.392	9.627
		1	4.25	68	29.337	11.097
		3	4.62	68	27.816	11.827
	Average	0	6.62	72	31.014	11.285
		1	6.79	72	30.08	11.783
		3	6.93	72	29.407	11.942
	Very Good	0	9.03	76	30.388	11.738
		1	9.08	76	30.108	11.897
Table 13		3	9.12	76	29.899	11.938

We need not carry the exercise further, since the gain advantages grow smaller with rising frequency, and the ratio of advantage from a single radial set to 3 full sets is relatively constant.

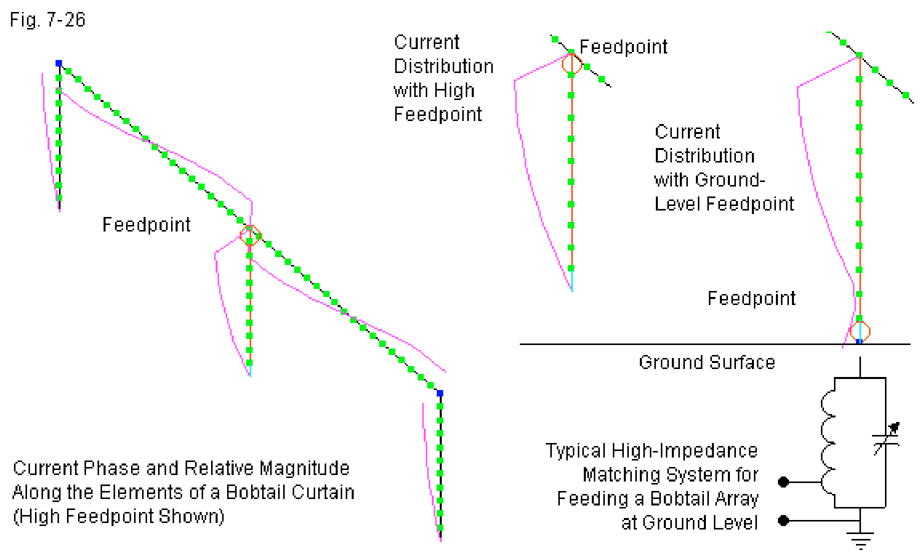
For convenient reference, **Table 7-14** provides the dimensions of the half-square and bobtail-curtain arrays used in these notes. All dimensions are in meters. The horizontal dimension is the total "left-right" spread of the array and includes the distance between the outer verticals of the bobtail. The distance between the center and outer verticals of the bobtail is half the listed horizontal dimension. The vertical dimension is the length of each vertical. The height above ground is the distance between the surface and the lower tip of each vertical. The wire diameter is a constant 0.002 m (2 mm or a radius of 1 mm) for all models in the sequence.

Reference Dimension of Arrays Used in Test Models				
Half Square and Bobtail Curtain				
Array	Freq MHz	Horiz m	Vert m	Height m
Half Sq	1.85	74	45.4	10
	3.6	38	23.5	5
	7.15	19	11.91	4
Bobtail	1.85	176	39.4	8
	3.6	90	20.37	5
	7.15	46	10.16	3.5
Notes	Horiz m = total horizontal length in meters			
	Vert m = vertical element length in meters			
	Height m = distance from ground to lower			
Table 7-14		vertical tip in meters		

Alternative Bobtail Curtain Feedpoints

Several facets of bobtail curtain operation draw incomplete and sometimes confusing accounts from radio amateurs. For example, the average ham knows that the currents on the outer vertical elements are in phase with and about ½ the magnitude of the current on the center vertical. However, they remain uncertain about the current levels and phasing along the horizontal wires. (A similar uncertainty exists for the half square.) The left portion of **Fig. 7-26** may go some distance in clarifying the situation. The graphic comes from EZNEC and allows simultaneous display of both the relative current magnitude and phase.

Note that the junction of the center vertical and the horizontal wire is a point of rapid value change as the magnitude and phase go to zero. The phase in each direction along the horizontal wire is opposite the other, with equal current magnitudes. The region precisely at the junction is very small, and for all general-purpose analyses, we may view the current on the horizontal wire at the junction as having a very high relative magnitude, although we cannot forget the phase reversal. In fact, this condition is the reverse of what we obtain from a 1-λ center-fed doublet. That type of antenna has minimum current magnitude at the feedpoint. Along each ½-λ leg, the current reaches its highest magnitude at the approximate center point. As well, the currents at any points equal distances from the feedpoint have the same phase angle. Hence, the doublet provides added gain over a simple ½-λ dipole. In contrast, the conditions along the bobtail horizontal wire provide almost no radiation. (Normal wire has slight material losses, and the horizontal wire ends are distant from each other. Hence, field cancellation is not quite complete.)



On the right in **Fig. 7-26** are relative current magnitude and phase graphs for just the center vertical elements. To the left is the situation that we have modeled for these exercises. The feedpoint is on the top-most segment of the vertical. Many bobtail users prefer a low or ground level feed. To approach a model of this situation–without completely attaining it–I extended the center vertical downward to within 0.1 m (about 3.94") of ground. The lower right incomplete schematic shows a typical matching circuit (or the equivalent circuit of typical matching networks). Essentially, the resonant parallel tuned circuit places a very high impedance between the extended vertical element tip and the ground. Hence, the model without such a circuit is not far off the actual installation situation.

From a modeling perspective, in any version of NEC, wires should not directly touch the ground, not even vertical wires. NEC-4 introduces settings for the GE (geometry end) command. They do make a difference to models that allow a wire to touch the ground without connecting to one or more wires extending below the surface.

```
GE 1 0 0                    GE -1 0 0
```

Both versions of the command indicate that a ground plane is present. However, the left option directs the current expansion routine to interpolate an image below the wire. If a vertical antenna touches the ground, the results are not reliable. The option on the right does not modify the current expansion routine, so the current goes to zero at the end of the wire, that is, at ground level. For high-impedance wire ends, such as the lower tip of the bobtail vertical, this option is preferable if the modeler chooses to bring the vertical all of the way to the ground. Still, the best practice is to terminate high-impedance antenna ends above ground (unless those antennas have in fact a subsurface structure).

With the slightly elevated vertical tip, the bobtail array shows the same gain and pattern as it does when the feedpoint is placed high on the center vertical. However, the impedance is very high: something in the vicinity of 850 - j11000 Ω. (Small variations in structure can create very large changes in impedance in the high-impedance regions of an antenna, since the current and voltage change by large amounts in very short distances along the wire.) Tank circuits (often equipped with taps along the turns at the top end of the coil) can usually effect a high-efficiency match for a wide range of impedance values, so long as all of the values are high. Some radio amateurs who use some system similar to this one want to elevate the tank circuit so that it catches the vertical just where the impedance is purely resistive. Elevating the tank will work, but the odds of catching a purely resistive impedance are slim–and may vary with slight changes in the configuration of the vertical wire in the wind and weather. As well, the tank requires a very good ground lead, which becomes–so long as it is above the ground surface, an extended part of the antenna.

As the current magnitude and phase graph shows on the far right of **Fig. 7-26**, ground-level placement of the matching circuit or network poses no problems to antenna operation (whatever the problems it might impose upon the operation of the circuit). The feedpoint itself does not change the antenna's performance. Moreover, as we saw in the exercises involving placing radial systems beneath the vertical elements, these additions to the bobtail curtain add little to nothing with respect to performance. Nonetheless, we still encounter reports to the effect that adding radials did affect antenna performance in operationally detectable ways.

The notes concerning the need for a good ground lead uncover part of the situation, a part that goes outside of these modeling exercises and back to material briefly sketched in Chapter 1. The matching circuit, whatever its nature, requires a good earth ground, as does the energy source (at the transmitter) or the energy load (at the receiver). Between these 2 points, effective RF return paths must have negligible impedance to provide the lowest possible voltage differential between points. Most bobtail installations with base feeding use a coaxial cable between the transmitter and the matching circuit. It may or may not provide the required near-zero-impedance path. Bobtail users who install radials do not affect direct antenna operation so much as they increase the effectiveness of the earth ground between the matching circuit and the transmitter/receiver. The questions facing the bobtail curtain installation with a base-matching system are not questions of antenna completion in the sense that would apply to monopoles with base-level ground planes. Instead, they are questions relating to the quality of the RF ground for the entire station system.

The Next Steps

Actually, this volume has only one more step to take before concluding our foray into ground planes. We gave only a cursory examination of monopole lengths and their affects on performance. However, the 5/8-λ monopole continues to have a much-vaunted advantage over the simple ¼-λ monopole–at least according to claims from various quarters. Before we close the book on ground planes, perhaps we should re-examine in better detail the mystique surrounding the 5/8-λ monopole.

8. ¼-λ to 5/8-λ Monopoles

The 5/8-λ vertical monopole has long held the reputation of providing about a 3-dB gain advantage over the ¼-λ vertical monopole. The foundation of that reputation rests upon theoretical calculations that show the longer monopole to have the derived gain increase when both monopoles are set over a perfect ground. For an example of the claim or illustrations of the theoretical gain of the 5/8-λ monopole over the ¼-λ monopole, see Terman's *Radio Engineers' Handbook* (McGraw-Hill, 1943), pp. 793-795. Recent college antenna texts fold vertical monopole concepts into more general considerations, although many antenna texts through at least 1970 present the theoretical relationship of a ¼-λ radiator to a 5/8-λ radiator in the classic terms. This idea persists in amateur radio literature. For examples, see Orr and Cowan, *Vertical Antennas* (RAC, 1986), p. 162, and by the same authors, *Simple and Low-Cost Wire Antennas* (RAC, 1990), p. 115.

Almost lost in the shadows of the 5/8-λ monopole is a monopole length more favored by BC engineers (assuming that something longer than ¼ λ is suited to an application). For numerous reasons that we shall soon discover, the ½-λ monopole has proven more suitable to AM BC than the 5/8-λ antenna. Besides its radiation properties, the ½-λ monopole has other interesting features that may shed some light on some long-standing radio amateur questions. We might summarize the various forms in which amateurs pose the questions in this manner. What is the difference between a monopole and a dipole? Along the way, we may even be able to see a partial answer to the question of when a dipole becomes a doublet.

Our examination of the three key monopole lengths will have 3 parts, according to our earlier division of frequency ranges in which we find ground-plane monopoles at work. In the upper-MF and lower-HF regions, we encounter buried radial systems. More strikingly, we find monopoles brought to the ground surface or terminated just above the ground surface. These practical features set limits to the variations that we can create upon the monopole, whatever its vertical length. However, the limitations allow us to take a long look at the 3 monopole sizes and some allied questions.

In the upper HF range, we found that placing the base of a ground-plane above about 0.5 λ general results in the domination of the second elevation lobe, to the detriment performance at the lower radiation angles that enhance long-distance communication. However, within this range, we may easily create a number of variants of the standard ground-plane monopole, including versions with sloping radials. As well, we shall be able to learn something more about dipoles disguised as monopoles.

Finally, we shall look briefly at the VHF and UHF ranges, where monopole base heights begin at about 2 λ and move upward almost without limit. In these regions, we find blatant advertising literature touting the 3-dB advantage of the 5/8-λ monopole over the shorter ¼-λ standard. We shall want to discover whether those advertisements are true. In addition, numerous operators claim that 5/8-λ monopole provides successful mobile communication where ¼-λ monopoles fail. We may be able to detect a reason behind the claims.

Monopoles in the Upper-MF and Lower-HF Regions

The earliest work with monopoles of varied length used the lower end of the frequency spectrum. From that work emerged the very idea of a monopole, the concept of a perfectly reflecting ground, and the use of an image antenna extending below that surface to account for an idealized set of antenna properties. Since those days, these ideas have served as a baseline against which we tend–for better or worse–to measure the performance of real ground-plane monopoles over real or "lossy" ground.

The claim that a 5/8-λ monopole has a 3-dB advantage over a ¼-λ monopole arises from this context of antenna theory. To replicate this context, I used our standard NEC-4 monopoles of lossless wire with a standard 0.01-m diameter. Since basic antenna theory tends to begin with infinitesimally thin wire elements, the performance numbers for monopoles using the standard diameter will vary a tiny amount from fundamental theoretical values–but not much. I placed monopoles for each test frequency over the perfect ground. NEC's perfect-ground mode creates a mathematical image antenna for its computations.

Because a ¼-λ monopole exhibits a low source impedance with a relatively slow rate of change with small variations in monopole length, we can easily arrive at a length that is resonant to within +/-j0.1 Ω. However, a ½-λ monopole creates a problem: since the source reactance at exact half-wavelength resonance changes very rapidly, finding a resonant length becomes a tedious process. As well, since impedance values change rapidly in this region, a small change in segmentation can make large differences in the numerical impedance values. Moreover, a 5/8-λ monopole length is inherently non-resonant. As well, there is no standard impedance or impedance measure for such a monopole. As a consequence of these considerations, the longer monopoles used for these trials will be physically ½ λ and 5/8 λ, respectively. Electrically, each antenna will be slightly long, since the diameter of the element is significant. With a standard physical diameter, the amount by which the longer monopoles are electrically long will vary with the test frequency.

Lossless Monopoles over Perfect Ground						Table 8-1
Freq MHz	Length wl	Length m	Gain dBi	Gain Add	Resist	React
1.85	0.25	39.272	5.15		36.207	0.048
	0.5	81.025	6.91	1.76	2261.31	-701.041
	0.625	101.281	8.11	2.96	91.027	-429.726
3.6	0.25	20.113	5.14		36.16	-0.002
	0.5	41.6379	6.92	1.78	1839.58	-697.097
	0.625	52.0473	8.1	2.96	87.241	-384.165
7.15	0.25	10.084	5.14		36.124	0.058
	0.5	20.9605	6.93	1.79	1447.02	-663.24
	0.625	26.2056	8.08	2.94	82.63	-337.185
Note	Gain Add = added gain over 1/4-wl monopole					

Table 8-1 shows the modeling data for ideal monopoles over ideal (perfectly reflecting) ground. The 3 ¼-λ monopoles are resonant within prescribed limits. However, the longer monopoles both show capacitive reactance, indicating that, for each frequency, both are long. The amount of capacitive reactance at the

source decreases as we raise the test frequency, showing the monopoles grow electrically longer as we raise frequency with a constant physical element diameter. The same growing electrical length with increasing frequency also appears in the decreasing source resistance values for each of the 2 longer lengths. Nevertheless, the gain values for each monopole remain constant within fairly close tolerances regardless of frequency. Likewise, the gain advantages of a ½-λ and of a 5/8-λ monopole over a ¼-λ monopole are close to constant. The half-wavelength monopole provides–ideally–about 1.8-dB added gain, while the 5/8-λ monopole shows nearly 3-dB added gain.

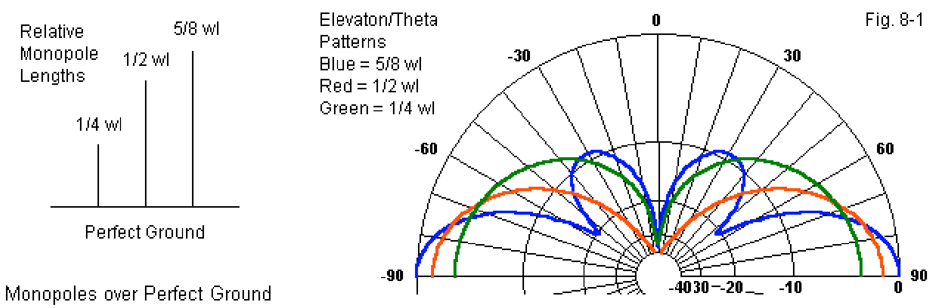


Fig. 8-1 shows the relative lengths of the monopoles over perfect ground. It also overlays the radiation patterns for the three monopoles. The differences in performance from one test frequency to the next lie wholly within the thickness of each line on the graph, so a single elevation/theta plot serves for all three test frequencies. If we used the green plot for the ¼-λ monopole as a standard, then the lower elevation/theta beamwidth of the ½-λ monopole plot is readily apparent. Equally apparent is the second elevation/theta lobe on the pattern for the 5/8-λ monopole. In the idealized model, the strength of the second lobe is modest, down by about 9 dB relative to maximum strength in the lower lobe. We may note once more that most of the claims about the advantages of a 5/8-λ monopole emerge from exercises just like this one.

The time has arrived for us to "get real," that is to place the monopoles over real ground. As we did in past exercises, we shall use 3 widely separated soil qualities for our tests. Very poor soil has a conductivity of 0.001 S/m and a relative permittivity of 5. The corresponding values for average soil are 0.005 S/m and 13. For very good soil, the standard values are 0.0303 S/m and 20. We need to survey our monopoles–without changing their lengths–over all 3 soil qualities at all 3 test frequencies. As we learned from earlier exercises, frequency will make a difference in the effects of soil quality upon monopole performance.

For the tests we may use a standard radials system consisting of ¼-λ radials for each frequency. Each radial system will use lossless wire that is 0.001 m in radius. The radials will be buried 0.1 m deep. The models use the sloping-radial technique, with the first wire segment angling from the monopole base at Z = 0 down to the remainder of the radial at -0.1 m. Because we shall apply different monopoles, but use the same radial system in each test within a given test frequency, we may profitably use Green's files to store radial information. As well, we can use the GR command to simplify these files with symmetry.

```
GW 2 1 3.65 0 -.1 0 0 0 .001
GW 2 10 40.5125 0 -.1 3.65 0 -.1 .001
GR 0 64
GE -1 -1 0
GN 2 0 0 0 20 .0303
FR 0 1 0 0 1.85 1
WG r64-160-vg.ngf
EN
```

The sample lines show the model for creating .NGF files. We may reuse the same model for each soil quality by changing the values in the GN line and by altering the "vg" (very good) portion of the file name to "vp" and to "av" for very poor and average soils, respectively. The length of the radial in the second GW line (and the "160" in the file name) tells us that this file is for 1.85 MHz. The models for 3.6 and 7.15 MHz have identical structures.

The model that uses the .NGF radial file along with monopole information is also very simple in structure. It calls upon the .NGF file for the desired frequency and soil conditions in the GF line. The GW line sets the length of the monopole and the segmentation that applies to that length. Since the ¼-λ monopole uses

11 segments, the half-wavelength antenna uses 21 and the 5/8-λ monopole uses 27. Hence, the segment lengths remain relatively constant and close to the length of segments in the radials. Since ground quality and frequency information resides in the .NGF file, we need only 2 control commands for the executing model: the excitation or source placement and the request for an elevation/theta pattern.

```
GF 0 r64-160-vg.ngf
GW 1 10 0 0 0 0 0 39.272 .01
GE -1 -1 0
EX 0 1 1 0 1 0
RP 0 181 1 1000 -90 0 1.00000 1.00000
EN
```

The data for the tests for all 3 test frequencies and all 3 soil qualities appears in **Table 8-2**. The results for 1.85 MHz may contain some surprises if we begin by expecting a replication of the ideal patterns. **Fig. 8-2** shows the plots for each soil quality. Note especially the second lobe of the blue 5/8-λ monopole. Even over very good soil, its strength is less than 5-dB down from the lower lobe, and its grows relatively stronger as we decrease the soil quality.

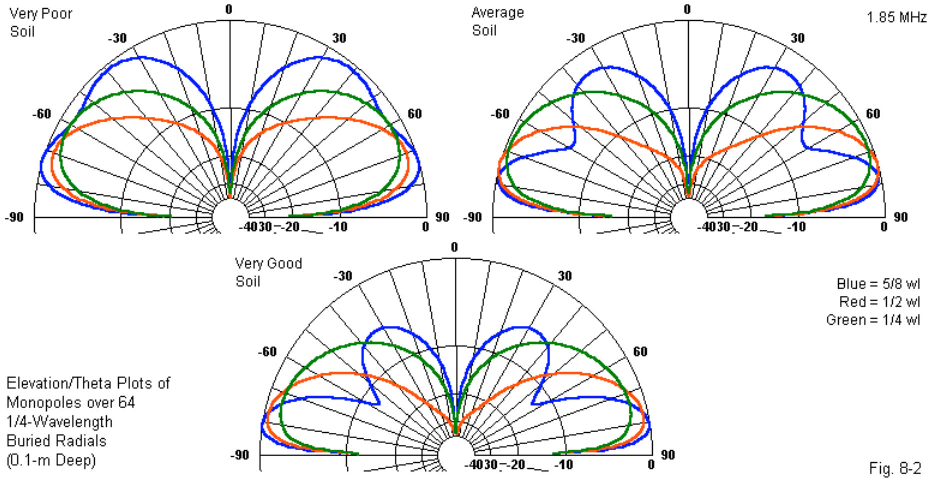


Fig. 8-2

Lossless Monopoles with 64 Lossless Buried Radials over Real Ground								Table 8-2
Freq MHz	Soil	Length wl	Length m	Gain dBi	Gain Add	TO Angle	Resist	React
1.85	Very Poor	0.25	39.272	-0.91		62	36.143	-1.256
		0.5	81.025	-0.62	0.29	70	2439.68	-696.977
		0.625	101.281	0.13	1.04	73	87.172	-423.448
	Average	0.25	39.272	1.15		67	38.448	1.266
		0.5	81.025	1.51	0.36	74	2319.65	-683.18
		0.625	101.281	1.29	0.14	78	86.458	-426.043
	Very Good	0.25	39.272	2.9		73	38.448	1.488
		0.5	81.025	3.91	1.01	78	2274.19	-688.137
		0.625	101.281	4.28	1.38	81	86.754	-427.962
3.6	Very Poor	0.25	20.113	-0.99		61	33.513	-1.862
		0.5	41.6379	-0.23	0.76	69	2022.61	-750.148
		0.625	52.0473	1.08	2.07	71	84.765	-377.88
	Average	0.25	20.113	0.5		65	37.508	0.89
		0.5	41.6379	0.78	0.28	73	1913.54	-701.679
		0.625	52.0473	0.75	0.25	76	83.127	-379.874
	Very Good	0.25	20.113	2.35		71	38.595	1.717
		0.5	41.6379	3.14	0.79	77	1858.69	-687.076
		0.625	52.0473	3.24	0.89	80	83.011	-381.884
7.15	Very Poor	0.25	10.084	-0.61		60	31.309	-0.709
		0.5	20.9605	0.42	1.03	68	1590.67	-755.195
		0.625	26.2056	1.8	2.41	71	81.161	-331.093
	Average	0.25	10.084	0.21		64	36.199	1.355
		0.5	20.9605	0.65	0.44	71	1517.49	-695.758
		0.625	26.2056	1.09	0.88	75	79.297	-332.365
	Very Good	0.25	10.084	1.69		79	38.607	2.385
		0.5	20.9605	2.25	0.56	75	1472.29	-660.237
		0.625	26.2056	2.13	0.44	79	78.612	-333.978
Note	Gain Add = added gain over 1/4-wl monopole							

At the same time, the gain advantage of the 5/8-λ monopole over a monopole only 40% as long has decreased from an ideal 3-dB down to a little over 1 dB maximum. Over average soil, the 5/8-λ monopole shows less gain than the 1.85-MHz half-wavelength monopole.

Now note the cleanliness of the single-lobe pattern for the ½-λ monopole. The contrast in patterns with the 5/8-λ monopole accounts in large measure for the absence of 5/8-λ monopoles in the AM BC industry, where strong high-angle radiation tends not only to be wasteful, but as well may present unwanted skip signals. (Longer monopoles for AM BC tend to show up only in the upper part of the band, which itself has a 3:1 frequency ratio from end to end.)

The relationships among the radiation patterns for the 3 monopole lengths change only slowly as we raise the test frequency. Over very poor soil, 7.15 MHz shows the greatest gain advantage for the 5/8-λ monopole: about 2.4 dB over the ¼-λ monopole. If we have average soil, the advantage drops to under 0.5 dB. With very good soil, the gain advantage of the 5/8-λ monopole over the ¼-λ monopole decreases with frequency. **Fig. 8-3** shows the elevation/theta plots for 7.15 MHz, for comparison with the plots in **Fig. 8-2** for 1.85 MHz. As we increase frequency, the second lobe of the 5/8-λ monopole shows lesser development over very poor soil. However, as we improve the soil quality, the 5/8-λ-monopole plot shows greater relative development. By the time we reach very good soil, the second lobe shows more development and less definition (a shallower null) than the corresponding pattern for 1.85 MHz.

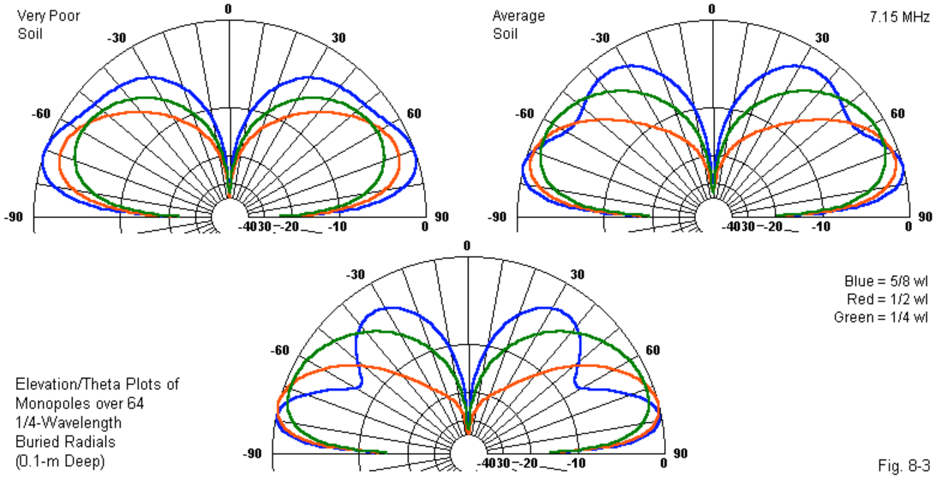


Fig. 8-3

The modeling results accrue from the use of a 64-radial field. The patterns would not significantly differ with fields that are one step smaller (32 radials) or one step larger (128 radials). My operating assumption is that if one considers the construction of a longer monopole in the upper-MF or lower-HF range, that added effort would also include laying down a set of radials that would maximize the performance potential of the ground-based monopole.

The Half-Wavelength Monopole and Special Questions

One of the special advantages offered by the ½-λ and 5/8-λ monopoles relates to the pattern of current distribution along the antenna. **Fig. 8-4** uses EZNEC graphics for monopoles over perfect ground to illustrate the current distribution. The distribution for antennas over buried radial systems would be virtually identical to the ones for ideal monopoles. The ½-λ monopole fails to describe a perfect arc partly because of its slightly excessive electrical length (and partly because of the location of its source).

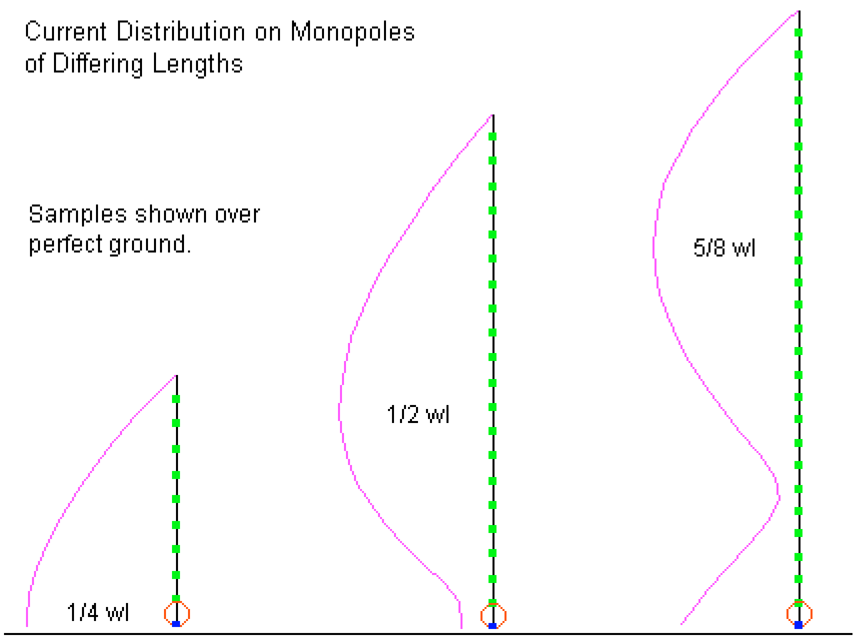
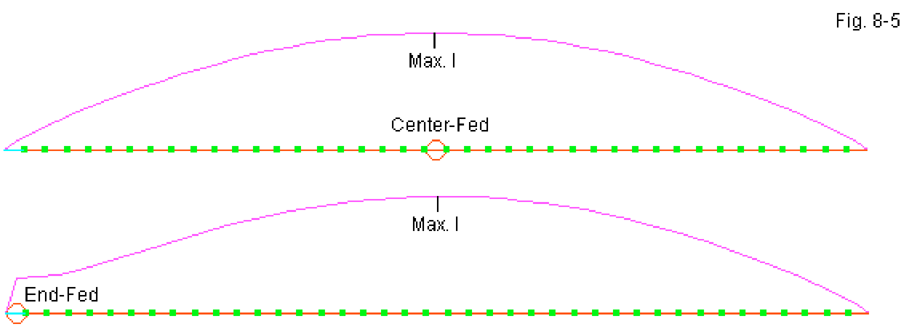


Fig. 8-4

A number of amateur-band vertical antennas have appeared over the last decade or so, all of which create or simulate ½-λ antennas on as many bands as possible. One advertised advantage of these antennas is the elevation of the maximum current region of the antenna from ground level to some point well above ground. Even though the maximum current region for the ½-λ monopole in **Fig. 8-4** is slightly below the midpoint of the vertical element, it nonetheless has a considerable height advantage over the ground-mounted ¼-λ monopole. In general–but not universally–ground clutter diminishes with the height above ground, and we may define clutter simplistically as any natural or constructed objects that might absorb or reflect RF energy in unwanted ways.

Interestingly, the designs for the multi-band half-wavelength antennas come in 2 varieties: some use a base-feeding system and some use a center-feeding system. The design of a multi-band vertical that exhibits ½-λ properties on many of the bands of operation is a complex task, subject to better and worse performance on each of the bands covered. However, placing the feedpoint at the center or at one end of the ½-λ antenna has little effect on the current distribution curve. **Fig. 8-5** shows a half-wavelength antenna fed at the center and at the end, along with the current distribution curves for each situation.



Relative Current Distribution on Center-Fed and End-Fed 1/2-Wavelength Wires in Free Space

`The curve for the end-fed wire shows a slight departure from the perfect arc that applies to the center-fed version. However, maximum current occurs at the center of both elements. We have a fairly precise name for the center-fed version of the antenna: a resonant ½-λ center-fed dipole. It is resonant because the source reactance is nearly zero. It is ½-λ long electrically, one of many lengths at which we might obtain resonance. Physically, it is center fed, since the wire lengths on each side of the source point have identical lengths. It is a dipole because (in part) the current show on each side of center a single curve from maximum to minimum value, corresponding to an ascending charge distribution from center to end. Basic texts, such as Stutzman and Theile (*Antenna Theory and Design*, 2nd Ed., pp. 56 ff), provide more detailed information on these defining notions.

The aspect of the defining terms of greatest interest here is the current distribution along a dipole. Note in Fig. **8-5** that we have essentially the same current distribution despite the change in the source point from center to end. The end-fed ½-λ wire (also called an end-fed Zepp, where the term "Zepp" has no technical but great historical content) is in principle identical to the ½-λ monopole in **Fig. 8-4**.

There is a second set of non-technical uses for the terms "dipole" and "monopole." In many circles, they dominate over technical uses. In non-technical terms, if it looks like a dipole or looks like a monopole, then it is just that. The visual cue for a dipole is the center-feedpoint. Hence, common parlance labels any center-fed antenna as a dipole, even if it is many wavelengths long at some operating frequency and therefore has many current and charge distribution excursions along the way. (Multi-band wires for which the multiple excursion condition is true on at least some bands are often called doublets to distinguish them from essentially monoband resonant ½-λ center-fed dipoles.) Similarly, if an antenna is vertical and fed at the base or bottom end, it must be a monopole. However convenient these labels may be, they are singularly uninformative about antenna operation.

We can perform a small modeling exercise to see whether our ½-λ monopole is in fact a monopole in more than visual identification terms. Let's model the antenna in a variety of conditions, varying the exact base height, the presence of radials, and even the feedpoint position. For each variation, we shall run models over the 3 soil types. However, a single test frequency (1.85 MHz) should suffice to indicate any significant performance differences related to the variables. Of course, the element length will remain constant at exactly ½ λ. **Table 8-3** shows the results of the test runs.

1.85-MHz 1/2-WL (81.025-m) Lossless Monopoles in Various Modeling Configurations							
			Soil	Gain dBi	TO Angle	Resist	React
1. Z=0 with 64 Buried Radials							
			Very Poor	-0.62	70	2439.68	-696.977
			Average	1.51	74	2319.65	-683.18
			Very Good	3.91	78	2274.19	-688.137
2. Elevated 0.1 m with 64 Buried Radials							
			Very Poor	-0.69	70	3811.95	-6083.07
			Average	1.46	74	3622.79	-6069.69
			Very Good	3.86	78	3552.09	-6081.05
3. Elevated 0.1 m with No Radials							
			Very Poor	-1.21	71	3642.36	-5972.52
			Average	1.29	74	3569.21	-6020.59
			Very Good	3.82	78	3540.4	-6068.05
4. Z=0 with No Radials							
			Very Poor	-1.23	71	3661.28	-5921.87
			Average	1.28	74	3582.14	-5964.13
			Very Good	3.81	78	3551.47	-6010.9
5. Center-Fed, Elevated 0.1 m, No Radials							
			Very Poor	-1.67	71	112.096	55.285
			Average	1.13	74	114.181	63.09
			Very Good	3.75	78	114.205	66.877
6. Center-Fed, Elevated 0.1m, 64 Radials							
			Very Poor	-0.96	70	104.386	67.152
			Average	1.37	74	110.902	67.153
			Very Good	3.81	78	113.321	67.884
		Note	GE = -1 -1 0 (no current expansion) for al models				
Table 8-3			Z=0 = Bottom of monopole touches ground				

The first test simply replicates the data for the 1.85-MHz ½-λ monopole from **Table 8-2**. We must note that in this model, the base of the vertical element contacts the radial system hub directly, that is, with no intervening impedance.

Many implementations of a 1/2-λ monopole will include a tank circuit between the monopole base and the ground and the ground plane. In such cases, the design places a very high impedance between the monopole and the ground plane. As a partial simulation of that situation, I raised the monopole 0.1 m above ground, separating it from the ground plane. The second test shows the results. The performance of the monopole does not differ significantly from the performance in the first test. However, we should note the 50% increase in source resistance, along with a very large increase in capacitive source reactance. In the first case, the radial system within its second medium formed part of the antenna, lengthening it considerably beyond the physical half-wavelength. As we move beyond a half-wavelength, the source resistance decreases and so too does the capacitive reactance. Without the radials as part of the antenna, the physical half-wavelength is closer to an electrical half wavelength, pushing up the source resistance and reactance.

The third test uses the elevated monopole, but takes away the radials. As we saw in earlier chapters, we lose a small amount of gain when a vertical ½-wavelength antenna is very close to ground, although the earlier exercises used a center-fed vertical dipole. In the fourth test, the base-fed monopole drops to just touch the ground, but again, without radials. The results are insignificantly different from those of the third test. In both of these tests, the impedance values at the base feedpoint remain at the same levels as we found for the second test.

To bring the earlier vertical dipole results into a comparative position with the base-fed monopole results, I used the elevated antenna of the third test (with no radials), but moved the feedpoint to a center position. In this fifth test, we find that the gain drops slightly, especially over very poor soil. The source impedance values confirm what we already know: the antenna is too long to be resonant as a center-fed vertical dipole. The final test adds 64 buried radials below the center-fed vertical dipole, which remains 0.1 m above ground at its lower tip. The radials have a gain restorative effect that is most noticeable with poorer quality soils. As well, relative to the fifth test, the source impedance values change more as the soil quality decreases.

The bottom line of these exercises is the conclusion that there is little or no electrical difference between a vertical dipole and a vertical monopole when both are ½-λ long. As a second medium beneath the antenna and in very close proximity to the end of the antenna element, the ground has effects. However, they are minor from the perspective of basic operation.

There are good engineering reasons for placing a full, buried ground plane beneath a ½-λ element. For just one reason, the radial system stabilizes the range of impedance excursions that may occur as a result of changing weather, ground contamination, and other influences on soil quality. Matching the base impedance of a ½-λ radiator is difficult enough (especially at high power levels) without requiring re-adjustment with every summer shower or winter snow.

We also saw that, even for a ½-λ vertical element, the radials become an integral part of the antenna, as shown by the impedance difference between the first and second tests. In the first chapter, I referred to ground-plane radials as a form of antenna completion "ground." For the ½-λ vertical element in direct contact with the ground-plane hub, the radials become an extension of the half-wavelength to some indeterminate total length.

Fig. 8-6

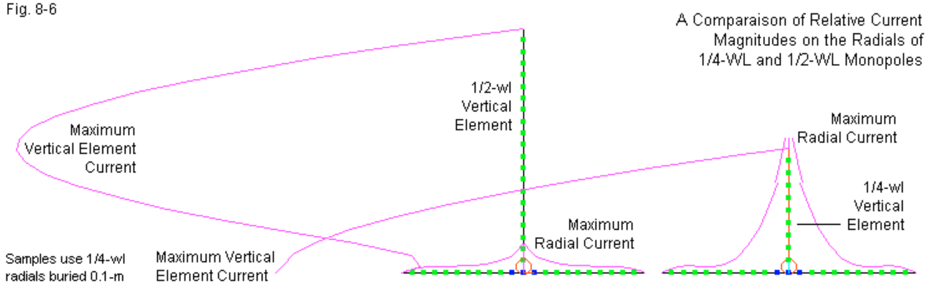


Fig. 8-6 shows the relative current magnitudes on the elements of a sample model using both a ½-λ and a ¼-λ vertical element. The number of radials is 4 so as not to obscure the radial current magnitudes in a morass of lines. The two sketches are to scale. In both cases, the maximum current level has been graphically extended to the same visual value. This step was necessary to show

the radial current magnitudes on the ½-λ assembly. Since the radials form the completion of the ¼-λ monopole, the radial currents are high, about ¼ the level of the base current on the monopole. In contrast, the current levels on the ½-λ radial are very low. In fact, the current at the lower end of the ½-λ vertical element does not go to zero, but only to a very low value. The initial radial current magnitudes are each about 1/4 of the terminal vertical element value.

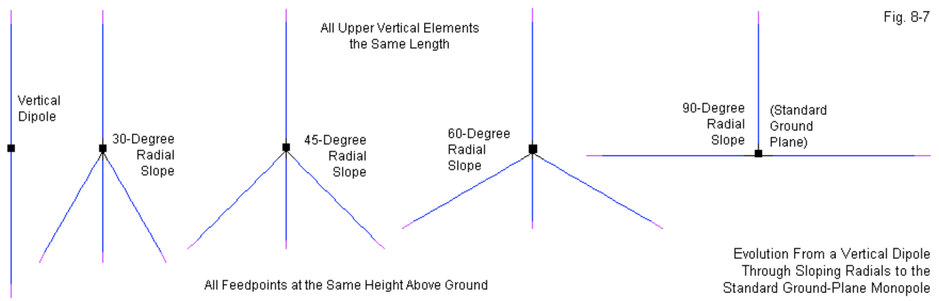
The exercise strongly suggests that electrically, there may be no such thing as a true monopole. At most, there may be monopoles in the sense that the exact dimensions of the antenna-completion ground do not make large differences in performance. However, every so-called monopole is actually a dipole in disguise, regardless of the feedpoint. Of course, from a certain perspective, not every dipole is an electrical dipole, since some wires may exhibit multiple current and charge distribution excursions at some operating frequencies. Nevertheless, the final goal of these exercises is not resolve a terminological conundrum. Rather the goal is to alert you to the importance of examining the current distribution along antenna elements (all of them, including radials) and to reach a better understanding of how an antenna performs its function. In the end, we shall likely continue to employ common usage and call an antenna by a familiar name based on its appearance. As we finish our final stages of exploration, we shall continue to call the subject antennas ground-plane monopoles.

Monopoles in the Upper-HF Region

As we move into the upper HF range, ground-plane monopoles remain fairly close to the ground, but normally have their bases or feedpoints above the surface. The region is useful in the present context for providing some further details about the evolution or progression from a true vertical dipole to a monopole with its ground-plane radials at 90° to the vertical element.

In an earlier chapter, we discovered that there are very few differences in the basic performance of ground-plane monopoles set at 20 and at 10 meters. Therefore, we may simplify our procedure in this chapter by using a 21.225-MHz test frequency. At this frequency, a wavelength is 14.1245 m. We shall use vertical elements that have a radius of 0.00667 m (a diameter of about 0.6"). Radials will use a radius of 0.00333 m (a bit over a quarter inch in diameter). Although upper HF ground-plane monopoles come in many dimensions for both components, these values may serve us as somewhere in the middle of the ranges.

Typically, when we explore the transition from a vertical dipole to a 90° ground-plane monopole, we make only 1 intermediate stop, that is, with radials that slope 45° relative to the vertical element. However, let's expand our range to include radial sets that slope 30° and 60° to the vertical element. **Fig. 8-7** shows the range of antenna shapes that we shall examine.



The figure shows our starting point: a ½-λ vertical dipole that becomes a ¼-λ monopole with a set of 4 ¼-λ radials. As always, we shall use lossless wire throughout, but even with that measure, we already know that the vertical element will be physically shorter than ¼ λ, and the radials are likely to be longer. The layout of shapes also shows our initial technique in examining the evolution: we shall maintain a constant base height, that is, the height of the feedpoint above ground. For our first run with ¼-λ half elements, we can place the feedpoint an electrical quarter wavelength (3.5311 m) above ground and still have clearance for the lower tip of the vertical dipole. For this first antenna, we shall also select radial lengths that restore the assembly to near resonance. The initial vertical dipole that determines the vertical element length in the monopoles is resonant in free space and therefore shows some reactance over ground. As a result, we shall be interested in both the physical and the electrical properties of the antenna assemblies that emerge.

1/4-WL Vertical Element With Radials at Various Angles						
Frequency: 21.225 MHz; All Antennas Near Resonance						
Vertical Element = 3.379 m; All Feedpoints 1/4-WL Above Ground						
Rad Ang	Rad L m	Soil	Gain dBi	TO Angle	Resist	React
0	0	Very Poor	-0.15	68	89.928	3.071
		Average	0.29	71	95.797	5.281
		Very Good	0.69	73	99.76	6.417
30	3.1	Very Poor	0.41	69	64.95	1.607
		Average	0.74	71	67.71	0.238
		Very Good	1.02	74	69.783	-1.093
45	3.32	Very Poor	0.61	69	55.327	1.76
		Average	0.85	72	56.993	-0.001
		Very Good	1.04	74	58.179	-1.612
60	3.53	Very Poor	0.82	69	43.457	1.412
		Average	0.95	72	44.027	-0.272
		Very Good	1.03	75	44.316	-1.743
90	4.01	Very Poor	1.07	71	20.363	0.596
		Average	0.86	74	19.871	0.097
		Very Good	0.6	76	19.396	-0.259
	Note	Rad Ang = Angle from vertical formed by				
		radials. 0 degrees = vertical dipole				
Table 8-4		Rad L m - Radial length in meters				

Table 8-4 shows the results of the exercise. As we increase the angle of the radials with respect to the vertical, the required length of the radials grows longer if we wish to maintain resonance with a constant upper vertical element. The one exception to this progression is the vertical dipole itself, which has a single lower element that is 3.379 m. However, the diameter of that element is considerably smaller than the effective diameter of the 4 radials, even if we could model them together straight down.

Also evident in the table is the decreasing source resistance as we increase the radial angle relative to the vertical element. For a 50-Ω match, an angle between 45° and 60° seems most appropriate. Indeed, many who build antennas like these prefer multiple radials–whatever the selected angle, since the structure reduces problems associated with dressing the feedline for minimal coupling from the radiated signal.

With a fixed feedpoint height above ground, we may examine the pattern of gain over each soil type with a graph. **Fig. 8-8** presents the gain data for each soil quality as we move through the various radial angles. Remember that the angles do not form a linear progression.

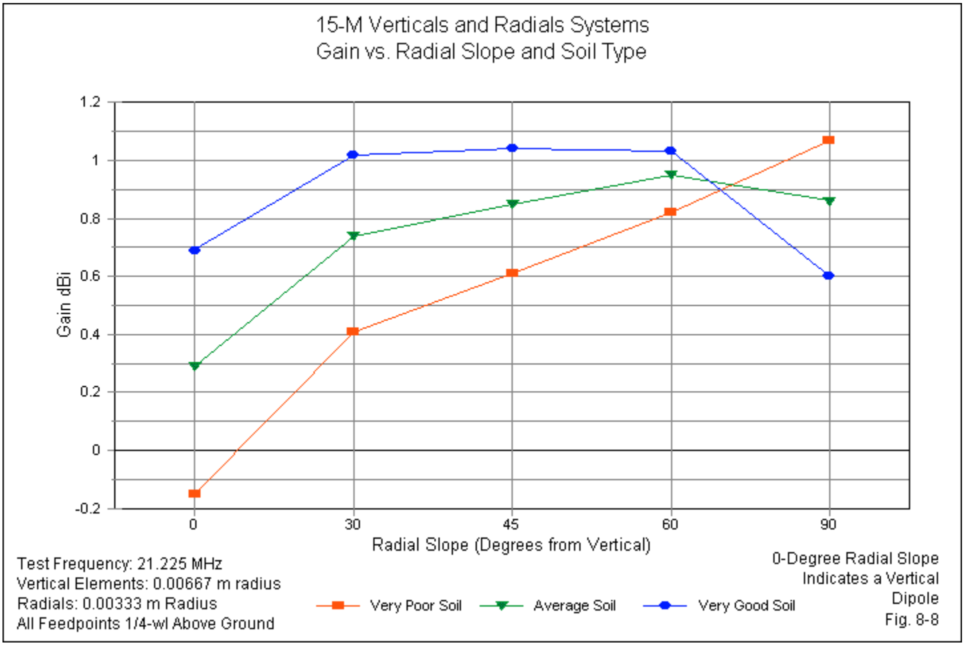


Fig. 8-8

As we might expect, for most radial angles, very good soil provides the highest gain, and all gain values move upward from the vertical dipole. Of course, the tips of the radials also move upward from the ground surface as we increase the radial angle. However, note that over average and very good soil, the assembly reaches peak gain prior to reaching 90° radials. These curves are general guidance only due to a modeling limitation. Because the radial angles change with each step, the intersecting wire segments vary in their inter-penetration. As a result, the average gain test (AGT) scores also vary slightly, producing raw gain reports that are about 0.14 dB too high with 30° radials and about 0.13 dB too low with 90° radials. The required corrective values are not enough to change the general curve shapes or to alter the peak-gain points shown in the graph.

We sometimes encounter 5/8-λ monopoles in the upper HF region. They generally take 1 of 2 forms: a long monopole with ¼-λ radials and a long monopole with 5/8-λ radials. **Fig. 8-9** sketches the differences in antenna proportions.

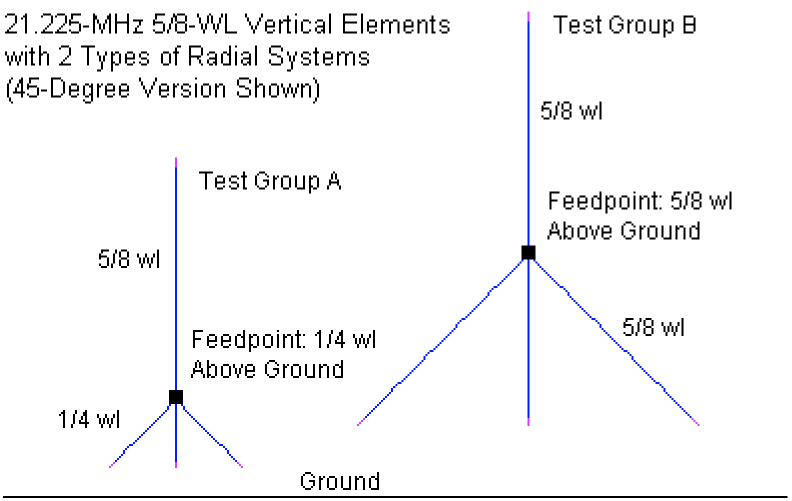


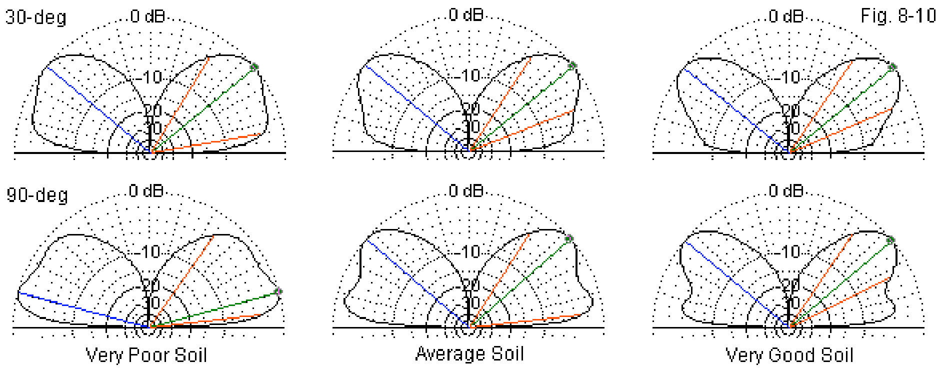
Fig. 8-9

Since we may use the same base height value (1/4 λ) for the first case, let's begin by exploring what happens as we increase the radial angle. A vertical monopole is not possible, of course, using this configuration; therefore, we shall begin with the 30° radial situation. As well, since the assembly is non-resonant by nature, all radials may be ¼-λ long (3.5311 m). The monopole will be 8.8278 m long for all 5/8-λ models in this series. **Table 8-5** provides the results of the modeling exercise over our span of soil types.

5/8-WL Vertical Element With 1/4-WL Radials at Various Angles						Table 8-5
Frequency: 21.225 MHz; All Feedpoints 1/4-WL Above Ground						
Vertical Element = 8.8278 m; Radials 3.5311 m; Height 3.5311 m						
Rad Ang	Soil	Gain dBi	TO Angle	Resist	React	
30	Very Poor	3.49	50	106.868	-267.883	
	Average	4.33	50	111.768	-266.594	
	Very Good	5.02	51	115.643	-265.698	
45	Very Poor	3.27	50	96.371	283.516	
	Average	4.13	50	99.854	-283.187	
	Very Good	4.85	51	102.483	-283.041	
60	Very Poor	2.85	50	90.046	-295.07	
	Average	3.73	50	92.502	-295.129	
	Very Good	4.49	51	94.232	-295.219	
90	Very Poor	2.62	75	88.039	-309.215	Note
	Average	2.55	49	88.987	-309.396	
	Very Good	3.4	50	89.577	-309.409	

Note that the gain decreases for all 3 soil types as we increase the angle of the radials toward a horizontal position. However, we should not neglect the TO Angle column. Except for the noted entry (90° radials over very poor soil), all of the gain values apply to the second elevation lobe counting from the horizon. **Fig. 8-10** provides a small gallery of elevation/theta patterns (using the EZNEC format) that accounts for this phenomenon. With 30° radials, the second lobe clearly dominates the pattern. As we saw in preceding chapters, the better the soil quality, the less we see of the lower lobe.

As we increase the angle of the radials toward 90°. The lower lobe grows stronger. The maximum gain level goes down because–with large radial angles with respect to the vertical element–the energy is split more evenly between the two lobes. Nevertheless, for only one survey point does the lower lobe dominate–and just barely. Over very poor soil, with 90° radials, the lower lobe is stronger than the second lobe. We have seen this pattern in ground-planes monopoles in earlier chapters. Very poor soil tends to show a slower development of the second lobe and a slower reduction in the strength of the lower lobe than do average and very good soils. Whatever the precise lobe development, the 5/8-λ monopole with ¼-λ radials has limited utility in upper HF amateur radio service, where the goal is usually low angle radiation for long distance communication.



Selected Elevation/Theta Patterns of 5/8-WL Vertical Radiator over
4 1/4-WL Radials Sloped 30 and 90 Degrees from Vertical

The second scenario that results in a 5/8-λ vertical with 5/8-λ radials demonstrates that the ½-λ vertical dipole is not the only antenna that may evolve into a ground-plane monopole. The extended double Zepp (EDZ) normally appears as a horizontal wire antenna. However, in principle, nothing prevents us from using the antenna vertically. Since the antenna is inherently non-resonant, we may use a true 5/8-λ element on each side of the center feedpoint. As well, all elements of the ground-plane versions of the antenna will also use true 5/8-λ (8.8278 m) elements.

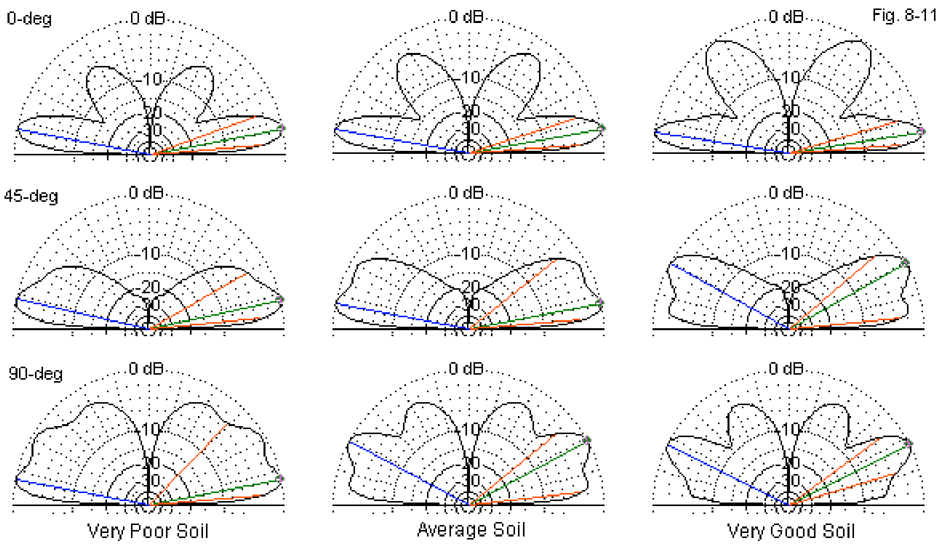
The element length creates a limitation in our exercise. If all vertical assemblies are to have the same feedpoint height, we must us a value slightly greater than 5/8 λ so that the vertical EDZ can avoid touching the ground. Therefore, the exercise used a height of 8.84 m. The radii of the elements are the same as we used for the previous 2 exercises.

The results of all modeling runs appear in **Table 8-6**. The table introduces a new column listing the dominant lobe, counting from the horizon upward. The pattern of lobe domination is too varied to allow a simple notation method.

5/8-WL Vertical Element With 5/8-WL Radials at Various Angles						
Frequency: 21.225 MHz; All Feedpoints 1/4-WL Above Ground						
Vertical Element = 8.8278 m; Radials 8.8278 m; Height 8.84 m						
Rad Ang	Soil	Gain dBi	TO Angle	Dom Lobe	Resist	React
0	Very Poor	2.96	79	1	156.094	-507.939
	Average	2.18	80	1	159.905	-493.422
	Very Good	0.92	81	1	162.921	-483.709
30	Very Poor	4.81	77	1	182.702	-407.918
	Average	4.05	78	1	190.854	-410.13
	Very Good	2.81	80	1	197.341	-413.341
45	Very Poor	4.63	78	1	135.888	-415.513
	Average	3.4	79	1	135.343	-415.517
	Very Good	3.26	61	2	134.412	-414.968
60	Very Poor	3.71	78	1	117.543	-385.796
	Average	3.74	61	2	119.377	-385.63
	Very Good	4.73	62	2	121.049	-385.703
90	Very Poor	2.3	79	1	107.411	-337.562
	Average	3.06	62	2	106.052	-338.006
	Very Good	4.13	63	2	104.838	-338.071
	Note	Rad Ang = Angle from vertical formed by				
		radials. 0 degrees = vertical dipole				
Table 8-6		Dom Lobe = Dominant elevation lobe				

As the table shows, lowest lobe dominates the elevation/theta pattern through a 30° angle to the radials. Such an angle creates a sharp cone. Indeed, we might increase the number of radials to a large number to simulate a true cone. The elevation of the lowest portion of the antenna from nearly touching the ground shows a remarkable increase in gain, especially for very good soil. Remember, though, that the 30° radials make a considerable contribution to the vertically polarized radial. It matters little if we consider than antenna to be 5/8-λ monopole with radically sloping radials or an EDZ with the lower half flared. Note that by the time we reach a radial angle of 60°, both average and very good soil yield domination by the second lobe. Only very poor soil (barely) escapes the phenomenon.

Fig. 8-11 provides another gallery of elevation/theta patterns to show the evolution of the lobe structure with an increasing radial angle. The 3 checkpoint angles allow you to interpolate the intermediate stages of lobe development.



Selected Elevation/Theta Patterns of 5/8-WL Vertical Radiator over
4 5/8-WL Radials Sloped 0, 45, and 90 Degrees from Vertical

If we had omitted the 90°-radial patterns, we might easily miss the emergence of the third elevation lobe in the progression. The third lobe is not present in the patterns for vertical EDZ (0°), and it is vividly present in the 90°-radial patterns. In the 45°-radial patterns, the 3rd lobe shows itself only as a step in the progression of the upper pattern line from the center outward.

Although the vertical EDZ and its first cousin, the flared EDZ or 30°-radial long monopole are usable in the upper HF region, the other versions of the antenna have dubious value. Indeed, to use the long vertical assembly with larger radial angles would require that we have some specific knowledge of the soil quality in the region responsible for reflections that define the far field radiation pattern. If the soil is too good, then the pattern goes to pot, that is to say, to the second elevation lobe.

Few, if any, installations will follow the constant feedpoint height limitation that we imposed upon our initial models. Normally, monopole installations in the upper VHF region will use 90° radials (or no more than a small lope downward). But they will also use a variety of heights above ground for the feedpoints. Therefore, we may adopt the 90°-radial model as a constant and vary the feedpoint or base height above ground. For this exercise, I selected increments of 0.05 λ (0.7062 m) for each step. However, the lowest level will be 0.01 λ (0.14125 m) above ground. The antenna dimensions retain the values used in the preceding 90°-radial tests.

1/4-WL Vertical Element With 1/4-WL Radials at 90 Degrees								Table 8-7
Frequency: 21.225 MHz; Base Height Variable 0.01-WL to 0.25-WL								
Vertical Element = 3.379 m; Radials 4.01 m								
Ht wl	Ht m	Soil	Gain dBi	TO Angle	Dom Lobe	Resist	React	Notes
0.01	0.14125	Very Poor	-0.51	61	1	28.865	6.867	
		Average	0	63	1	32.959	10.322	
		Very Good	0.38	66	1	36.367	9.928	
0.05	0.7062	Very Poor	-0.16	63	1	25.532	-1.601	
		Average	0.34	66	1	27.831	-1.865	
		Very Good	0.77	69	1	29.513	-2.699	
0.1	1.4125	Very Poor	0.21	66	1	22.987	-2.145	
		Average	0.57	69	1	24.16	-3.176	
		Very Good	0.9	71	1	24.979	-4.214	
0.15	2.1187	Very Poor	0.55	68	1	21.41	-1.408	
		Average	0.75	71	1	21.768	-2.515	
		Very Good	0.93	73	1	21.937	-3.491	+
0.2	2.8249	Very Poor	0.84	69	1	20.59	-0.393	=
		Average	0.84	73	1	20.391	-1.263	=
		Very Good	0.83	75	1	20.12	-1.971	=
0.25	3.5311	Very Poor	1.07	71	1	20.363	0.596	+
		Average	0.86	74	1	19.871	0.097	+
		Very Good	0.6	76	1	19.396	-0.259	
Note	Ht wl = Base (feedpoint) height above ground in wavelengths							
	Ht m = Base (feedpoint) height above ground in meters							
	Dom Lobe = Dominant elevation lobe							

Table 8-7 shows the data for the ¼-λ monopole with ¼-λ radials. The column labeled "Notes" shows a + sign to indicate the highest gain for each soil type. A special feature of this table is an interesting coincidence of gain values at a height of

0.2 λ above ground. Since the lowest lobe dominates all survey entries, we can graph the gain values. See **Fig. 8-12**.

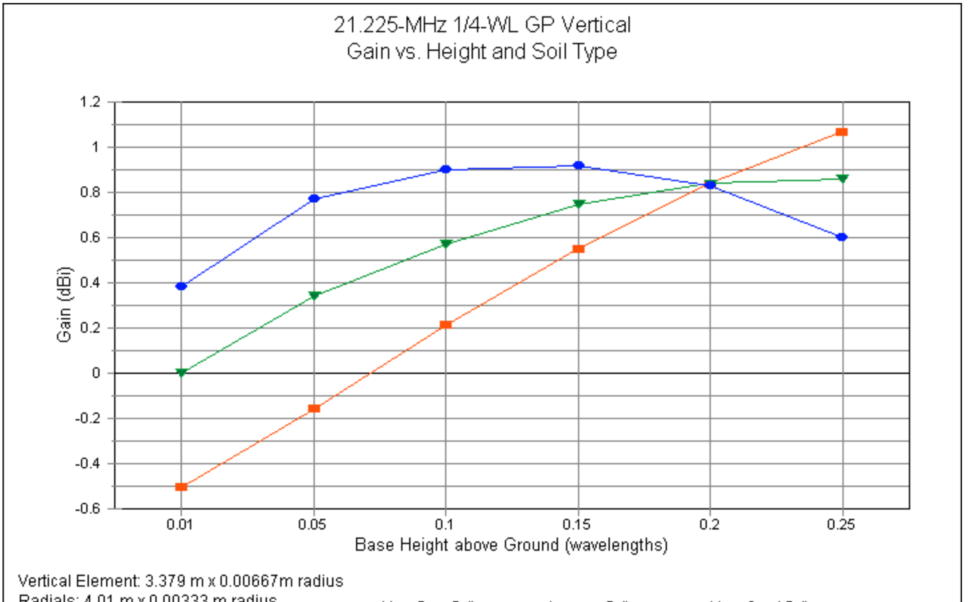


Fig. 8-12

The crossing lines clearly show the intersection of gain values at the feedpoint height of 0.2 λ. Equally evident is the fact that soil quality has a large bearing on the gain curve. Over very good soil, the array reaches peak gain at 0.15-λ, while the other 2 soil types show continued gain increases to the survey limit. However, over average soil, the gain value is leveling out. These data are consistent with the galleries of patterns that show a more rapid development of the second lobe and a more rapid reduction of the lowest lobe as we improve soil quality.

If we combine a 5/8-λ vertical element with 90° ¼-λ radials, we obtain the data in **Table 8-8** for the range of surveyed feedpoint heights.. Note that over very good soil, the antenna reaches maximum gain at the lowest height. At the next height

(0.05 λ), the second lobe already dominates the pattern. Maximum gain over average soil occurs with a height of 0.1 λ and, by the next step, the second lobe dominates. Even though the lowest lobe dominates all entries for very poor soil, the antenna reaches maximum gain at 0.2 λ above ground and shows a small decrease at the next level. The peak and reduction phenomenon strongly suggests that at some height not too far above the survey limit, the second lobe will dominate over the worst soil in the test.

5/8-WL Vertical Element With 1/4-WL Radials at 90 Degrees								Table 8-8
Frequency: 21.225 MHz; Base Height Variable 0.01-WL to 0.25-WL								
Vertical Element = 8.8278 m; Radials 3.5311 m								
Ht wl	Ht m	Soil	Gain dBi	TO Angle	Dom Lobe	Resist	React	Notes
0.01	0.14125	Very Poor	2.17	71	1	79.811	-302.733	
		Average	1.72	74	1	78.528	-301.074	
		Very Good	1.08	77	1	77.879	-301.012	+
0.05	0.7062	Very Poor	2.46	72	1	77.108	-308.386	
		Average	1.92	75	1	74.575	-308.963	
		Very Good	1.46	39	2	72.898	-309.216	
0.1	1.4125	Very Poor	2.65	73	1	76.186	-308.609	
		Average	1.96	76	1	73.296	-309.03	+
		Very Good	2.65	41	2	71.597	-308.884	
0.15	2.1187	Very Poor	2.72	73	1	77.777	-308.734	
		Average	2.32	44	2	75.474	-308.99	
		Very Good	3.24	44	2	74.279	-308.703	
0.2	2.8249	Very Poor	2.63	74	1	83.845	-309.6	+
		Average	2.44	47	2	83.465	-309.951	
		Very Good	3.32	47	2	83.332	-309.866	
0.25	3.5311	Very Poor	2.62	75	1	88.039	-309.215	
		Average	2.55	49	2	88.987	-309.346	
		Very Good	3.4	50	2	89.577	-309.409	
Note	Ht wl = Base (feedpoint) height above ground in wavelengths							
	Ht m = Base (feedpoint) height above ground in meters							
	Dom Lobe = Dominant elevation lobe							

If we increase the radials to 5/8 λ, the data in **Table 8-9** show increased domination by the second elevation lobe above the horizon. Indeed, even at the lowest height (0.01 λ), the model over very good soil has a dominant second lobe. Over average soil, the second lobe dominates by a height of 0.05 λ, and in one further step, the second lobe dominates even the model over very poor soil.

5/8-WL Vertical Element With 5/8-WL Radials at 90 Degrees								Table 8-9
Frequency: 21.225 MHz; Base Height Variable 0.01-WL to 0.25-WL								
Vertical Element = 8.8278 m; Radials 8.8278 m								
Ht wl	Ht m	Soil	Gain dBi	TO Angle	Dom Lobe	Resist	React	Notes
0.01	0.14125	Very Poor	1.35	70	1	99.255	-315.819	
		Average	0.76	74	1	96.811	-316.267	+
		Very Good	0.19	37	2	91.211	-319.764	
0.05	0.7062	Very Poor	1.38	70	1	98.617	-330.961	+
		Average	1.28	38	2	92.094	-333.823	
		Very Good	2.31	37	2	84.42	-334.568	
0.1	1.4125	Very Poor	1.69	41	2	98.703	-331.824	
		Average	2.55	39	2	91.724	-331.594	
		Very Good	3.56	39	2	86.257	-329.257	
0.15	2.1187	Very Poor	2.17	41	2	102.136	-331.527	
		Average	3.14	40	2	97.074	-329.445	
		Very Good	4.03	41	2	93.924	-326.448	
0.2	2.8249	Very Poor	2.3	43	2	110.34	-332.73	
		Average	3.22	42	2	108.694	-330.081	
		Very Good	3.99	43	2	107.977	-327.237	
0.25	3.5311	Very Poor	2.33	44	2	117.299	-333.907	
		Average	3.2	44	2	118.602	-331.135	
		Very Good	3.92	46	2	119.816	-328.696	
Note	Ht wl = Base (feedpoint) height above ground in wavelengths							
	Ht m = Base (feedpoint) height above ground in meters							
	Dom Lobe = Dominant elevation lobe							

The upper-HF exercises have shown us that the evolution of vertical center-fed antennas into ground-plane antennas does not stop with the vertical dipole and its ¼-λ ground-plane monopole derivative. The EDZ is equally ripe for such an evolutionary development, assuming that we can work with the resulting feedpoint impedance values. Indeed, spot modeling has resulted in proponents for such antennas. Unfortunately, most of the modeling is incomplete and does not take into account the highly variable performance of the antenna as we change the ground quality beneath it or make small changes in its height above ground. The more complete modeling of our survey suggests something quite different. Overall, the antenna has a dubious place in amateur service that strives for low-angle radiation (and reception). Without a complete knowledge of the soil quality and without due attention to limitations in height over some of those ground types, it is very easy to end up with an antenna whose radiation angle is too high for effective communications. In the upper-HF region, the 5/8-λ monopole is not an antenna for either the beginning antenna builder or the beginning antenna modeler.

Monopoles in the VHF and UHF Regions

Longer vertical monopoles and monopole arrays are very common in the VHF and UHF ranges. Mobile services, especially amateur FM repeaters, create a very large niche for these antennas. Of course, they are also nearly universal in cell phone and other wireless commercial services. However, for our exercises, we shall use the same test frequencies employed in Chapter 6: 144 and 432 MHz. The 3:1 frequency ratio will give us a fair sampling of antenna capabilities.

VHF and UHF vertical monopoles present us with two major scenarios: antennas at relatively high positions, such as tower tops, and antennas placed low, for example, on vehicles. We shall explore the comparison of ¼-λ and 5/8-λ vertical elements at both heights. Arbitrarily, we shall place all high antennas 4.1638 m above ground. This height is 2 λ at 144 MHz and 6 λ at 432 MHz. Although the height is only 13.66' above ground in U.S. measures, it is high enough to see the potential performance at all heights above this level.

The higher antennas will include standard ¼-λ and 5/8-λ monopoles using radials that slope at all of the angles explored in the upper HF range, from the vertical monopole to the 90° radial system. All models (except vertical dipoles) will use 4 radials. The ¼-λ monopoles will use radials with lengths tuned to near resonance. The 5/8-λ monopoles will use exact ¼-λ radials, since the systems are inherently non-resonant.

The question that fuels this exploration over the entire RF spectrum is where we gain any advantage from extending the length of a monopole. 5/8-λ is simply the most notable long monopole typically used in amateur serves. However, the small physical size of VHF and UHF antennas opens the door to collinear arrays. We shall add such an array to the list of antennas surveyed. **Fig. 8-13** provides sample outlines of some of the antennas in the survey. All of the antennas are roughly to the same scale. So the sketch may serve as a rough guide to relative sizes.

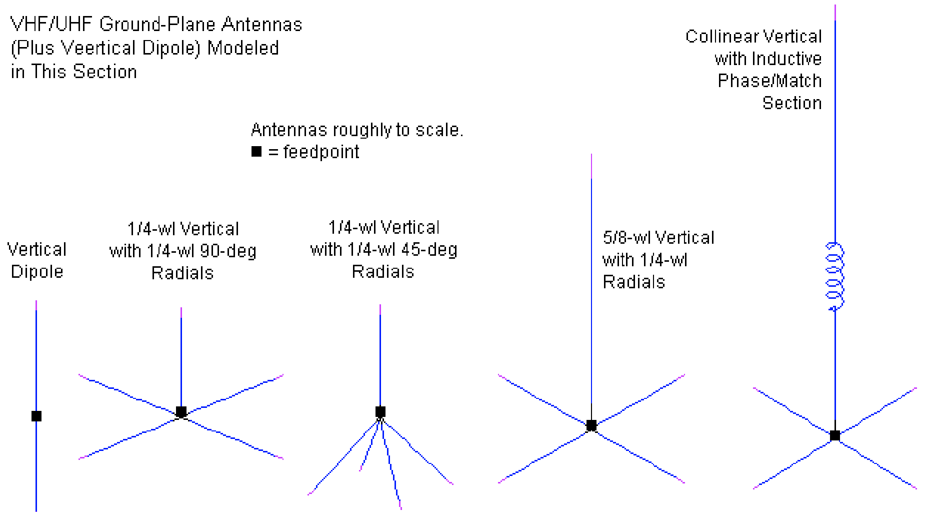


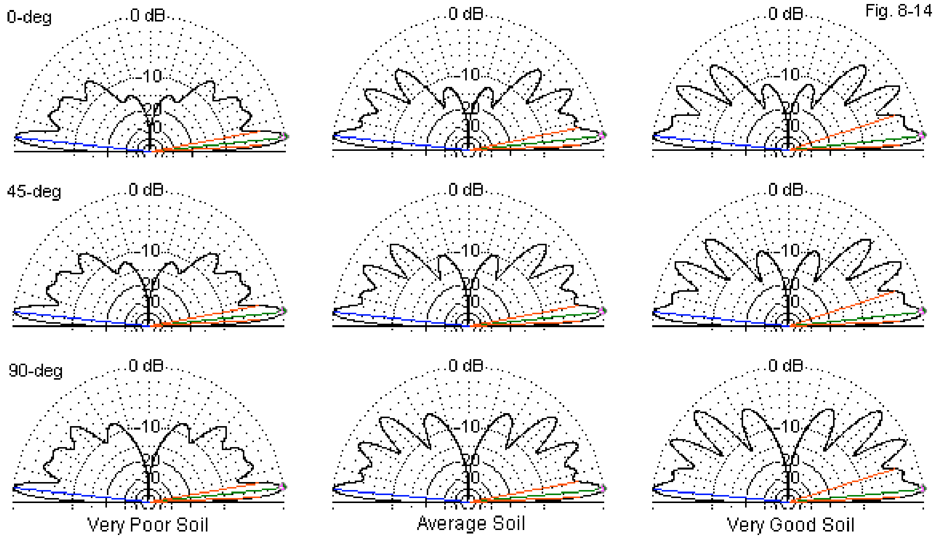
Fig. 8-13

The 144-MHz monopole antennas use lossless wire with a 0.0045-m radius for the vertical elements. The radials are 0.0015 m in radius. **Table 8-10** presents the performance survey results for the antenna when 2-λ above ground. The vertical dipole, of course, has a lower element that is smaller in effective diameter than the combined diameters of the radials. Note the constant TO angle (6° above the horizon) for all antennas in the group, regardless of the radial angle or the soil type.

The ¼-λ vertical monopole with 4 radials has long provided very credible service in the VHF and UHF ranges. The source resistance forms a good match to the ubiquitous 50-Ω coaxial cable with a radial angle between 30° and 45° relative to the vertical element. Indeed, many home-built monopoles in this class undergo a radial bending session until the antenna presents the lowest possible SWR at the operating frequency and use position. As the angle increases toward the 90° mark, the gain of the assembly decreases. For any given soil type, there is about a full dB gain differential between 30° and 90° radial systems.

1/4-WL Vertical Element With Radials at Various Angles						
Frequency: 144 MHz; All Antennas Near Resonance						
Vertical Element = 0.4877 m; Feedpoints 2 WL Above Ground; Height 4.1638 m						
Rad Ang	Rad L m	Soil	Gain dBi	TO Angle	Resist	React
0	0	Very Poor	5.82	84	71.778	0.014
		Average	4.91	84	71.735	0.018
		Very Good	4.32	84	71.718	0.024
30	0.4248	Very Poor	6.08	84	52.499	0.017
		Average	5.17	84	52.466	0.033
		Very Good	4.6	84	52.455	0.043
45	0.4562	Very Poor	5.88	84	48.042	-0.021
		Average	4.98	84	48.013	0
		Very Good	4.41	84	48.004	0.011
60	0.496	Very Poor	5.63	84	41.212	-0.075
		Average	4.76	84	41.192	-0.048
		Very Good	4.19	84	41.187	-0.036
90	0.598	Very Poor	5.02	84	22.094	-0.027
		Average	4.21	84	22.101	-0.005
		Very Good	3.65	84	22.106	0.002
	Note	Rad Ang = Angle from vertical formed by				
		radials. 0 degrees = vertical dipole				
Table 8-10		Rad L m - Radial length in meters				

The elevation/theta patterns give almost no clue to the gain reduction that results from increasing the radial angle from 30° to 90°. **Fig. 8-14** presents a gallery of selected patterns. One must look intently at the plots to detect in any column for soil type differences between the pattern shapes. Much more evident is the change in pattern shape for any given radial angles as we move from very poor to very good soil. Two facets of pattern evolution are striking. First is the increase in the relative strength of higher angle lobes with improving soil quality. Second is the increasing depth of the nulls between lobes with improving soil quality. We observed these features in the patterns for the upper-HF monopoles, with feedpoint height at ¼-λ above ground. Increasing the antenna height to 2 λ above ground has made the changes more subtle but no less clear.

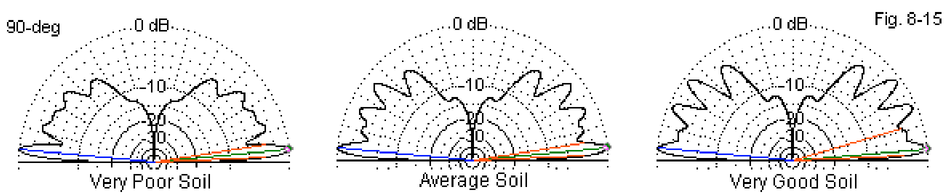


Selected Elevation/Theta Patterns of 144-MHz 1/4-WL Vertical Element over 4 1/4-WL Radials Sloped 0, 45, and 90 Degrees fron Vertical

When we increase the monopole length to 5/8 λ and retain the 2-λ feedpoint height above ground, we encounter some of the same variability of results that we experienced with upper-HF long monopoles. Since VHF and UHF monopoles almost universally use ¼-λ radials or their approximation, we shall survey only models using those radials.

Table 8-11 provides the results of the modeling survey. The table covers all radial angles (except, of course, for 0°, the case of the vertical dipole). Due to the high TO angle, no version of the 5/8-λ monopole is suitable for line-of-sight service in the VHF and UHF ranges except the 90° radial models. Therefore, **Fig. 8-15** provides sample elevation/theta patterns only for those models. The 5/8-λ 90° radial monopole provides about a half-dB advantage over the ¼-λ 90° radial monopole but slightly less gain than the ¼-λ monopole with radials sloped to match a 50-Ω coaxial cable. These results apply to our high-position models only. We shall explore simulated mobile antennas later.

5/8-WL Vertical Element With 1/4-WL Radials at Various Angles						
Frequency: 144 MHz; All Feedpoints 2 WL Above Ground						
Vertical Element = 1.3012 m; Radials 0.5205 m; Height 4.1638 m						
Rad Ang	Soil	Gain dBi	TO Angle	Dom Lobe	Resist	React
30	Very Poor	4.31	54	4	104.064	-195.63
	Average	5.23	54	4	104.011	-195.734
	Very Good	5.61	54	4	103.981	-195.77
45	Very Poor	3.95	54	4	97.847	-208.947
	Average	4.87	54	4	97.798	-209.03
	Very Good	5.34	54	4	97.771	-209.058
60	Very Poor	4.17	85	1	93.207	-220.736
	Average	4.37	53	4	93.168	-220.797
	Very Good	4.75	53	4	93.147	-220.818
90	Very Poor	5.52	85	1	92.126	-232.938
	Average	4.77	85	1	92.115	-232.972
	Very Good	4.27	85	1	92.107	-232.984
	Note	Rad Ang = Angle from vertical formed by radials				
Table 8-11		Dom Lobe = Dominant elevation lobe				



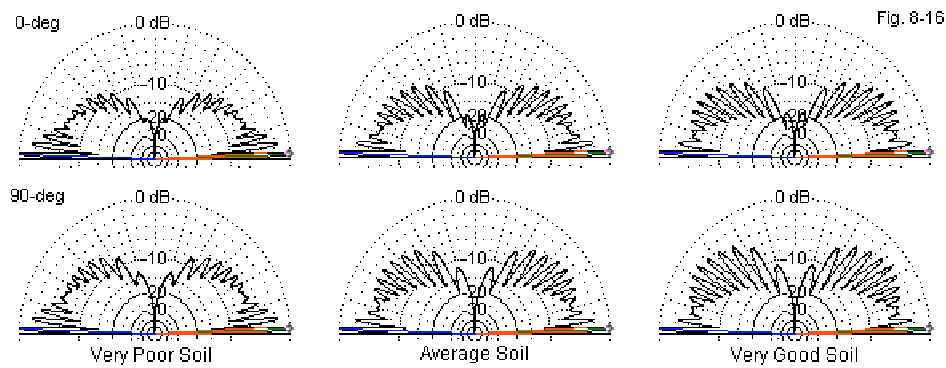
Selected Elevation/Thate Patterns of 144-MHz 5/8-WL Vertical Element over 4 1/4-WL Radials 90 Degrees to the Vertical

The 432-MHz versions of these antennas use the same feedpoint height above ground, which amounts to 6 λ at the new frequency. Because changes become ever more subtle with increasing frequency and height, we can reduce the detail of the survey into a single table. For the ¼-λ monopole, it includes radial angles of 0°, 45°, and 90°, but only covers 90° radials for the 5/8-λ monopole. As **Table 8-12** shows, the impedance changes with soil type are completely negligible for any of the antennas in the survey. As well, all of the antennas show the same TO angle.

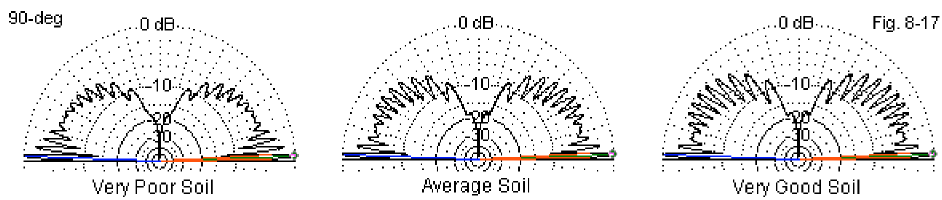
432-MHZ Vertical Element With 1/4-WL Radials at Various Angles						
1/4-WL Vertical Element; Length 0.1626 m						
Feedpoints 6 WL Above Ground; Height 4.1638 m						
Rad Ang	Rad L m	Soil	Gain dBi	TO Angle	Resist	React
0	0	Very Poor	7.22	88	71.858	-0.001
		Average	6.8	88	71.853	0
		Very Good	6.54	88	71.851	0
45	0.1521	Very Poor	7.22	88	48.091	-0.065
		Average	6.8	88	48.087	-0.062
		Very Good	6.53	88	48.086	-0.061
90	0.1993	Very Poor	6.26	88	22.077	-0.065
		Average	5.84	88	22.078	-0.062
		Very Good	5.58	88	22.078	-0.061
5/8-WL Vertical Element; Length .4337 m						
Feedpoints 6 WL Above Ground; Height 4.1638 m						
90	0.1735	Very Poor	6.3	88	92.165	-232.913
		Average	5.9	88	92.164	-232.918
		Very Good	5.65	88	92.163	-232.92
	Note	Rad Ang = Angle from vertical formed by				
Table 8-12		radials. 0 degrees = vertical dipole				

The 5/8-λ monopole shows no particular advantage over the simpler ¼-λ monopole at a height of 6 λ above ground. However, the 5/8-λ monopole does require attention to matching due to the high capacitive reactance and the source resistance that is about twice the value of standard coaxial cables used in most amateur installations.

Fig. 8-16 provides a simplified elevation/theta plot gallery for the ¼-λ monopoles. The added height increases the number of elevation lobes in each pattern. However, we can detect the patterns of change with improving soil by tracing the tips of the nulls within each overall pattern. The oval on each side of the zenith line becomes shallower as soil improves because the nulls are deeper and the lobes are stronger at higher angles relative to the horizon. **Fig. 8-17** provides a set of patterns for the 5/8-λ monopole at 432 MHz.



Selected Elevation/Thate Patterns of 432-MHz 1/4-WL Vertical Element
over 4 1/4-WL Radials Sloped 0 and 90 Degrees to the Vertical



Selected Elevation/Theta Patterns of 432-MHz 5/8-WL Vertical Element
over 4 1/4-WL Radials 90 Degrees to the Vertical

Anyone seriously interested in improving vertical antenna gain must eventually examine collinear arrays. As one example–but perhaps not the very best example–of such designs I adapted models of 144-MHz and 432-MHz arrays that use a ¼-λ lower section with radials and a 5/8-λ upper section. Actually, neither section is precisely the length generally given. Rather, each requires adjustment so that a single wide-spaced inductor can provide a combination of impedance match and phase change needed so that the position of the current peaks are in phase. The coil is also part of the overall radiating structure and contributes to the length of the array. The 5/8-λ monopoles are 2.5 times the length of the ¼-λ monopoles. The collinear array is about 1.63 times the length of the 5/8-λ monopole or about 4 times as long as the ¼-λ monopole. See **Fig. 8-13** to review the relative antenna sizes.

Note that part of the procedure in adjusting the collinear array involves finding the correct combination of lower monopole length and radial length to arrive at a usable feedpoint impedance. For these models, the radials are shorter than for the other monopoles.

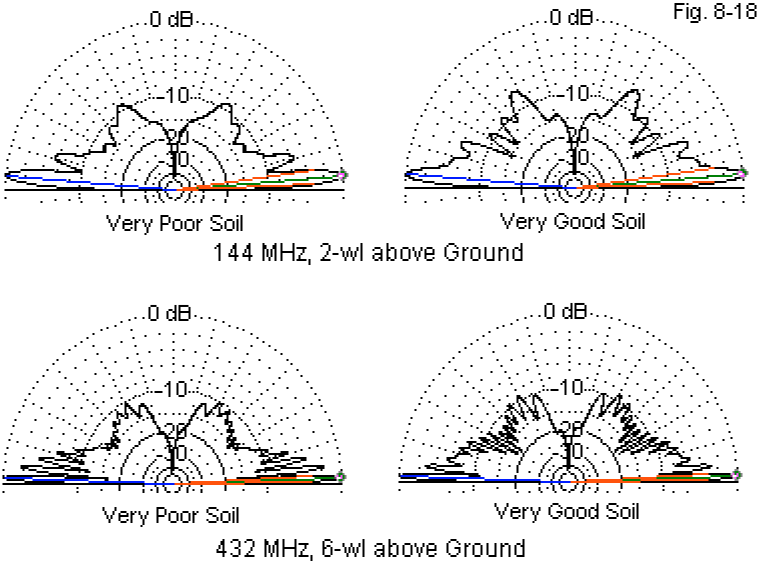
The models for these antennas use odd radii for the elements relative to the other models in the VHF/UHF sequence. The 432-MHz wire diameter is 1/8" throughout, while the 144-MHz model uses about a 3/8" diameter wire. Commercial manufacture of these antennas tends to use a single length of uniform-diameter wire for the entire structure, and this practice coincides well with the NEC preferences for the same condition. The physically modeled coils use 8 segments per turn (in lieu of using NEC loads for the coils at high-impedance points in the structure). Hence, the models are too large to include within the text, although they are attached to this volume.

Collinear Arrays for 144 and 432 MHz				Table 8-13
144 MHz 2 WL above Ground: Height 4.1638 m				
Soil	Gain dBi	TO Angle	Resist	React
Very Poor	8.1	85	47.165	-1.354
Average	7.39	85	47.14	-1.365
Very Good	6.88	85	47.129	-1.367
432 MHz 6 WL above Ground: Height 4.1638 m				
Very Poor	9	88	47.284	0.387
Average	8.59	88	47.281	0.384
Very Good	8.33	88	47.28	0.383

Table 8-13 provides performance reports from the models. The data is compatible with other modeling data, since the AGT scores for the collinear arrays are similar to those for the monopoles. The collinear models show for each frequency a gain advantage between 2 to 3 dB over any of the monopoles surveyed.

Part of the gain advantage of the collinear arrays arises from the suppression of higher-angle lobes. The elevation/theta patterns in **Fig. 8-18** show some reduction in the highest angle lobes, but even more reduction of the mid-angle lobes between

30° and 45° above the horizon. However, the growth of higher angle lobes as we move from very poor to very good soil remains a feature of these arrays (and of virtually any vertically polarized antenna).

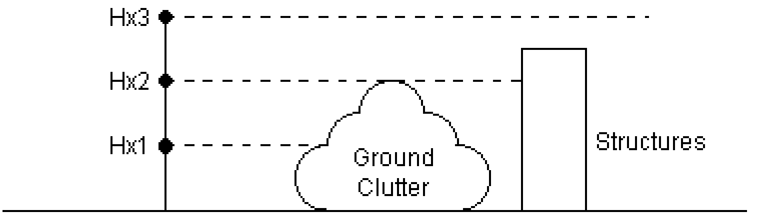


Selected Elevation/Theta Patterns: Collinear Vertical Array

For high fixed locations, the collinear array offers far more benefit over simple monopoles of any length than the 5/8-λ monopole offers over the ¼-λ monopole. Where the additional height required by the collinear array is not a major hindrance to use, this type of antenna is likely preferable to simpler antennas. The models used in arriving at the performance data represent only one design option. There are many routes to phasing monopoles into collinear arrays. The models used here provide some general guidance, but do not pretend to be operating specifications. Like all the models in our work, they use lossless wire. Therefore, the phase/match coils have no resistive losses. This limitation would be important in selecting a final collinear design, but does not impede the general guidance of the data trends.

Vertical antennas in the VHF and UHF ranges rely upon line-of-sight radiation for much of their utility. For mobile communications, the problem is not the curvature of the earth, but instead the ground clutter in the immediate vicinity of the antenna. The goal is for the antenna to be able to "see over" the clutter of objects that might absorb, refract, or reflect RF energy in undesired ways. **Fig. 8-19** provides a general sketch of the situation and its relationship to antenna height. Ideally, a portable, field, or mobile antenna should be higher than the highest object between it and the target of the communication.

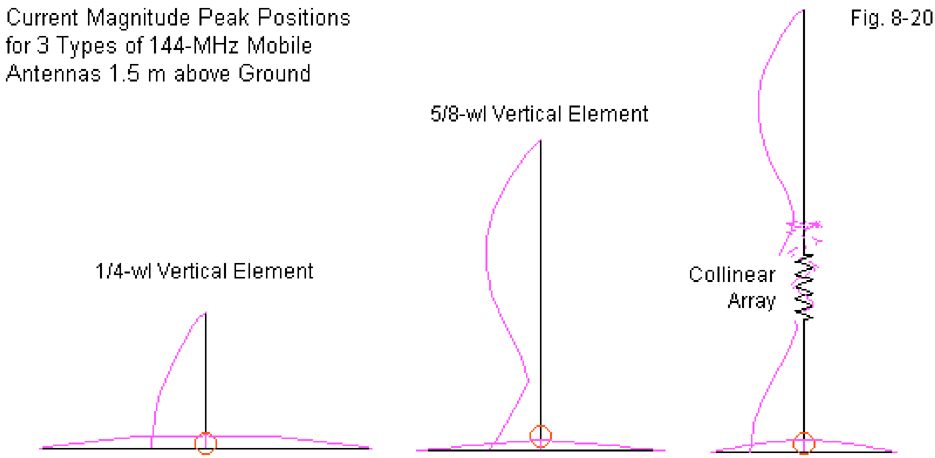
Fig. 8-19



Immediate-Area Height Concerns

Mobile services normally include antennas positioned at low heights, for example on vehicles. One advantage offered by the longer monopoles and arrays is the location of the regions of high current magnitude along the length of the antenna. For any given mounting height, a 1/4-λ monopole has its region of high current magnitude at the lowest point on the vertical. See the current graph to the left in **Fig. 8-20**.

In contrast, the 5/8-λ monopole has its region of highest current about ¼-λ down from the upper tip of the antenna. This position is well above the upper end of the shorter monopole. The much taller collinear array has two high-current regions. The upper region is above the upper end of even the 5/8-λ monopole. See the right-most current graph in **Fig. 8-20**. Although the idea of high-current magnitude regions coincides neatly with the idea of seeing over obstructions, it is not amenable to decisive modeling. The obstructions encountered by mobile antennas are simply too many and too varied for ready modeling.



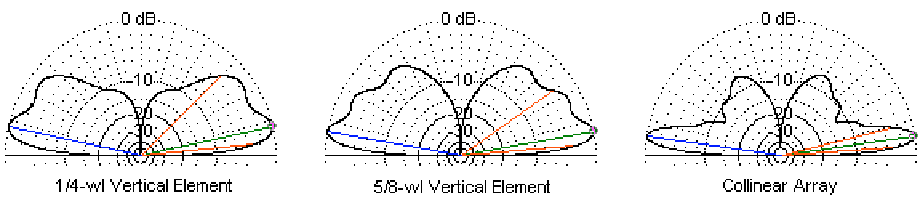
However, we can do a general comparison of the performance of the antenna options in a generalized mobile situation–one that does not take into account the auto itself or the position of the antenna on the vehicle. We can simply transfer the high-position models down to mobile level. To sample this condition with our monopoles, I selected for comparison 3 144-MHz antennas from the survey: a ¼-λ monopole with 90° radials, a 5/8-λ monopole with 90° radials, and a collinear array. The feedpoint height for all 3 antennas is 1.5 m (about 4.92') above ground. The goal is to discover whether the longer arrays offer any advantage over the basic monopole at a height similar to those found in mobile antennas.

The results appear in **Table 8-14**. Over very poor soil–which might be typical of urban and roadway situations–the 5/8-λ monopole offers about 1.2-dB advantage over the ¼-λ monopole. The collinear array provides an additional 2.1-dB advantage. Unfortunately, its overall height at 144 MHz might convert it into an inverted-L under some limited-clearance bridge or in a parking garage.

Fig. 8-21 presents elevation/theta patterns for the 3 antennas. The patterns use very poor soil in all 3 cases. The pattern conditions that we observed at higher feedpoint positions show up at the low height, but with few lobes.

Comparison of 3 144-MHz Antennas 1.5-m above Ground						Table 8-14
Rough Simulation of Mobile Service						
Antenna	Soil	Gain	TO Angle	Resist	React	
1/4 WL	Very Poor	2.89	77	21.974	-0.38	
	Average	2.75	55	21.961	-0.523	Note
	Very Good	3.32	56	21.945	-0.582	Note
5/8 WL	Very Poor	4.11	80	92.24	-232.571	
	Average	3.3	64	92.247	-232.414	Note
	Very Good	3.79	65	92.268	-232.352	Note
Collinear	Very Poor	6.18	82	47.441	-1.337	
	Average	5.15	82	47.557	-1.3	
	Very Good	4.44	83	47.61	-1.301	

Comparative Elevation/Theta Patterns of 3 Mobile Antennas 1.5 m above Ground



All patterns over very poor (urban) soil.

Fig. 8-21

As we improve the soil quality beneath the hypothetical mobile antenna, only the collinear array maintains a low TO angle. Over very good and average soils, both the ¼-λ and the 5/8-λ monopoles show a high TO angle, indicating dominance by the second lobe rather than the lowest lobe. The 2 lobes are not radically different in strength, but in accord with trends that we have seen in other cases, the second lobe has a higher proportional strength over very good soil than over average soil. The changing balance of lobe strength with the change in soil quality may go some distance in accounting for the variability of field reports about the relative capabilities of the 5/8-λ monopole relative to the shorter standard monopole.

At least 2 factors reduce the reliability of these modeling results relative to actual mobile operation. First, mobile VHF and UHF verticals find various locations on vehicles. Positions range from the vehicle top to trunk lids to various side-mounting positions. Hence, the vehicle itself may create many reflections and refractions to disrupt the smooth circular patterns shown by all of the models in this volume. Second, many mobile antennas do not provide ground-plane radials. Instead, they rely upon the vehicle's metal surfaces to act as a ground plane. The result is a ground plane of incredible complexity that is also installation specific. Together, these 2 factors may give a mobile antenna performance properties that are quite different from those of the model.

Modeling guidance thus has severe limitations wherever the installation and operating environment is complex and variable. At most, models can supply some expectations of antenna operation in a normal or clean environment. Variations in performance then call for field investigation to locate, identify, and hopefully quantify the elements that create them.

The Next Steps

In this volume, we have no further steps to take, having completed the exploration of ground planes and their models that we defined in the first chapter. We have covered much ground, both figuratively and literally. Much remains to be done by way of developing more precise theory and calculations and more revelatory field experiments. Indeed, in time, even better software will emerge for the analysis of data trends and patterns than we have in NEC-4.

Nevertheless, we have seen that the ground-plane–as the completion of an antenna's electrical assembly–gives the dipole the primary role in the analysis of ground-plane monopoles. This change of perspective–especially in the somewhat simplified presentations of monopole theory available to radio amateurs–alters our perception of the ground itself. No longer is it simply a lossier version of a perfectly conducting ground. Rather, real ground defines a very broad territory between a perfectly reflecting surface for RF at one extreme to a completely transparent medium at the other. Actual refractions and reflections in the stratified and variable medium of real ground are more complex than virtually any model can accommodate. However, students of ground may wish to explore King and Smith's *Antennas in Matter* (MIT, 1981) as a start.

Models Used in These Studies

Appended to this volume is a special directory of models. The "Models" directory is subdivided into folders containing the models used in each chapter. All are in .NEC format for use with programs that make available the complete command set. Each model emerged from NEC-4. Those models that employ a buried radial system will not run on NEC-2. Models that employ the GM command, even if they do not use buried radials, may require revision to make the GM entry compatible with the format required by NEC-2.

The 330 or so models attached to this volume do not encompass all of the models used in these notes. In many instances, data gathering required only a single change–such as the antenna height or the ground quality–to move from one model run to the next. In these cases, the model collection includes a baseline model, and you may vary the entry values as necessary to replicate all of the steps of the data progression. Since all models use ASCII, the file size for each model is small.

Do not run the models from the CDROM. Instead, move the models to a directory on your hard drive. You may move them individually, in chapters, or as a total group, according to your needs and interests. Placing them on your own hard drive will allow you to know where the output files are at all times within the terms of the program you use. As well, moving the files opens them to modifications without changing a file name or folder location.

Note that the models used in this set of studies are for general guidance only and do not constitute design models en route to a specific construction project.

Other Publications

We hope you've enjoyed this Volume of the **Ground-Plane Notes.** You'll find many other very fine books and publications by the author L.B. Cebik, W4RNL in the ***antenneX Online Magazine BookShelf*** at the web site shown below.

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