Chapter 4

Antenna Modeling & System Planning

OVERVIEW: ANTENNA ANALYSIS BY COMPUTER

As pointed out in Chapter 3, The Effects of Ground, irregular local terrain can have a profound effect on the launch of HF signals into the ionosphere. A *system approach* is needed to create a scientifically planned station. We pointed out in Chapter 3 that antenna modeling programs do not generally take into account the effects of irregular terrain, and by "irregular" we mean any sort of ground that is not flat. Most modeling programs based on *NEC-2* or *MININEC* do model reflections, but they do not model diffractions.

On the other hand, while a ray-tracing program like *HFTA* (HF Terrain Assessment) does take into account diffraction, it doesn't explicitly factor in the mutual impedance between an antenna and the ground. Instead, *HFTA* makes the basic assumption that the antenna is mounted sufficiently high above ground so that the mutual impedance between an antenna and the ground is minimal.

In this chapter we'll look at modeling the antennas themselves on the PC. We'll evaluate some typical antennas over flat ground and also in free space. Once characterized—or even optimized for certain characteristics—these antennas can then be analyzed over real terrain using *HFTA* and the other tools discussed in Chapter 3.

A Short History of Antenna Modeling

With the proliferation of personal computers since the early 1980s, amateurs and professionals alike have made significant strides in computerized antenna system analysis. It is now possible for the amateur with a relatively inexpensive computer to evaluate even complicated antenna systems. Amateurs can obtain a keener grasp of the operation of antenna systems—a subject that has been a great mystery to many in the past. We might add that modern computing tools allow hams to debunk overblown claims made about certain antennas.

The most commonly encountered programs for antenna analysis are those derived from a program developed at US government laboratories called *NEC*, short for "Numerical Electromagnetics Code." *NEC* uses a so-called *Method of Moments* algorithm. This intriguing name derives from a mathematical convention dealing with how "momentous" the accumulated error becomes when certain simplifying assumptions are made about the current distribution along an antenna wire. If you want to delve into details about the method of moments, John Kraus, W8JK, has an excellent chapter in his book *Antennas*, 2nd edition. See also the article "Programs for Antenna Analysis by the Method of Moments," by Bob Haviland, W4MB, in *The ARRL Antenna Compendium, Vol 4*.

The mathematics behind the method-of-moments algorithm are pretty formidable, but the basic principle is simple. An antenna is broken down into a number of straight-line wire *segments*, and the field resulting from the RF current in each segment is evaluated by itself and also with respect to other mutually coupled segments. Finally, the field from each contributing segment is vector-summed to yield the total field, which can be computed for any elevation or azimuth angle desired. The effects of flat-earth ground reflections, including the effect of ground conductivity and dielectric constant, may be evaluated as well.

In the early 1980s, *MININEC* was written in BASIC for use on personal computers. Because of limitations in memory and speed typical of personal computers of the time, several simplifying assumptions were necessary in *MININEC* and these limited potential accuracy. Perhaps the most significant limitation was that perfect ground was assumed to be directly under the antenna, even though the radiation pattern in the far field did take into account real ground parameters. This meant that antennas modeled closer than approximately 0.2 λ over ground sometimes gave erroneous impedances and inflated gains, especially for horizontal polarization. Despite some limitations, *MININEC* represented a remarkable leap forward in analytical capability. See Roy Lewallen's (W7EL) "*MININEC*—the Other Edge of the Sword" in Feb 1991 *QST* for an excellent treatment on pitfalls when using *MININEC*.

Because source code was made available when *MININEC* was released to the public, a number of programmers produced some very capable commercial versions for the amateur market, many incorporating exciting graphics showing antenna patterns in 2D or 3D. These programs also simplify the creation of models for popular antenna types, and several come with libraries of sample antennas.

By the end of the 1980s, the speed and capabilities

Commercial Implementations of *MININEC* and *NEC-2* Programs

Ever since the source code for *NEC-2* and *MININEC* came into in the public domain, enterprising programmers have been upgrading, extending and improving these programs. There are a number of "freeware" versions available nowadays, and there are also a variety of commercial implementations.

This sidebar deals only with the most popular commercial versions, programs that many hams use. You should keep in mind that whatever program you choose will require an investment in learning time, if not in dollars. Your time is valuable, of course, and so is the ability to swap modeling files you create with other modelers. Other peoples' modeling files, particularly when you are just starting out, are a great way to learn how the "experts" do their modeling. For example, there are archives of *EZNEC/ELNEC* files available on the Internet, since this popular modeling program has been around for a number of years. (*ELNEC* is the DOS-only, *MININEC*-core predecessor of EZNEC.)

The following table summarizes the main features and the pricing as of 2006 for some popular commercial antenna modeling programs. The programs that use the *NEC-4* core require separate licenses from Lawrence Livermore National Laboratories.

Commercial Implementations of *MININEC* and *NEC 2* programs

Name	***EZNEC 4.0 (+ ver.)***	***EZNEC-M Pro***	***EZNEC/4***	***NEC-Win Plus +***	***NEC-Win Pro***	***GNEC***	***Antenna Model***
Manufacturer	Roy Lewallen	Roy Lewallen	Roy Lewallen	Nittany Scientific	Nittany Scientific	Nittany Scientific	Teri Software
Core	*NEC-2*	*NEC-2*	*NEC-4*	*NEC-2*	*NEC-2*	*NEC-2/NEC-4*	*MININEC*
Operating System	Windows 32-bit	Windows 32-bit	Windows 32-bit	Windows 32-bit	Windows 32-bit	Windows 32-bit	Windows 32-bit
Number Segments	500 (1500, + ver.)	20,000	20,000	10,000	10,000	80,000	Limited by memory
NEC-Card Inputs	No	Yes	Yes	Yes	Yes	Yes	No
Other Input	ASCII (NEC, + ver.)	ASCII, NEC	ASCII, NEC	CAD *.DXF	CAD *.DXF	CAD *.DXF	No
Wires by Equation	No	No	No	Yes	Yes	Yes	Yes
Source Setting	By %	By %	By %	By %	By %	By %	By %
Source Type	Current/ Voltage/Split	Current/ Voltage/Split	Current /Voltage/Split	Current/ Voltage/Split	All types	All types	Current/Voltage
R + *j* X Loads	Yes	Yes	Yes	Yes	Yes	Yes	Yes
RLC Loads	Series, Parallel, Trap	Series, Parallel, Trap	Series, Parallel, Trap	Series, Parallel	Series, Parallel	Series, Parallel	Series, Parallel
True Trap Loads	Yes	Yes	Yes	No	No	No	No
Laplace Loads	Yes	Yes	Yes	Yes	Yes	Yes	No
Conductivity Table	Yes *	Yes *	Yes *	Yes	Yes	Yes	Yes
Average Gain Test	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Transmission Lines	Yes	Yes	Yes	Yes	Yes	Yes	No
View Geometry	Excellent	Excellent	Excellent	Good	Good	Good	Very Good
Geometry Checking	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Easy Height Change	Yes	Yes	Yes	No	No	No	No
Polar Plots	ARRL, linear-dB Az/El, Circ. (+ ver.)	ARRL, linear-dB Az/El, Circ.	ARRL, linear-dB Az/El, Circ.	ARRL, linear-dB Az/El Patterns	ARRL, linear-dB Az/El Patterns	ARRL, linear-dB Az/El Patterns	ARRL, Linear -dB Az/El Patterns
Rectangular Plots	SWR	SWR	SWR	SWR, Zin	SWR, Zin, Az/El, Near/Far Plots, Currents	SWR, Zin, Az/El, Near/Far Plots, Currents	Gain, SWR, F/B, F/R, Rin, Xin
Operating Speed	Fast	Fast	Fast	Very Fast	Very Fast	Very Fast	Slow
Smith Chart	Data for Ext. Smith program	Data for Ext. Smith program	Data for Ext. Smithprogram	No	Yes	Yes	Yes
Near/Far Field Tables	Both	Both	Both	Far	Both	Both	Both
Ground Wave Analysis	No	Yes	Yes	No	Yes	Yes	No
Pricing	$89 Web; $99 CD-ROM, $139 (+ ver.)	$450	$600; must have *NEC-4* license	$150	$425	$795	$85

* Wire conductivity is the same for all wires.

Excellent, Very Good, Good ratings done by *Antenna Book* editor.

of personal computers had advanced to the point where PC versions of *NEC* became practical, and several versions are now available to amateurs. The most recent public-domain version is *NEC-2* and this is the computational core that we'll use as an example throughout this chapter.

Like *MININEC*, *NEC-2* is a general-purpose modeling package and it can be difficult to use and relatively slow in operation for certain specialized antenna forms. Thus, custom commercial software has been created for more user-friendly and speedier analysis of specific antenna varieties, mainly Yagi arrays. See Chapter 11, HF Yagi Arrays. Also see the sidebar, "Commercial Implementations of *MININEC* and *NEC-2* Programs."

For this edition of *The ARRL Antenna Book*, Roy Lewallen, W7EL, has graciously provided a special version of his *EZNEC 3.0* program, called *EZNEC-ARRL*. This version works with the specific antenna models also bundled on the CD-ROM. Please note that this ARRL-specific version of *EZNEC* is limited to a maximum of 20 segments (we'll explain segments later) for all models except for the special ones included on this CD-ROM. You can find information on how to purchase the full-fledged version of *EZNEC* in the **Help** section of the *EZNEC-ARRL* program.

The following material on antenna modeling is by necessity a summary, since entire books have been written on this subject. Serious modelers would be well-advised to enroll in the online Antenna Modeling course, part of the ARRL Certification and Continuing Education series. L. B. Cebik, W4RNL created the ARRL Antenna Modeling course and it contains a great deal of information, tips and techniques concerning modeling by computer. See: **http://www.arrl.org/news/stories/2002/02/06/2/** for more information. We also strongly recommend that you read the Help files in *EZNEC-ARRL*. There is a wealth of practical information on the finer points of antenna modeling there.

THE BASICS OF ANTENNA MODELING

This chapter will discuss the following antenna-modeling topics for an *NEC-2*-based modeling software, using *EZNEC-ARRL* as an example:

- Program outputs
- Wire geometry
- Segmentation, warnings and limitations
- Source (feed point) placement
- Environment, including ground types and frequency
- Loads and transmission lines
- Testing the adequacy of a model

PROGRAM OUTPUTS

Instruction manuals for software programs traditionally start out describing in detail the input data needed by the program. They then demonstrate the output data the program can generate. We feel it is instructive, however, to turn things around and start out with a brief overview of the output from a typical antenna-modeling program.

We'll look at the output from public-domain *NEC-2*. Next, we'll look at the output information available from commercial adaptations of *NEC-2*, using *EZNEC-ARRL* provided by W7EL. After this brief overview of the output data, we'll look in detail at the input data needed to make a modeling program work. In the following discussions it will be very instructive if you to bring up *EZNEC-ARRL* on your computer and open the specific modeling files used in each example. [From now on in this chapter we'll refer merely to *EZNEC* rather than *EZNEC 3.0*, the official name or *EZNEC-ARRL*, a specialized subset of *EZNEC 3.0*. Where there are specific differences between *EZNEC 3.0* and the limited-edition *EZNEC-ARRL* we'll identify them.]

Native *NEC-2*

The native *NEC-2* program produces pages and pages of output formatted for a mainframe "line printer." You may be old enough to remember the stacks of green-and-white, tractor-feed, 132-column computer paper that such a line printer produced. Corporate MIS departments stored untold number of boxes of that paper.

Native *NEC-2* was written in the Fortran language, which stands for *Formula Translation*. Programmers used punched cards to enter the program itself and its accompanying input data into huge mainframe computers. To say that the paper output from *NEC-2* is massive, even intimidating, is putting it mildly. There is a strong distinction between "useful information" and "raw data" and the raw output from native *NEC-2* bombards the user with raw data.

Commercial versions that use the *NEC-2* computational core shield the user from the ugliness of raw line-printer output, as well as punched-card input (or disk surrogates for punched cards). Commercial versions like *EZNEC* do produce output numerical tables where this is useful. These tables show parameters such as the source impedance and SWR at a single frequency, or the characteristics of a load or a transmission line. But as the old saying goes, "One picture is worth a thousand words." This is as true for modeling programs as it is for other endeavors dealing with reams of numbers. Thus, most commercial modeling software packages create *graphs* for the user. *EZNEC* produces the following types of graphs:

- Polar (linear-dB or ARRL-style) graphs of the far-field elevation and azimuth responses.
- 3-D wire-frame graph of the total far-field response.
- Graph of the SWR across a frequency band.
- Graphical display of the RF currents on various conductors in a model.
- Rotatable, zoomable 3-D views of the wires used to make a model.
- Output to programs capable of generating Smith charts.

Fig 1A and 1B shows the computed far-field 2-D elevation and azimuth patterns for a 135-foot long horizontal dipole, mounted in a flattop configuration 50 feet above flat ground. These figures were generated using *EZNEC* at 3.75 MHz. Fig 1C shows a 3-D wire-frame picture of the far-field response, but this time at 14.2 MHz. For comparison, **Table 1** shows a short portion of the line-printer output for the azimuth pattern at 3.75 MHz. The actual printout is many pages long. One picture can indeed replace thousands of numbers!

Fig 2 shows the computed SWR curve over the frequency range 3.0 to 4.0 MHz for this dipole, fed with lossless 50-Ω transmission line. *EZNEC* generated this plot using the “SWR” button. Figs 1 and 2 are typical of the kind of graphical outputs that commercial implementations of the *NEC-2* computing core can produce.

Now, let’s get into the details of what kind of input data is required to run a typical method-of-moments antenna-modeling program.

PROGRAM INPUTS: WIRE GEOMETRY

Coordinates in an X, Y and Z World

The most difficult part of using a *NEC*-type of modeling program is setting up the antenna’s geometry—you must condition yourself to think in three-dimensional, Cartesian coordinates. Each end point of a wire is represented by three numbers: an x, y and z coordinate. These coordinates represent the distance from the origin (x-axis), the width of an antenna (y-axis), and the height (z-axis).

An example should help sort things out. **Fig 3** shows a simple model of a 135-foot center-fed dipole, made of #14 copper wire placed 50 feet above flat ground. The common term for this antenna is *flattop dipole*. For convenience, the ground is located at the *origin* of the coordinate system, at (0, 0, 0) feet, directly under the center of the dipole. **Fig 4** shows the *EZNEC* spreadsheet-like input data for this antenna. (Use model file: **Ch4-Flattop Dipole.EZ**.) *EZNEC* allows you to specify the type of conductor material from its main window, using the **Wire Loss** button to open a new window. We will click on the **Copper** button for this dipole.

Above the origin, at a height of 50 feet on the z-axis, is the dipole’s *feed point*, called a *source* in *NEC* terminology. The width of the dipole goes toward the left (that is, in the “negative-y” direction) one-half the overall length of 135 feet, or –67.5 feet. Toward the right, our dipole’s other end is at +67.5 feet. The x-axis dimension of our dipole is zero, meaning that the dipole wire is parallel to and directly above the x-axis. The dipole’s ends are thus represented by two points, whose coordinates are (0, –67.5, 50) and (0, 67.5, 50) feet. The use of parentheses with a sequential listing of (x, y, z) coordinates is a common practice among antenna modelers to describe a wire end point.

Fig 3B includes some other useful information about this antenna beyond the wire geometry. Fig 3B overlays the wire geometry, the current distribution along the wire and the far-field azimuth response, in this case at an elevation angle of 30°.

Although not shown specifically in Fig 3, the thickness of the antenna is the diameter of the wire, #14 gauge. Note that native *NEC* programs specify the *radius* of the

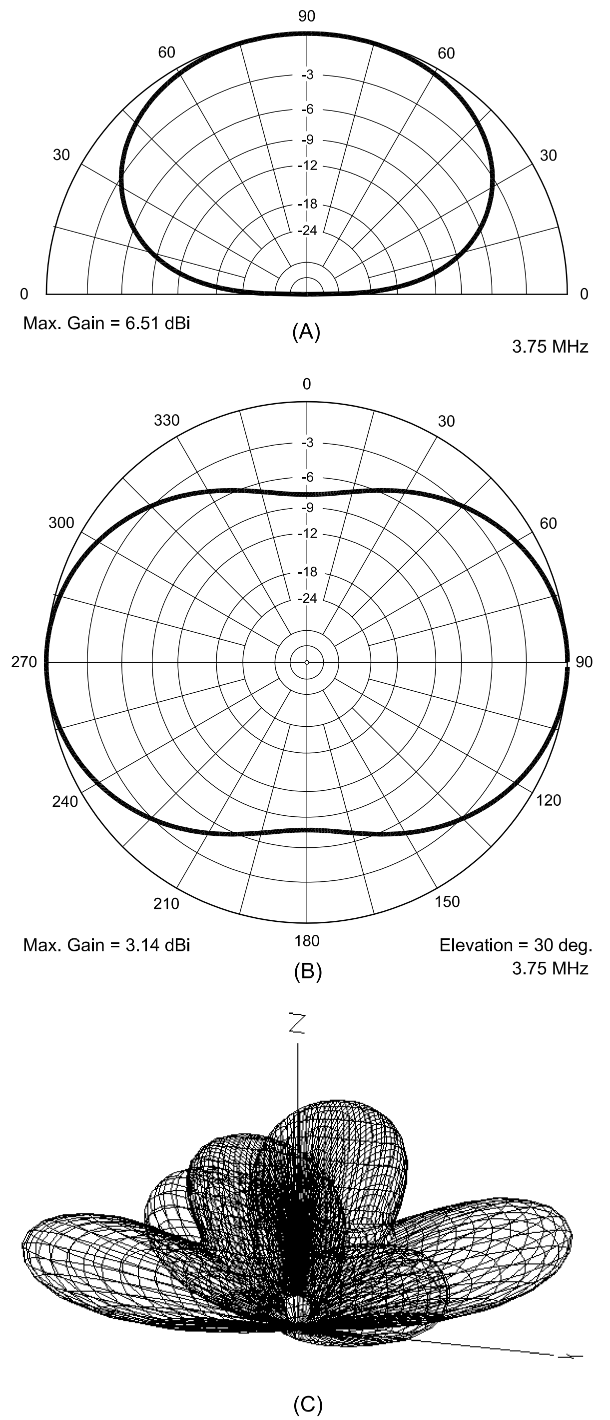


Fig 1—At A, far-field elevation-plane pattern for a 135-foot-long horizontal dipole, 50 feet above flat ground, at 3.5 MHz. At B, the far-field azimuth-plane pattern at an elevation angle of 30°.

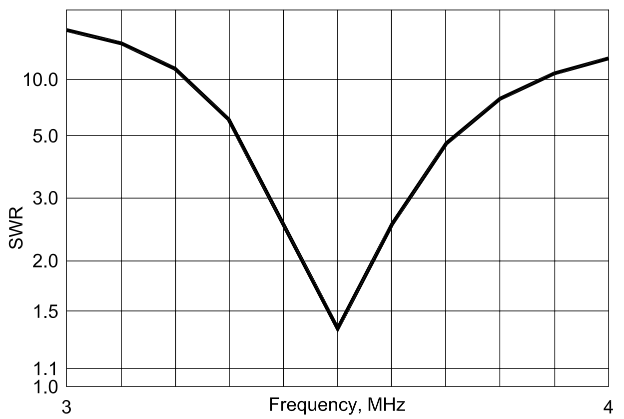


Fig 2—SWR curve for 135-foot flattop dipole over the frequency range 3.0 to 4.0 MHz for a 50-Ω feed line. This antenna is an example and is not optimized for the amateur band.

wire, rather than the diameter, but programs like *EZNEC* use the more intuitive diameter of a wire rather than the radius. *EZNEC* (and other commercial programs) also allows the user to specify the wire as an AWG gauge, such as #14 or #22, for example.

We've represented our simple dipole in Fig 3 using a single, straight wire. In fact, all antenna models created for method-of-moment programs are made of combinations of straight wires. This includes even complex antennas, such as helical antennas or round loops. (The mathematical basis for modeling complex antennas is that they can be simulated using straight-wire *polygons*. A circular loop, for example, can be modeled using an octagon.)

Segmentation and Specifying a Source Segment

We've specified the physical geometry of this simple one-wire dipole. Now several more modeling details surface—you must specify the number of *segments* into which the dipole is divided for the method-of-moment analysis and you must somehow feed the antenna. The *NEC-2* guideline for setting the number of segments is to use at least 10 segments per half-wavelength. This is a general rule of thumb, however, and in many models more dense segmentation is mandatory for good accuracy.

In Fig 3, we've specified that the dipole be divided into 11 segments for operation on the 80-meter band. This follows the rule of thumb above, since the 135-foot dipole is about a half-wavelength long at 3.5 MHz.

Setting the Source Segment

The use of 11 segments, an odd rather than an even number such as 10, places the dipole's feed point (the

Table 1
Portion of line-printer output from *NEC-2* for 135-foot dipole.

- - - RADIATION PATTERNS - - -											
- - ANGLES - -		*- POWER GAINS -*			*- - - POLARIZATION - - -*			*- - - E(THETA) - - -*		*- - - E(PHI) - - -*	
Theta Degrees	*Phi Degrees*	*Vert dB*	*Hor dB*	*Total dB*	*Axial Ratio*	*Tilt Degrees*	*Sense*	*Magnitude Volts*	*Phase Degrees*	*Magnitude Volts*	*Phase Degrees*
60.00	0.00	–999.99	3.14	3.14	0.00000	90.00	LINEAR	0.00000E+00	0.00	6.62073E-01	–66.87
60.00	1.00	–37.87	3.13	3.14	0.00301	89.52	LEFT	5.89772E-03	–86.64	6.61933E-01	–66.87
60.00	2.00	–31.85	3.13	3.13	0.00603	89.04	LEFT	1.17915E-02	–86.64	6.61512E-01	–66.87
60.00	3.00	–28.33	3.12	3.12	0.00904	88.56	LEFT	1.76776E-02	–86.64	6.60812E-01	–66.87
60.00	4.00	–25.84	3.11	3.11	0.01206	88.08	LEFT	2.35520E-02	–86.64	6.59834E-01	–66.87
60.00	5.00	–23.91	3.09	3.10	0.01508	87.59	LEFT	2.94109E-02	–86.64	6.58577E-01	–66.87
60.00	6.00	–22.34	3.07	3.08	0.01810	87.11	LEFT	3.52504E-02	–86.64	6.57045E-01	–66.87
60.00	7.00	–21.01	3.05	3.06	0.02112	86.62	LEFT	4.10669E-02	–86.63	6.55237E-01	–66.87
60.00	8.00	–19.87	3.02	3.04	0.02415	86.14	LEFT	4.68565E-02	–86.63	6.53158E-01	–66.87
60.00	9.00	–18.86	2.99	3.02	0.02718	85.65	LEFT	5.26156E-02	–86.63	6.50808E-01	–66.87
60.00	10.00	–17.96	2.95	2.99	0.03022	85.15	LEFT	5.83405E-02	–86.63	6.48190E-01	–66.87
60.00	11.00	–17.15	2.91	2.96	0.03327	84.66	LEFT	6.40278E-02	–86.63	6.45308E-01	–66.86
60.00	12.00	–16.42	2.87	2.92	0.03631	84.16	LEFT	6.96739E-02	–86.63	6.42165E-01	–66.86
60.00	13.00	–15.75	2.83	2.89	0.03937	83.66	LEFT	7.52755E-02	–86.63	6.38764E-01	–66.86
60.00	14.00	–15.13	2.78	2.85	0.04243	83.16	LEFT	8.08291E-02	–86.63	6.35108E-01	–66.86
60.00	15.00	–14.56	2.72	2.80	0.04550	82.65	LEFT	8.63317E-02	–86.62	6.31203E-01	–66.86
60.00	16.00	–14.03	2.66	2.76	0.04858	82.14	LEFT	9.17800E-02	–86.62	6.27051E-01	–66.86
60.00	17.00	–13.53	2.60	2.71	0.05166	81.62	LEFT	9.71711E-02	–86.62	6.22657E-01	–66.85
60.00	18.00	–13.07	2.54	2.66	0.05475	81.10	LEFT	1.02502E-01	–86.62	6.18027E-01	–66.85

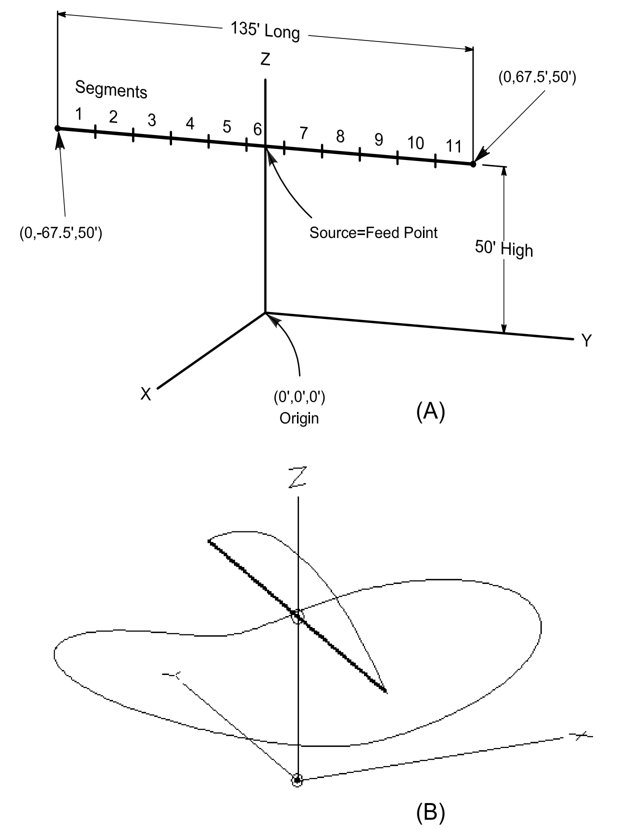
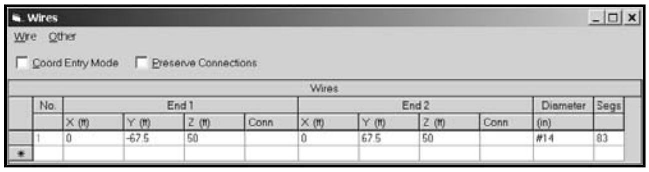


Fig 3—At A, simple model for a 135-foot long horizontal dipole, 50 feet above the ground. The dipole is over the y-axis. The wire has been segmented into 11 segments, with the center of segment number 6 as the feed point. The left-hand end of the antenna is -67.5 feet from the center feed point and that the right-hand end is at 67.5 feet from the center. At B, *EZNEC* "View Antenna" drawing, showing geometry of wire and the x, y and z axes. Overlaid on the wire geometry drawing are the current distribution along the wire and the far-field azimuthal response at an elevation angle of 30°.

source in *NEC*-speak, a word choice that can befuddle beginners) right at the antenna's center, at the center of segment number six. In concert with the "EZ" in its name, *EZNEC* makes choosing the source segment easy by allowing the user to specify a percentage along the wire, in this case 50% for center feeding.

At this point you may very well be wondering why no center insulator is shown in the middle of our center-fed dipole. After all, a real dipole would have a center insulator. However, method-of-moment programs assume that a source generator is placed across an infinitely small gap in the antenna wire. While this is convenient from a mathematical point of view, the unstated use of such an infinitely small gap often confuses newcomers to the world of antenna modeling. We'll get into more details, caveats and limitations in source placement later in this


Wires

Wire Other

Coord Entry Mode Preserve Connections

No.	End 1				End 2				Diameter	Segs
	X (ft)	Y (ft)	Z (ft)	Conn	X (ft)	Y (ft)	Z (ft)	Conn	(in)	
1	0	-67.5	50		0	67.5	50		#14	83

Fig 4—*EZNEC* "Wires" spreadsheet for simple flattop dipole in Fig 3. The numbers shown are in feet, except for the wire diameter, which *EZNEC* allows you to specify as an AWG gauge, in this case #14. Note that 83 segments have been specified for this antenna for analysis over the range from 3.5 to 29.7 MHz.

chapter. For now, just trust us that the model we've just described with 11 segments, fed at segment 6, will work well over the full amateur band from 3.5 to 4.0 MHz.

Now, let's consider what would happen if we want to use our 135-foot long dipole on all HF amateur bands from 3.5 to 29.7 MHz, rather than just from 3.5 to 4.0 MHz. Instead of feeding such an antenna with coax cable, we would feed it with open-wire line and use an antenna tuner in the shack to create a 50-Ω load for the transmitter. To comply with the segmentation rule above, the number of segments used in the model should vary with frequency—or at least be segmented at or above the minimum recommended level at the highest frequency used. This is because a half wavelength at 29.7 MHz is 16.6 feet, while a half wavelength at 3.5 MHz is 140.6 feet. So the number of segments for proper operation on 29.7 MHz should be 10 × 135/16.6 = 81. We'll be a little more conservative than the minimum requirement and specify 83 segments. **Fig 4** shows the *EZNEC* input spreadsheet for this model. (Use model file: **Ch4-Multiband Dipole.EZ**.)

The penalty for using more segments in a program like *NEC* is that the program slows down roughly as the square of the segments—double the number of segments and the speed drops to a fourth. If we try to use too few segments, we'll introduce inaccuracies, particularly in computing the feed-point impedance. We'll delve into this area of segmentation density in more detail later when we discuss testing the adequacy of a model.

Segment Length-to-Wire-Diameter Ratio

Even if you're willing to live with the slowdown in computing speed for situations involving a large number of wire segments, you should make sure the ratio between the segment length and the diameter of any wire is greater than 1:1. This is to say that the length of each segment is longer than the diameter of the wire. Doing so stays away from internal limitations in the *NEC* program.

For the #14 wire specified in this simple 135-foot long dipole, it's pretty unlikely that you'll bump up against this limitation for any reasonable level of segmentation. After all, #14 wire has a diameter of 0.064 inches and 135 feet is 1620 inches. To keep above a segment length of 0.064 inches, the maximum number of segments is 1620/

0.064 = 25,312. This is a *very* large number of segments and it would take a very long time to compute, assuming that your program can handle that many segments.

Keeping above a 1:1 ratio in segment length to wire diameter can be more challenging at VHF/UHF frequencies, however. This is particularly true for fairly large "wires" made of aluminum tubing. Incidentally, this is another point where newcomers to antenna modeling can be led astray by the terminology. In a *NEC*-type program, all conductors in a model are considered to be *wires*, even if they consist of hollow aluminum or copper tubes. Surface effect keeps the RF current in any conductor confined to the outer surface of that conductor, and thus it doesn't matter whether the conductor is hollow or solid, or even made using a number of stranded wires twisted together.

Let's look at a half-wave dipole at 420 MHz. This would be about 14.1 inches long. If you use 1/4-inch diameter tubing for this dipole, the maximum segment length meeting the 1:1 diameter-to-length ratio requirement is also 1/4 inches long. The maximum number of segments then would be 14.1/0.25 = 56.4, rounded down to 56. From this discussion you should now understand why method-of-moment programs are known for using a "thin-wire approximation." Really fat conductors can get you into trouble, particularly at VHF/UHF.

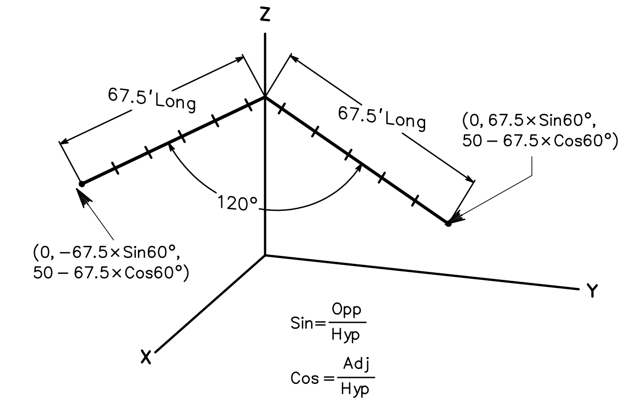
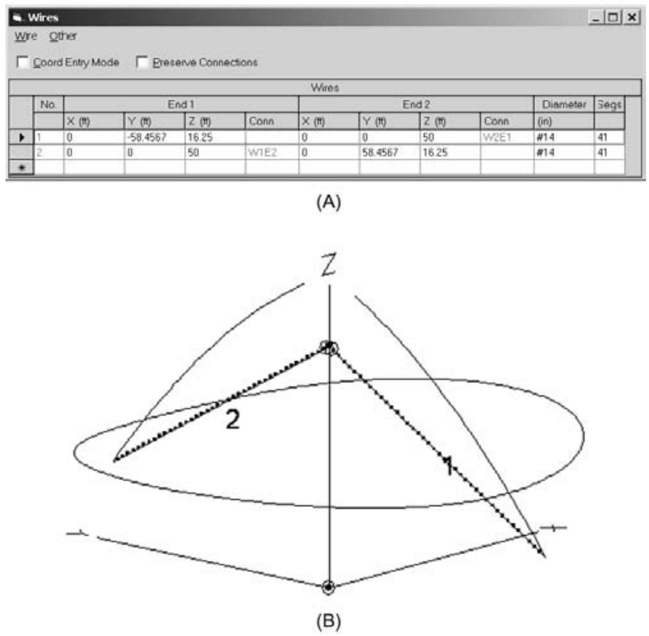


Fig 5—Model for an inverted-V dipole, with an included angle between the two legs of 120°. Sine and cosine functions are used to describe the heights of the end points for the sloping arms of the antenna.



Wires										
No.	End 1				End 2				Diameter	Segs
	X (ft)	Y (ft)	Z (ft)	Conn	X (ft)	Y (ft)	Z (ft)	Conn	(in)	
1	0	-58.4567	16.25		0	0	50	W2E1	#14	41
2	0	0	50	W1E2	0	58.4567	16.25		#14	41

Fig 6—At A, *EZNEC* spreadsheet for inverted-V dipole in Fig 5. Now the ends of the inverted-V dipole are 16.25 feet above ground, instead of 50 feet for the flattop dipole. At B, *EZNEC* "View Antenna" drawing, with overlay of geometry, current distribution and azimuth plot.

Some Caveats and Limitations Concerning Geometry

Example: Inverted-V Dipole

Now, let's get a little more complicated and specify another 135-foot-long dipole, but this time configured as an *inverted V*. As shown in **Fig 5**, you must now specify two wires. The two wires join at the top, at (0, 0, 50) feet. (Again, the program doesn't use a center insulator in the model.)

If you are using a native version of *NEC*, you may have to go back to your high-school trigonometry book to figure out how to specify the end points of our "droopy" dipole, with its 120° included angle. Fig 5 shows the details, along with the trigonometric equations needed. *EZNEC* is indeed more "easy" here, since it allows you to tilt the ends of each wire downwards an appropriate number of degrees (in this case –30° at each end of the dipole) to automatically create an inverted-V configuration. **Fig 6A** shows the *EZNEC* spreadsheet describing this inverted-V dipole with a 120° included angle between the two wires.

See the *EZNEC* **Help** section under "Wire Coordinate Shortcuts" for specific instructions on how to use the "elevation rotate end" shortcut "RE–30" to create the sloping wires easily by rotating the end of the wire down 30°. Now the specification of the source becomes a bit more complicated. The easiest way is to specify two sources, one on each end segment at the junction of the two wires. *EZNEC* does this automatically if you specify a so-called *split-source* feed. Fig 6B shows the two sources as two open circles at the top ends of the two wires making up the inverted-V dipole. What *EZNEC* is doing is creating two sources, each on the closest segments on either side of the junction of the two wires. *EZNEC* sums up the two source impedances to provide a single readout.

Navigating in the View Antenna Window

At this point it's worthwhile to explore some of the ways you can see what the wire geometry looks like using the *EZNEC* **View Ant** button on the main window. Bring up the file **Ch4-Inverted V Dipole.EZ** in *EZNEC*, and click on the **View Ant** button. You will see a small inverted-V dipole raised over the (0, 0, 0) origin on the ground directly under the feed point of the inverted-V dipole. First, "rotate" the dipole by holding down the left-mouse button and moving the mouse. You can orient the picture any way you wish.

Let's take a closer look at the junction of the two wires at the feed point. Click the **Center Ant Image** checkbox toward the bottom of the window to anchor the center of the image at the center of the window, and then move the **Zoom** slider upwards to zoom in on the image. At some point the junction of the two slanted wires will move up off the edge of the window, so you will need to click on the left-hand side of the **Z Move Image** slider to bring the junction back into view. Now you should be able to see a zoomed view of the junction, along with the two open circles that represent the location of the split sources in the middle of the segments adjacent to the wire junction.

Now put the mouse cursor over one of the slanted wires and double click the left-mouse button. *EZNEC* will now identify that wire and show its length, as well as the length of each segment on that wire. Pretty slick, isn't it?

Short, Fat Wires and the Acute-Angle Junction

Another possible complication can arise for wires with short, fat segments, particularly ones that have only a small included angle between them. These wire segments can end up inter-penetrating within each other's volumes, leading to problems in a model. Once you think of each wire segment as a thick cylinder, you can appreciate the difficulty in connecting two wires together at their ends. The two wires always inter-penetrate each other's volume to some extent. **Fig 7** depicts this problem graphically for two short, fat wires joined at their ends at an acute angle. A rule of thumb is to avoid creating junctions where more than $^1/_3$ of the wire volumes inter-penetrate. You can achieve this by using longer segment lengths or thinner wire diameters.

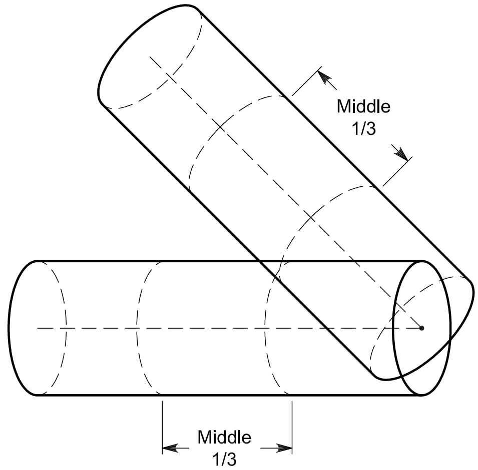


Fig 7—A junction of two short, fat wire segments at an acute angle. This results in inter-penetration of the two wire volumes beyond the middle-1/3 recommended limit.

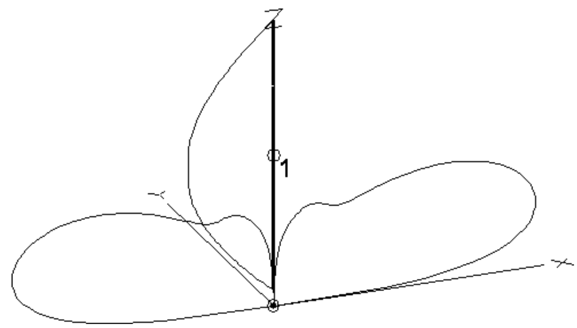


Fig 8—A vertical half-wave dipole, created by turning the dipole in Fig 3 on its end, with a minimum height at the lower end of 8 feet to keep the antenna away from people and animals. The current distribution and the elevation pattern for this antenna are also shown overlaid on the wire geometry.

Some Other Practical Antenna Geometries

A Vertical Half-Wave Dipole

If you turn the 135-foot-long horizontal dipole in Fig 1 on its end you will create a vertical half-wave dipole that is above the origin of the x, y and z axes. See **Fig 8**, where the bottom end of the dipole is placed 8 feet off the ground to keep it away from humans and animals for safety, at (0, 0, 8) feet. The top end is thus at 8 + 135 = 143 feet off the ground at (0, 0, 143). Fig 8 also shows the current distribution and the elevation pattern for this antenna. (Use *EZNEC* model file: **Ch4-Vertical Dipole.EZ**.)

A Ground-Plane Antenna

The ground-plane model is more complicated than previous ones because a total of five wires are now needed: one for the vertical radiator and four for the radials. **Fig 9** shows the *EZNEC* view for a 20-meter ground plane mounted 15 feet off the ground (perhaps on a garage roof), with the overlay of both the current distribution and the elevation-plane plot. (Use *EZNEC* model file: **Ch4-GP.EZ**.) Note that the source has been placed at the

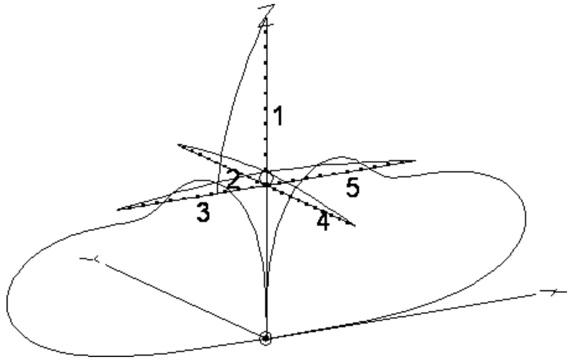


Fig 9—A vertical ground-plane antenna. The radials and the bottom of the vertical radiator are located 15 feet off the ground in this model. The current distribution along each wire and the far-field elevation-plane pattern are overlaid on the antenna geometry.

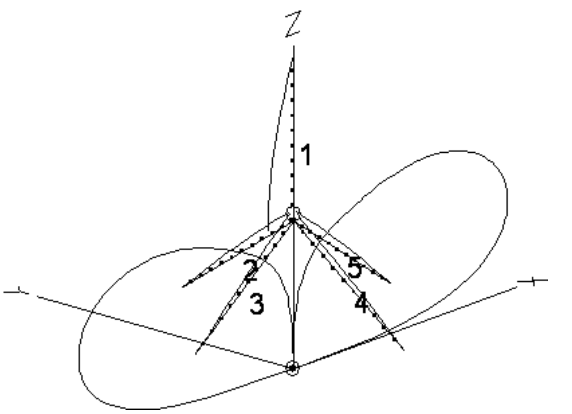


Fig 10—*EZNEC* View Antenna for the ground-plane antenna with its four radials tilted downwards by 40° to improve the SWR at the feed point.

bottom segment of the vertical radiator. Once again, the program needs no bottom insulator, since all five wires are connected together at a common point. *EZNEC* reports that this antenna has a resonant feed-point impedance of about 22 Ω, which would show an SWR of 2.3:1 for a 50-Ω coax feed line if no matching system is used, such as a gamma or hairpin match.

Fig 10 shows the same antenna, except that the radials have now been tilted downwards by 35° to facilitate an almost perfect 50-Ω match (SWR = 1.08:1). In addition, the length of the radiator in this model was shortened by 6 inches to re-resonate the antenna. (Use *EZNEC* model file: **Ch4-Modified GP.EZ**.) The trick of tilting the radials downwards for a ground-plane antenna is an old one, and the modeling programs validates what hams have been doing for years.

A 5-Element Horizontal Yagi

This is a little more challenging modeling exercise. Let's use a 5-element design on a 40-foot boom, but rather than using telescoping aluminum tubing for the elements, we'll use #14 wire. The *SCALE* program included with this book on the CD-ROM converted the aluminum-tubing 520-40.YW to a design using #14 copper wire. **Table 2** shows the element lineup for this antenna. (Later in this chapter we'll see what happens when telescoping aluminum tubing is used in a real-world Yagi design.)

Some explanations of what Table 3 means are in order. First, only one half of each element is shown. The *YW* program (Yagi for Windows), also included on the CD-ROM, computes the other half of the Yagi automatically, essentially mirroring the other half on the opposite side of the boom. Having to enter the dimensions for only half of a real-world Yagi element that uses telescoping aluminum tubing is much easier this way.

Second, the placement of the elements along the boom starts at 0.0 inches for the reflector. The distance between adjacent elements defined in this particular file is the spacing between the element itself and the element just before it. For example, the spacing between the driven element and the reflector is 72 inches, and the spacing between the first director and the driven element is also 72 inches. The spacing between the second director and the first director is 139 inches.

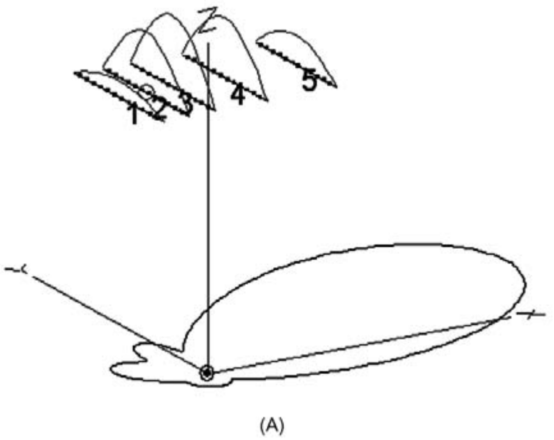
Fig 11A shows the wire geometry for this Yagi array when it is mounted 720 inches (60 feet) above flat ground and Fig 11B shows the *EZNEC* Wires spreadsheet that describes the coordinates. (Use *EZNEC* model file: **Ch4-520-40W.EZ**.) You can see that the x-axis coordinates for the elements have been automatically moved by the *SCALE* program so that the center of the boom is located directly above the origin. This makes it easier to evaluate the effects of stacking different monoband Yagis on a rotating mast in a "Christmas Tree" arrangement. A typical Christmas Tree stack might include 20, 15 and 10-meter monobanders on a single rotating mast sticking out of the top of the tower.

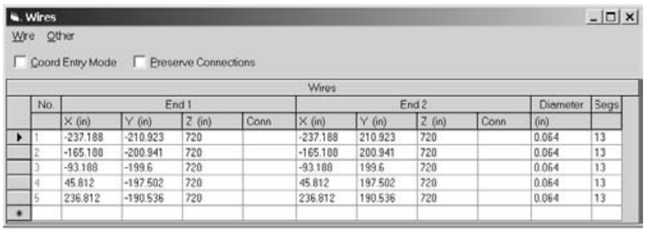
Fig 12 shows the computed azimuth pattern for this Yagi at 14.175 MHz, at an elevation angle of 15°, the angle where the peak of the forward lobe occurs at this

Table 2

520-40W.YW, using #14 wire from 520-40H.YW
14.000 14.174 14.350 MHz

5 elements,	inches
Spacing	.064
0.000	210.923
72.000	200.941
72.000	199.600
139.000	197.502
191.000	190.536





No.	End 1 X (in)	End 1 Y (in)	End 1 Z (in)	End 1 Conn	End 2 X (in)	End 2 Y (in)	End 2 Z (in)	End 2 Conn	Diameter (in)	Segs
1	-237.188	-210.923	720		-237.188	210.923	720		0.064	13
2	-165.188	-200.941	720		-165.188	200.941	720		0.064	13
3	-93.188	-199.6	720		-93.188	199.6	720		0.064	13
4	45.812	-197.502	720		45.812	197.502	720		0.064	13
5	236.812	-190.536	720		236.812	190.536	720		0.064	13

(B)

Fig 11—At A, geometry for 5-element Yagi on a 40-foot boom, mounted 720 inches (60 feet) above flat ground, with an overlay of current and the azimuth pattern. At B, *EZNEC* Wires spreadsheet for this antenna. This design uses #14 wire for simplicity.

height above flat ground. The antenna exhibits excellent gain at 13.1 dBi, as well as a clean pattern behind the main lobe. The worst-case front-to-rear ratio at any point from 90° to 270° in azimuth is better than 23 dB. *EZNEC* says the feed-point impedance is 25 – *j* 23 Ω, just the right impedance suited for a simple hairpin or gamma match.

A Monoband 2-Element Cubical Quad

Unlike a Yagi, with its elements existing only in the x-y plane, a quad type of beam is a three-dimensional sort of antenna. A quad loop has height in the z-axis, as well as width and length in the x-y plane. Each individual loop for a monoband quad consists of four wires, joined together at the corners. **Fig 13** shows the coordinates for a 2-element 15-meter quad, consisting of a reflector and a driven element on a 10-foot boom.

You can see that the axis of symmetry, the x-axis, runs down the center of this model, meaning that the origin of this particular x, y and z-coordinate scheme is in the center of the reflector. The (0, 0, 0) origin is placed this way for convenience in assigning corner coordinates for each element. For actual placement of the antenna at a particular height above real ground, the heights of all z-axis coordinates are changed accordingly. *EZNEC* has a convenient built-in function to change the height of all wires at a single stroke.

Fig 14 shows the input *EZNEC* spreadsheet for this quad in free space, clearly showing the symmetrical nature of the corner coordinates. (Use *EZNEC* model file: **Ch4-Quad.EZ**.) This is a good place to emphasize that you should enter the wire coordinates in a logical

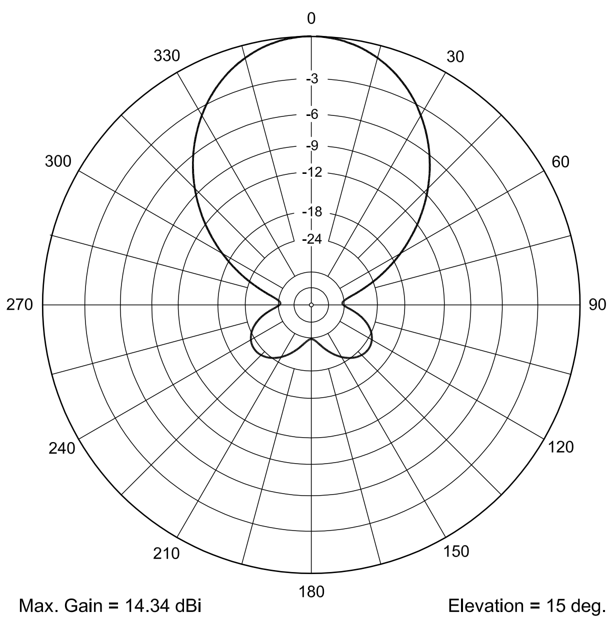


Fig 12—*EZNEC* azimuth-plane pattern at an elevation angle of 15° for #14 wire Yagi described in Fig 11.

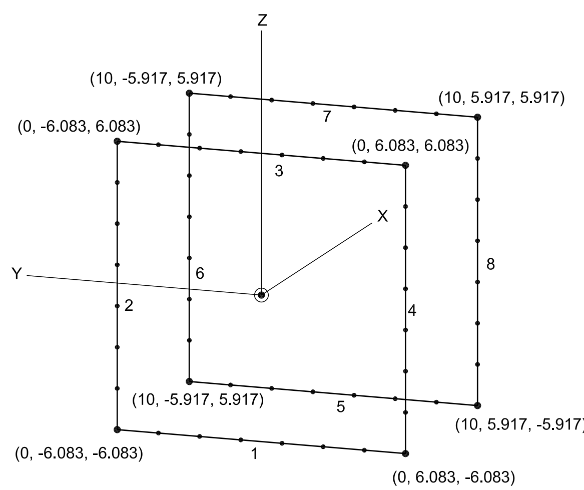


Fig 13—Wire geometry for a 2-element cubical quad, with a reflector and driven element. The x-axis is the axis of symmetry for this free-space model.

Wires

Wire Other

Coord Entry Mode Preserve Connections

No.	End 1 X (ft)	End 1 Y (ft)	End 1 Z (ft)	End 1 Conn	End 2 X (ft)	End 2 Y (ft)	End 2 Z (ft)	End 2 Conn	Diameter (in)	Segs
1	0	-6.083	-6.083	W4E2	0	6.083	-6.083	W2E1	#12	7
2	0	6.083	-6.083	W1E2	0	6.083	6.083	W3E1	#12	7
3	0	6.083	6.083	W2E2	0	-6.083	6.083	W4E1	#12	7
4	0	-6.083	6.083	W3E2	0	-6.083	-6.083	W1E1	#12	7
5	10	-5.917	-5.917	W8E2	10	5.917	-5.917	W6E1	#12	7
6	10	5.917	-5.917	W5E2	10	5.917	5.917	W7E1	#12	7
7	10	5.917	5.917	W6E2	10	-5.917	5.917	W8E1	#12	7
8	10	-5.917	5.917	W7E2	10	-5.917	-5.917	W5E1	#12	7

Fig 14—*EZNEC* Wires spreadsheet showing the coordinates used for the quad in Fig 13. Note how the x-axis describes the position of an element on the 10-foot boom and also is the axis of symmetry for each element. The values for the z-axis and y-axis vary above and below the axis of symmetry.

sequence. The most obvious example in this particular model is that you should group all the wires associated with a particular element together—for example, the four wires associated with the reflector should be in one place. In Fig 14 you can see that all four wires with an x-coordinate of zero represent the reflector.

It's best to follow a convention in entering wires in a loop structure in a logical fashion. The idea to connect the end point of one wire to the starting point of the next wire. For example, in Fig 13 you can see that the left-hand end of Wire 1 is connected to the bottom of Wire 2, and that the top of Wire 2 connects to the left-hand end of Wire 3. In turn, Wire 3 connects to the top of Wire 4, whose bottom end connects to the right-hand end of Wire 1. The pattern is known as "going around the horn" meaning that the connections proceed smoothly in one direction, in this case in a clockwise direction.

You can see that the entry for the wires making up the elements in the 5-element Yagi in Fig 11B also proceeded in an orderly fashion by starting with the reflector, then the driven element, then director 1, then director 2 and finally director 3. This doesn't mean that you couldn't mix things up, say by specifying the driven element first, followed by director 3, and then the reflector, or whatever. But it's a pretty good bet that doing so in this quasi-random fashion will result in some confusion later on when you revisit a model, or when you let another person see your model.

THE MODELING ENVIRONMENT

The Ground

Above, when considering the 135-foot dipole mounted 50 feet above flat earth, we briefly mentioned the most important environmental item in an antenna model—the ground beneath it. Let's examine some of the options available in the *NEC-2* environment in *EZNEC*:

- Free space
- Perfect ground
- *MININEC* type ground
- "Fast" type ground
- Sommerfeld-Norton ground.

The free space environment option is pretty self-explanatory—the antenna model is placed in free space away from the influence of any type of ground. This option is useful when you wish to optimize certain characteristics of a particular antenna design. For example, you might wish to optimize the front-to-rear ratio of a Yagi over an entire amateur band and this might entail many calculation runs. The free-space ground will run the fastest among all the ground options.

Perfect ground is useful as a reference case, especially for vertically polarized antennas over real ground. Antenna evaluations over perfect ground are shown in most classical antenna textbooks, so it is useful to compare models for simple antennas over perfect ground to those textbook cases.

MININEC type ground is useful when modeling vertical wires, or horizontal wires that are higher than 0.2 λ above ground. A *MININEC* type ground will compute faster than either a "Fast" ground or a Sommerfeld-Norton type of ground because it assumes that the ground under the antenna is perfect, while still taking into account the far-field reflections for ground using user-specified values of ground conductivity and dielectric constant. The fact that the ground under the antenna is perfect allows the *NEC-2* user of a *MININEC* type ground to specify wires that touch (but don't go below) the ground surface, something that only users of the advanced *NEC-4* program can do with the more accurate Sommerfeld-Norton type of ground described below. (*NEC-4* is presently not in the public domain and is strictly restricted and licensed by the US government.) The ability to model grounded wires is useful with vertical antennas. The modeler must be wary of the feed-point source impedances reported for either horizontally or vertically polarized wires because of the perfect-ground assumption inherent in a *MININEC*-type ground.

The "fast" type of ground is a hybrid type of ground that makes certain simplifying assumptions that allow it to be used provided that horizontal wires are higher than about 0.1 λ above ground. With today's fast computers the Sommerfeld-Norton model is preferred.

The Sommerfeld-Norton ground (referred to in *EZNEC* as the "high accuracy" ground) is preferable to the other ground types because it has essentially no practical limitations for wire height. It has the disadvantage that it can run about four times slower than a *MININEC* type of ground, but today's fast computers make that almost a non-issue. Again, *NEC-2*-based programs cannot model wires that penetrate into the ground (although there are work-arounds described below).

As mentioned above, for any type of ground other than perfect ground or free space, the user must specify the conductivity and dielectric constant of the soil. *EZNEC* allows the entry by several user-friendly categories, where σ is conductivity in Siemens/meter and ε is dielectric constant:

- Extremely poor: cities, high buildings (σ = 0.001, ε = 3)
- Very Poor: cities, industrial (σ = 0.001, ε = 5)
- Sandy, dry (σ = 0.002, ε = 10)
- Poor: rocky, mountainous (σ = 0.002, ε = 13)
- Average: pastoral, heavy clay (σ = 0.005, ε = 13)
- Pastoral: medium hills and forestation (σ = 0.006, ε = 13)
- Flat, marshy, densely wooded (σ = 0.0075, ε = 12)
- Pastoral, rich soil, US Midwest (σ = 0.010, ε = 14)
- Very Good: pastoral, rich, central US (σ = 0.0303, ε = 20)
- Fresh water (σ = 0.001, ε = 80)
- Saltwater (σ = 5, ε = 80)

Let's use *EZNEC*'s ability to overlay one or more plots together on one graph to compare the response of the vertical ground plane antenna in Fig 9 for two different types of ground: Saltwater and Poor. Open the **Ch4-GP.EZ** file in *EZNEC*. Click the **Ground Descrip** button and then right-click anywhere in the Media window that opens up. Choose first the "Poor: rocky, mountainous" option button, click **OK** and then **FF Plot**. When the elevation plot appears, click the **File** menu at the top of the main window, and then **Save As**. Choose an appropriate name for the trace, perhaps "Poor Gnd.PF."

Go back and select saltwater as your **Ground Descrip** and follow the same procedure to compute the far-field plot for saltwater ground. Now, add the Poor Gnd.PF trace, by clicking menu selection **File**, **Add Trace**. **Fig 15** shows this comparison, which greatly favors the saltwater environment, particularly at low elevation angles. At 5° the ground plane mounted over saltwater has about a 10 dB advantage compared to its landlocked cousin.

You might be wondering what happens if we move the ground-plane antenna down closer to the ground. The lower limit to how far the radials can approach the lossy earth is 0.001 λ or twice the diameter of the radial wire. A distance of 0.001 λ at 1.8 MHz is about 6 inches, while it is 0.4 inches at 30 MHz. While *NEC-2*-based programs cannot model wires that penetrate the ground, radial systems just above the ground with more than about eight radial wires can provide a work-around to simulate a direct-ground connection.

Modeling Environment: Frequency

It's always a good idea to evaluate an antenna over a *range of frequencies*, rather than simply at a single spot frequency. Trends that become quite apparent on a frequency sweep are frequently lost when looking simply at a single frequency. Native *NEC-2* has built-in frequency sweep capabilities, but once again the commercial programs make the process easier to use and understand. You saw in the SWR curve in Fig 2 the result of one such frequency sweep using *EZNEC*. **Fig 16** shows a frequency sweep of the azimuth response for the 5-element Yagi in Fig 11 across the 20-meter band, using steps of 117 kHz so there are four evaluation frequencies. At 14.0 MHz this Yagi's gain is down a small amount compared to the gain at 14.351 MHz but the rearward pattern is noticeably degraded, dropping to a front-to-back ratio of just under 20 dB.

EZNEC can save to a series of output plot files a frequency sweep of elevation (or azimuth) patterns. In essence, this automates the process described above for

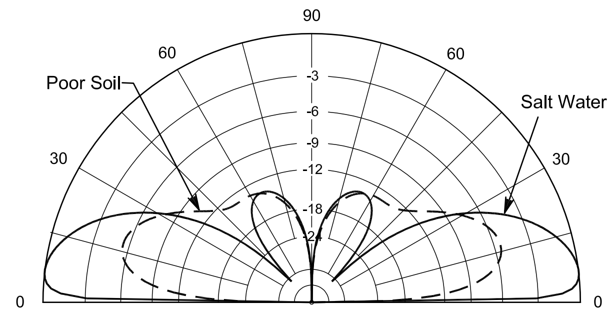


Fig 15—A comparison of the elevation response for the vertical ground plane in Fig 9 over saltwater and over "poor: rocky, mountainous" soil. Saltwater works wonders for verticals, providing excellent low-angle signals.

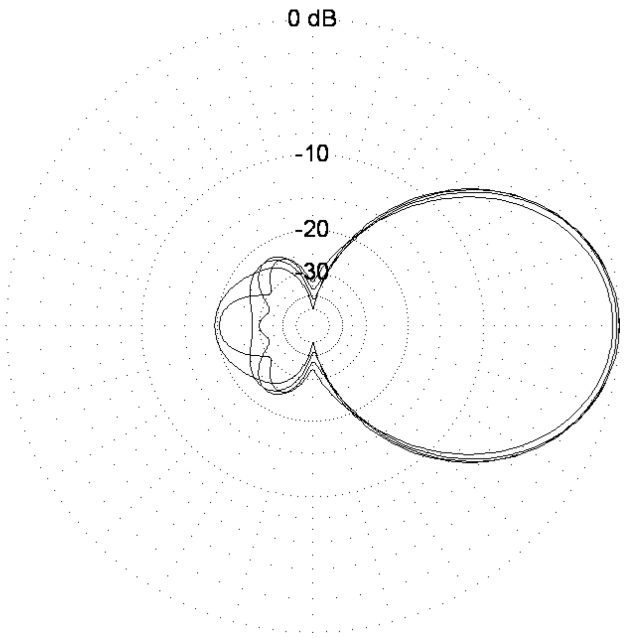


Fig 16—Frequency sweep of 5-element Yagi described in Fig 11, showing how the azimuth pattern changes with frequency.

saving a plot to disk and then overlaying it on another plot. *EZNEC* can save to a text file for later analysis (or perhaps importation into a spreadsheet) the following parameters, chosen by the user:

- Source data
- Load data
- Pattern data
- Current data
- MicroSmith numeric data
- Pattern analysis summary.

Frequency Scaling

EZNEC has a very useful feature that allows you to create new models *scaled* to a new frequency. You invoke the algorithm used to scale a model from one frequency to another by checking the **Rescale** box after you've clicked the **Frequency** button. *EZNEC* will scale all model dimensions (wire length, height and diameter) except for one specific situation—the wire diameter will stay the same at the new frequency if you originally specified wire size by AWG gauge. For example, #14 copper wire for a half-wave 80-meter dipole will stay #14 copper wire for a 20-meter half-wave dipole. If, however, you specified diameter as a floating point number originally, the diameter will be scaled by the ratio of new to old frequency, along with wire length and height.

Start up *EZNEC* and open up the file **Ch4-520-40W.EZ** for the 5-element 20-meter Yagi on a 40-foot boom. Click the **Frequency** box and then check the **Rescale** check box. Now, type in the frequency of 28.4 MHz and click **OK**. You have quickly and easily created a new 5-element 10-meter Yagi, that is mounted 29.9949 feet high, the exact ratio of 28.4 MHz to 14.1739 MHz, the original design frequency on 20 meters. Click the **FF Plot** button to plot the azimuth pattern for this new Yagi. You will see that it closely duplicates the performance of its 20-meter brother. Click **Src Dat** to see that the source impedance is 25.38 – *j* 22.19 Ω, again very close to the source data for the 20-meter version.

REVISITING SOURCE SPECIFICATION

Sensitivity to Source Placement

Earlier, we briefly described how to specify a source on a particular segment using *EZNEC*. The sources for the relatively simple dipole, Yagi and quad models investigated so far have been in the center of an easy-to-visualize wire. The placement for the source on the vertical ground plane was at the bottom of the vertical radiator, an eminently logical place. In the other cases we specified the position of the source at 50% of the distance along a wire, given that the wire being fed had an odd number of segments. Please note that in each case so far, the feed point (source) has been placed at a relatively low-impedance point, where the current changes relatively slowly from segment to segment.

Now we're going to examine some subtler source-placement problems. *NEC-2* is well-known as being very sensitive to source placement. Significant errors can result from a haphazard choice of the source segment and the segments surrounding it.

Let's return to the inverted-V dipole in Fig 5. The first time we evaluated this antenna (**Ch4-Inverted V Dipole.EZ**) we specified a split source in *EZNEC*. This function uses two sources, one on each of the segments immediately adjacent to the junction of the two downward slanting wires.

Another common method to create a source at the junction of two wires that meet at an angle is to separate these two slanted wires by a short distance and bridge that gap with a short straight wire, which is fed at its center. **Fig 17** shows a close-up of this scheme. In Fig 17 the length of the segments surrounding the short middle wire are purposely made equal to the length of the middle wire. The segmentation for the short middle wire is set to one. **Table 3** lists the source impedance and the maximum gain the *EZNEC* computes for three different models:

1. **Ch4-Inverted V Dipole.EZ** (the original model)
2. **Ch4-Inverted V Dipole Triple Segmentation.EZ**
3. **Ch4-Modified Inverted V Dipole.EZ** (as shown in Fig 17, for the middle wire set to be 2 feet long)
4. **Ch4-Mod Inverted V Poor Segmentation.EZ** (where the number of segments on the two slanted wires have been increased to 200)

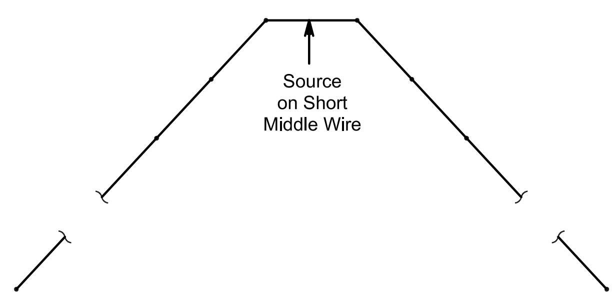


Fig 17—Model of inverted-V dipole using a short center wire on which the source is placed.

Table 3
135-Foot Inverted-V Dipole at 3.75 MHz

Case	Segments	Source Impedance Ω	Max. Gain dBi
1	82	72.64 + *j* 128.2	4.82
2	246	73.19 + *j* 128.9	4.82
3	67	73.06 + *j* 129.1	4.85
4	401	76.21 + *j* 135.2	4.67

Case 2 shows the effect of tripling the number of segments in Case 1. This is a check on the segmentation, to see that the results are stable at a lower level compared to a higher level of segmentation (which theoretically is better, although slower in computation). We purposely set up Case 4 so that the lengths of the segments on either side of the single-segment middle wire are significantly different (0.33 feet) compared to the 2-foot length of the middle wire.

The feed-point and gain figures for the first three models are close to each other. But you can see that the figures for the fourth model are beginning to diverge from the first three, with about a 5% overall change in the reactance and resistance compared to the average values, and about a 3% change in the maximum gain. This illustrates that it is best to keep the segments surrounding the source equal or at least close to equal in length. We'll soon examine a figure of merit called the *Average Gain* test, but it bears mentioning here that the average gain test is very close for the first three models and begins to diverge for the fourth model.

Things get more interesting if the source is placed at a high-impedance point on an antenna—for example, in the center of a full-wave dipole—the value computed for the source impedance will be high, and things will be quite sensitive to the segment lengths. We'll repeat the computations for the same inverted-V models, but this time at twice the operating frequency, at 7.5 MHz.

Table 4 summarizes the results. The impedance is high, as expected. Note that the resistance term varies quite a bit for all four models, a range of about 23% around the average value. Interestingly, the poorly segmented model's resistance falls in between the other three. The reactive terms are closer for all four models but still cover a range of 4% around the average value. The maximum gain shows the same tendancy to be somewhat lower in the fourth model compared to the first three and thus looks as potentially untrustworthy at 7.5 MHz as it does at 3.75 MHz.

This is, of course, but a small sampling of segmentation schemes, and caution dictates that you shouldn't take these results as being representative of all possibilities. Nevertheless, the lesson to be learned here is that the feed-point (source) impedance can vary significantly at a point where the current is changing rapidly, as it does where a high impedance feed is involved. Another general conclusion that can be drawn from Table 5 is that more segments, particularly if they surround the source segment improperly, is not necessarily better.

Table 4
135-Foot Inverted-V Dipole at 7.5 MHz

Case	*Segments*	*Source Impedance Ω*	*Max. Gain dBi*
1	82	2297 – *j* 2668	5.67
2	246	1822 – *j* 2553	5.66
3	67	1960 – *j* 2583	5.66
4	401	2031 – *j* 2688	5.48

Voltage and Current Sources

Before we leave the topic of sources, you should be aware that programs like *EZNEC* and others have the ability to simulate both voltage sources and current sources. Although native *NEC-2* has several source types, voltage sources are the most commonly used by hams. Native *NEC-2* doesn't have a current source, but a current source is nothing more than a voltage source delivering current through a high impedance. Basic network theory says that every Thevenin voltage source has a Norton current source equivalent. Various commercial implementations of *NEC-2* approach the creation of a current source in slightly different fashions. Some use a high value of inductive reactance as a series impedance, while others use a high value of series resistance.

Why would we want to use a current source instead of a voltage source in a model? The general-purpose answer is that models containing a single source at a single feed point can use a voltage source with no problems. Models that employ multiple sources, usually with different amplitudes and different phase shifts, do best with current sources.

For example, *phased arrays* feed RF currents at different amplitudes and phase shifts into two or more elements. The impedances seen at each element may be very different—some impedances might even have negative values of resistance, indicating that power is flowing out of that element into the feed system due to mutual coupling to other elements. Having the ability to specify the amplitude and phase of the current, rather than a feed voltage, at a feed point in a program like *EZNEC* is a valuable tool.

Next, we examine one more important aspect of building a model, setting up loads. After that, we'll look into two tests for the potential accuracy of a model. These tests can help identify source placement, as well as other problems.

LOADS

Many ham antennas, in particular electrically short ones, employ some sort of *loading* to resonate the system. Sometimes loading takes the form of *capacitance hats*, but these can and should be modeled as wires connected to the top of a vertical radiator. A capacitance hat is not the type of loading we'll explore in this section.

Here, the term *loads* refers to discrete inductances, capacitances and resistances that are placed at some point (or points) in an antenna system to achieve certain effects. One fairly common form of a load is a *loading coil* used to resonate an electrically short antenna. Another form of load often seen in ham antennas is a *trap*. *EZNEC* has a special built-in function to evaluate parallel-resonant traps, even at different frequencies beyond their main parallel resonance.

Just for reference, a more subtle type of load is a *distributed* material load. We encountered just such a load in our first model antenna, the 135-foot long flattop dipole—although we didn't identify it specifically as a load at that time. Instead, it was identified as a "wire loss" associated with copper.

The *NEC-2* core program has the capability of simulating a number of built-in loads, including distributed material and discrete loads. *EZNEC* implements the following discrete loads:

- Series R ± *j* X loads.
- Series R-L-C loads, specified in Ω of resistance, µH of inductance and pF of capacitance.
- Parallel R-L-C loads, specified in Ω of resistance, µH of inductance and pF of capacitance.
- Trap loads, specified in Ω of resistance in series with µH of inductance, shunted by pF of capacitance, at a specific frequency.
- Laplace loads, specified as mathematical Laplace coefficients (sometimes used in older modeling programs and left in *EZNEC* for backwards compatibility).

It is important to recognize that the discrete loads in an antenna modeling program *do not radiate* and they have zero size. The *NEC-2* discrete loads are described by L. B. Cebik in his antenna modeling course as being *mathematical loads*. The fact that *NEC-2* loads do not radiate means that the popular mobile antennas that use helical loading coils wound over a length of fiberglass whip cannot be modeled with *NEC-2*, because such coils do radiate.

Let's say that we want to put a air-wound loading coil with an unloaded Q of 400 at the center of a 40-foot long, 50-foot high, flattop dipole so that it is resonant at 7.1 MHz. The schematic of this antenna is shown in **Fig 18**. Examine the modeling file **Ch4-Loaded Dipole.EZ** to see how a discrete series RL load is used to resonate this short dipole at 7.1 MHz, with a feed-point (source) impedance of 25.3 Ω. This requires a series resistance of 1.854 Ω and an inductive reactance of +741.5 Ω. Note that we again used a single wire to model this antenna, and that we placed the load at a point 50% along the length of the wire.

This load represents a 16.62 µH coil with an unloaded Q of 741.5/1.854 = 400, just what we wanted. Let's assume for now that we use a perfect transformer to transform the 25.3-Ω source impedance to 50 Ω. If we now attempt to run a frequency sweep over the whole 40-meter band from 7.0 to 7.3 MHz, the load reactance and resistance will not change, since we specified fixed values for reactance and resistance. Hence, the source impedance will be correct only at the frequency where the reactance and resistance are specified, since the reactance changes with frequency.

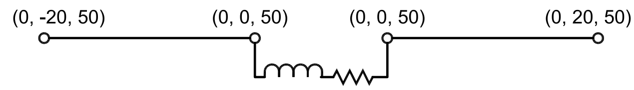


Fig 18—Schematic diagram of a 40-foot long flattop dipole with a loading coil placed at the center. This coil has an unloaded Q of 400 at 7.1 MHz.

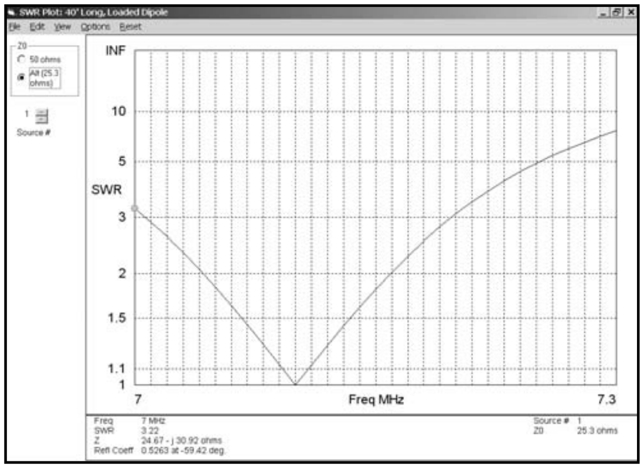


Fig 19—SWR graph of the loaded 40-foot long flattop dipole shown in Fig 18.

So let's use another load capability and substitute a 16.62 µH coil with a series 1.854-Ω resistance at 7.1 MHz. We'll let *EZNEC* take care of the details of computing both the reactance and the changing series resistance at various frequencies. The degree that both reactance and series loss resistance of the coil change with frequency may be viewed using the **Load Dat** button from the main *EZNEC* window.

Fig 19 shows the computed SWR curve for a 25.3-Ω **Alt SWR Z0** reference resistance. The 2:1 SWR bandwidth is about 120 kHz. As could be expected, the antenna has a rather narrow bandwidth because it is electrically short.

ACCURACY TESTS

There are two tests that can help identify accuracy problems in a model:

- The Convergence test.
- The Average Gain test.

Convergence Test

The idea behind the *Convergence* test is simple: If you increase the segmentation in a particular model and the results changes more than you'd like, then you increase the segmentation until the computations converge to a level that is suitable to you. This process has the potential for being subjective, but simple antenna models do converge quickly. In this section, we'll review several more of the antennas discussed previously to see how they converge.

Let's go back to the simple dipole in Fig 3. The original segmentation was 11 segments, but we'll start with a very low value of segmentation of three, well below the minimum recommended level. **Table 5** shows how the source impedance and gain change with increase in segmentation at 3.75 MHz. For this simple antenna, the gain levels off at 6.50 dBi by the time the segmentation has reached 11 segments. Going to ten times the minimum-recommended level (to 111 segments) results in an increase of only 0.01 dBi in the gain.

Arguably, the impedance has also stabilized by the time we reach a segmentation level of 11 segments, although purists may opt for 23 segments. The tradeoff is a slowdown in computational speed.

Let's see how the 5-element Yagi model converges with changes in segmentation level. **Table 6** shows how the source impedance, gain, 180° front-to-back ratio and worst-case front-to-rear ratio change with segmentation density. By the time the segmentation has reached 11 segments per wire, the impedance and gain have stabilized quite nicely, as has the F/R. The 180° F/B is still increasing with segmentation level until about 25 segments, but a relatively small shift in frequency will change the maximum F/B level greatly. For example, with 11 segments per wire, shifting the frequency to 14.1 MHz—a shift of only 0.5%— will change the maximum 180° F/B from almost 50 dB down to 27 dB. For this reason the F/R is considered a more reliable indicator of the adequacy of the segmentation level than is F/B.

Table 5
135-Foot Flattop Dipole at 3.75 MHz

Segments	*Source Impedance Ω*	*Max. Gain dBi*
3	85.9 + *j* 128.0	6.34
5	86.3 + *j* 128.3	6.45
7	86.8 + *j* 128.8	6.48
11	87.9 + *j* 129.5	6.50
23	88.5 + *j* 130.3	6.51
45	89.0 + *j* 130.8	6.51
101	89.4 + *j* 131.1	6.51

Table 6
5-element Wire Yagi at 14.1739 MHz

Segments	*Source Impedance Ω*	*Max. Gain dBi*	*180° F/B dB*	*F/R dB*
3	28.5 – *j* 30.6	12.79	23.2	22.4
5	26.3 – *j* 25.6	13.02	30.5	23.1
7	25.6 – *j* 24.0	13.07	34.8	23.1
11	25.1 – *j* 22.9	13.09	39.9	23.1
25	24.9 – *j* 22.0	13.10	43.7	23.1
99	24.7 – *j* 21.5	13.10	44.2	23.1

Average Gain Test

The theory behind the *Average Gain* test is a little more involved. Basically, if you remove all intentional losses in a model, and if you place the antenna either in free space or over perfect ground, then all the power fed to the antenna should be radiated by it. Internally, the program runs a full 3-D analysis, adding up the power in all directions and then dividing that sum by the total power fed to the antenna. Since *NEC-2* is very sensitive about source placement, as mentioned before, the Average Gain test is a good indicator that something is wrong with the specification of the source.

Various commercial versions of *NEC-2* handle the Average Gain test in different ways. *EZNEC* requires the operator to turn off all distributed losses in wires or set to zero any discrete resistive losses in loads. Next you set the ground environment to free space (or perfect ground) and request a 3-D pattern plot. *EZNEC* will then report the average gain, which will be 1.000 if the model has no problems. The average gain can be lower or higher than 1.000, but if it falls within the range 0.95 to 1.05 it is usually considered adequate.

As L. B. Cebik, W4RNL, stated in his ARRL Certification and Continuing Education Course on antenna modeling: "Like the convergence test, the average gain test is a necessary but not a sufficient condition of model reliability." Pass both tests, however, and you can be pretty well sure that your model represents reality. Pass only one test, and you have reason to worry about how well your model represents reality.

Once again, open the model file **Ch4-Mod Inverted V Poor Segmentation.EZ** and set **Wire Loss** to zero, **Ground Type** to Free Space and **Plot Type** to 3-Dimensional. Click on the **FF Plot** button. *EZNEC* will report that the Average Gain is 0.955 = –0.2 dB. This is very close to the lower limit of 0.95 considered valid for excellent accuracy. This is a direct result of forcing the segment lengths adjacent to the source segment to be considerably shorter than the source segment's length. The gain reported using this test would be approximately –0.2 dB from what it should be—just what Table 4 alludes to also.

Now, let's revisit the basic model **Ch4-Inverted V Dipole.EZ** and look at Case 2 in Table 4. Case 2 amounts to a Convergence test for the basic inverted-V model. Since the impedance and gain changes were small comparing the basic model to the one using three times the number of segments, the model passed the Convergence test. The Average Gain test for the basic model yields a value of 0.991, well within the limits for good accuracy. This model has thus passed both tests and can be considered accurate.

Running the Average Gain test for the 5-element Yagi (using 11 segments per wire and whose convergence we examined in Table 6) yields a value of 0.996, again well within the bounds indicating a good model. And the simple flattop dipole with 11 segments at 3.75 MHz yields an Average Gain result of 0.997, again indicating a very accurate model.

OTHER POSSIBLE MODEL LIMITATIONS

Programs based on the *NEC-2* core computational code have several well-documented limitations that you should know about. Some limitations have been removed in the restricted-access *NEC-4* core (which is not generally available to users), but other limitations still exist, even in *NEC-4*.

Closely Spaced Wires

If wires are spaced too close to each other, the *NEC-2* core can run into problems. If the segments are not carefully aligned, there also can be problems with accuracy. The worst-case situation is where two wires are so close together that their volumes actually merge into each other. This can happen where wires are thick, parallel to each other and close together. You should keep parallel wires separated by at least several diameters.

For example, #14 wire is 0.064 inches in diameter. The rule then is to keep parallel #14 wires separated by more than $2 \times 0.064 = 0.128$ inches. And you should run the Convergence test to assure yourself that the solution is indeed converging when you have closely spaced wires, especially if the two wires have different diameters. To model antennas containing closely spaced wires, very often you will need many more segments than usual and you must also carefully ensure that the segments line up with each other.

Things can get a little more tricky when wires cross over or under each other, simply because such crossings are sometimes difficult to visualize. Again, the rule is to keep crossing wires separated by more than two diameters from each other. And if you intend to join two wires together, make sure you do so at the ends of the two wires, using identical end coordinates. When any or all of these rules are violated, the Convergence and Average Gain tests will usually warn you of potential inaccuracies.

Parallel-Wire Transmission Lines and LPDAs

A common example of problems with closely spaced wires is when someone attempts to model a parallel-wire transmission line. *NEC-2*-based programs usually do not work as well in such situations as do *MININEC*-based programs. The problems are compounded if the diameters are different for the two wires simulating a parallel-wire transmission line. In *NEC-2* programs, it is usually better to use the built-in "perfect transmission line" function than to try to model closely spaced parallel wires as a transmission line.

For example, a Log Periodic Dipole Array (LPDA) is composed of a series of elements fed using a transmission line that reverses the phase 180° at each element. In other words, the elements are connected to a transmission line that reverses connections left-to-right at each element. It is cumbersome to do so, but you could model such a transmission line using separate wires in *EZNEC*, but it is a potentially confusing and a definitely painstaking process. Further, the accuracy of the resulting model is usually suspect, as shown by the Average Gain test.

It is far easier to use the **Trans Lines** function from the *EZNEC* main window to accurately model an LPDA. See **Fig 20**, which shows the **Trans Lines** window for the **9302A.EZ** 16-element LPDA. There are 15 transmission lines connecting the 16 elements, placed at the 50% point on each element, with a 200-Ω characteristic impedance and with Reversed connections.

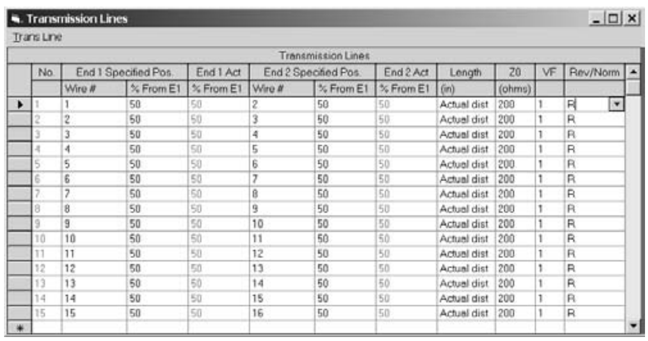
Fat Wires Connected to Skinny Wires

Another inherent limitation in the *NEC-2* computational core shows up when modeling several popular ham-radio antennas: many Yagis and some quads.

Tapered Elements

As mentioned before, many Yagis are built using telescoping aluminum tubing. This technique saves weight and makes for a more flexible and usually stronger element, one that can survive wind and ice loading better than a "monotaper" element design. Many vertical antennas are also constructed using telescoping aluminum tubing.

Unfortunately, native *NEC-2* doesn't model accurately such *tapered elements*, as they are commonly called. There is, however, a sophisticated and accurate work-around for such elements, called the *Leeson corrections*. The Leeson corrections, derived by Dave Leeson, W6NL, from pioneering work by Schelkunoff at Bell Labs, compute the diameter and length of an element that is electrically equivalent to a tapered element. This monotaper element is much easier to use in a pro-



Transmission Lines

Trans Line

Transmission Lines

No.	End 1 Specified Pos. Wire #	End 1 Specified Pos. % From E1	End 1 Act % From E1	End 2 Specified Pos. Wire #	End 2 Specified Pos. % From E1	End 2 Act % From E1	Length (in)	Z0 (ohms)	VF	Rev/Norm
1	1	50	50	2	50	50	Actual dist	200	1	R
2	2	50	50	3	50	50	Actual dist	200	1	R
3	3	50	50	4	50	50	Actual dist	200	1	R
4	4	50	50	5	50	50	Actual dist	200	1	R
5	5	50	50	6	50	50	Actual dist	200	1	R
6	6	50	50	7	50	50	Actual dist	200	1	R
7	7	50	50	8	50	50	Actual dist	200	1	R
8	8	50	50	9	50	50	Actual dist	200	1	R
9	9	50	50	10	50	50	Actual dist	200	1	R
10	10	50	50	11	50	50	Actual dist	200	1	R
11	11	50	50	12	50	50	Actual dist	200	1	R
12	12	50	50	13	50	50	Actual dist	200	1	R
13	13	50	50	14	50	50	Actual dist	200	1	R
14	14	50	50	15	50	50	Actual dist	200	1	R
15	15	50	50	16	50	50	Actual dist	200	1	R

Fig 20—Transmission-line window for the 9302A.EZ 16-element LPDA. Note that the transmission lines going between elements are "reversed," meaning that they are 180° out-of-phase at each element, a requirement for properly feeding an LPDA.

Table 7
5-element Yagi at 14.1739 MHz with Telescoping Aluminum Elements

	With Leeson Corrections			Without Leeson Corrections		
Freq. MHz	*Source Impedance Ω*	*Gain dBi*	*F/R dB*	*Source Impedance Ω*	*Gain dBi*	*F/R dB*
14.0	23.2 – *j* 26.5	14.82	23.3	22.4 – *j* 12.7	14.92	23.1
14.1	22.7 – *j* 20.5	14.87	22.8	18.6 – *j* 12.5	14.70	21.6
14.2	22.8 – *j* 14.8	14.87	22.7	6.6 – *j* 4.6	14.01	16.2
14.3	22.5 – *j* 11.9	14.76	21.5	1.9 + *j* 10.6	10.61	3.1
14.4	14.5 – *j* 10.5	14.45	19.9	1.6 + *j* 23.7	11.15	–11.4

gram like *NEC-2*. See Chapter 2, Antenna Fundamentals, for more information on the Leeson corrections.

EZNEC and other *NEC-2* programs can automatically invoke the Leeson corrections, providing that some basic conditions are met—and happily, these conditions are true for the telescoping aluminum-tubing elements commonly used as Yagi elements. *EZNEC* gives you the ability to disable or enable Leeson corrections, under the **Option** menu, under **Stepped Diameter Correction**, *EZNEC*'s name for the Leeson corrections. Open the modeling file **520-40H.EZ**, which contains tapered aluminum tubing elements and compare the results using and without using the Leeson corrections.

Table 7 lists the differences over the 20-meter band, with the 5-element Yagi at a height of 70 feet above flat ground. You can see that the non-Leeson corrected figures are very different from the corrected ones. At 14.3 MHz, the pattern for the non-corrected Yagi has degenerated to a F/R of 3.1 db, while at 14.4 MHz, just outside the top of the Amateur band, the pattern for the non-corrected antenna actually has reversed. Even at 14.2 MHz, the non-corrected antenna shows a low source impedance, while the corrected version exhibits smooth variations in gain, F/R and impedance across the whole band, just as the actual antenna exhibits.

Some Quads

Some types of cubical quads are made using a combination of aluminum tubing and wire elements, particularly in Europe where the "Swiss" quad has a wide following. Again, *NEC-2*-based programs don't handle such tubing/wire elements well. It is best to avoid modeling this type of antenna, although there are some ways to attempt to get around the limitations, ways that are beyond the scope of this chapter.

NEAR-FIELD OUTPUTS

FCC regulations set limits on the maximum permissible exposure (MPE) allowed from the operation of radio transmitters. These limits are expressed in terms of the electric (V/m) and magnetic fields (A/m) close to an antenna. *NEC-2*-based programs can compute the electric and magnetic *near fields* and the FCC accepts such computations to demonstrate that an installation meets their regulatory requirements. See Chapter 1, Safety, in this book.

Table 8
E- and H-Field Intensities for 1500 W into 5-Element Yagi at 70 Feet on 14.2 MHz

Height Feet	*H-Field (A/m)*	*E-Field (V/m)*
0	0.04	4.1
10	0.03	13.8
20	0.04	20.6
30	0.06	22.6
40	0.08	25.8
50	0.10	33.8
60	0.12	41.5
70	0.12	44.3

We'll continue to use the 5-element Yagi at 70 feet to demonstrate a near-field computation. Open **Ch4-520-40H.EZ** in *EZNEC* and choose **Setups** and then **Near Field** from the menu at the top of the main window. Let's calculate the E-field and H-field intensity for a power level of 1500 W (chosen using the **Options**, **Power Level** choices from the main menu) in the main beam at a fixed distance, say 50 feet, from the tower base. We'll do this at various heights, using 10-foot increments of height, in order to see the lobe structure of the Yagi at 70 feet height.

Table 8 summarizes the total H- and E-field intensities as a function of height. As you might expect, the fields are strongest directly in line with the antenna at a height of 70 feet. At ground level, the total fields are well within the FCC limits for rf exposure for both fields. In fact, the fields are within the FCC limits if someone were to stand at the tower base, directly under the antenna.

ANTENNA MODELING SUMMARY

This section on antenna modeling is by necessity only a brief introduction to the science of antenna modeling. The subject is partly art as well as science because there are usually several ways of creating a model for a particular antenna or antennas.

Indeed, the presence of other wires surrounding a particular antenna can affect the performance of that antenna. Finally, there are the practical aspects of putting a actual antenna up in the real world. We'll explore this next.

Practical Aspects, Designing Your Antenna System

The most important time spent in putting together an antenna system is the time spent in planning. In Chapter 3, The Effects of Ground, we outlined the steps needed to evaluate how your local terrain can affect HF communications. There we emphasized that you need to compare the patterns resulting from your own terrain to the statistically relevant elevation angles needed for coverage of various geographic areas. (The elevation-angle statistics were developed in Chapter 23, Radio Wave Propagation and are located on the CD-ROM included with this book, as is the terrain-assessment program *HFTA*.)

The implicit assumptions in Chapter 3 are (1) that you know where you want to talk to, and (2) that you'd like the most effective system possible. At the start of such a theoretical analysis, cost is no object. Practical matters, like cost or the desires of your spouse, can come later! After all, you're just checking out all the possibilities. If nothing else, you will use the methodology in Chapter 3 to evaluate any property you are considering buying so that you can build your "dream station."

Next, in the first part of this chapter we described modeling tools used to evaluate different types of antennas. These modeling tools can help you evaluate what type of antenna might be suitable to your own particular style of operating. Do you want a Yagi with a lot of rejection of received signals from the rear? Let's say that terrain analysis shows that you need an antenna at least 50 feet high. Do you really need a steel tower, or would a simple dipole in the trees serve your communication needs just fine? How about a vertical in your backyard? Would that be inconspicuous enough to suit your neighbors and your own family, yet still get you on the air?

In short, using the techniques and tools we've presented in Chapters 3, 23 and here in Chapter 4, you can scientifically plan an antenna *system* that will be best suited for your own particular conditions. Now, however, you have to get practical. Thinking through and planning the installation can save a lot of time, money and frustration. While no one can tell you the exact steps you should take in developing your own master plan, this section, prepared originally by Chuck Hutchinson, K8CH, should help you with some ideas.

WHAT DO YOU REALLY WANT?

Begin planning by spelling out your communications *desires*. What bands are you interested in? Who (or where) do you want to talk to? When do you operate? How much time and money are you willing to spend on an antenna system? What physical limitations affect your master plan?

From the answers to the above questions, begin to formulate *goals*—short, intermediate and long range. Be realistic about those goals. Remember that there are three station effectiveness factors that are under your control. These are: operator skill, equipment in the shack, and the antenna system. There is no substitute for developing operating skills. Some tradeoffs are possible between shack equipment and antennas. For example, a high-power amplifier can compensate for a less than optimum antenna. By contrast, a better antenna has advantages for receiving as well as for transmitting.

Consider your *limitations*. Are there regulatory restrictions on antennas in your community? Are there any deed restrictions or covenants that apply to your property? Do other factors (finances, family considerations, other interests, and so forth) limit the type or height of antennas that you can erect? All of these factors must be investigated because they play a major role determining the type of antennas you erect.

Chances are that you won't be able to immediately do all you desire. Think about how you can budget your resources over a period of time. Your resources are your money, your time available to work, materials you may have on hand, friends that are willing to help, etc. One way to budget is to concentrate your initial efforts on a given band or two. If your major interest is in chasing DX, you might want to start with a very good antenna for the 14-MHz band. A simple multiband antenna could initially serve for other frequencies. Later you can add better antennas for those other bands.

SITE PLANNING

A map of your property or proposed antenna site can be of great help as you begin to consider alternative antennas. You'll need to know the size and location of buildings, trees and other major objects in the area. Be sure to note compass directions on your map. Graph or quadrille paper (or a simple CAD program) can be very useful for this purpose. See **Fig 21** for an example. It's a good idea to make a few photocopies of your *site map* so you can mark on the copies as you work on your plans.

Use your map to plan antenna layouts and locations of any supporting towers or masts. If your plan calls for more than one tower or mast, think about using them as supports for wire antennas. As you work on a layout, be sure to think in three dimensions even though the map shows only two.

Be sensitive to your neighbors. A 70-foot guyed tower in the front yard of a house in a residential neighborhood is not a good idea (and probably won't comply with local ordinances!). You probably will want to locate that tower in the back yard.

ANALYSIS

Use the information earlier in this chapter and in Chapters 3 and 23 to analyze antenna patterns in both

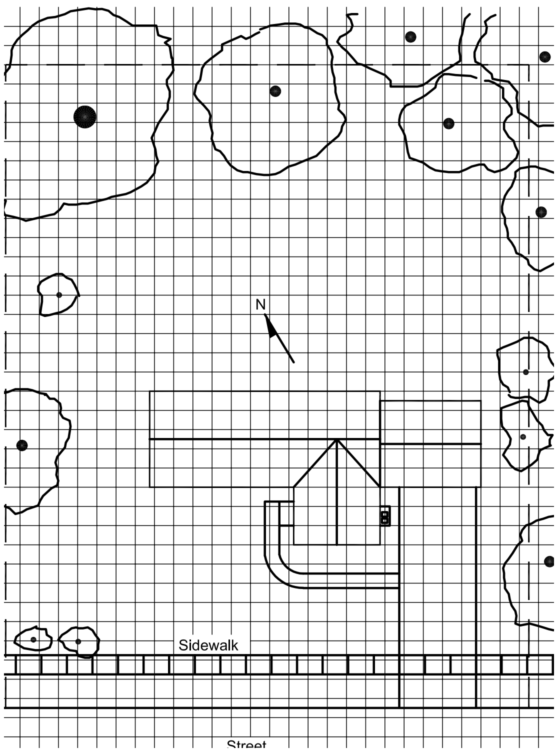


Fig 21—A site map such this one is a useful tool for planning your antenna installation.

horizontal and vertical planes towards geographic areas of interest. If you want to work DX, you'll want antennas that radiate energy at low as well as intermediate angles. An antenna pattern is greatly affected by the presence of ground and by the local topography of the ground. Therefore, be sure to consider what effect ground will have on the antenna pattern at the height you are considering. A 70-foot high antenna is approximately $\frac{1}{2}$, 1, $1\frac{1}{2}$ and 2 wavelengths (λ) high on 7, 14, 21 and 28 MHz respectively. Those heights are useful for long-distance communications. The same 70-foot height represents only $\lambda/4$ at 3.5 MHz, however. Most of the radiated energy from a dipole at that height would be concentrated straight up. This condition is not great for long-distance communication, but can still be useful for some DX work and excellent for short-range communications.

Lower heights can be useful for communications. However, it is generally true that "the higher, the better" as far as communications effectiveness is concerned. This general rule of thumb, of course, should be tempered by an exact analysis of your local terrain. Being located at the top of a steep hill can mean that you can use lower tower heights to achieve good coverage.

There may be cases where it is not possible to install low-frequency dipoles at $\lambda/4$ or more above the ground. A vertical antenna with many radials is a good choice for long-distance communications. You may want to install both a dipole and a vertical for the 3.5- or 7-MHz bands. On the 1.8-MHz band, unless extremely tall supports are available, a vertical antenna is likely to be the most useful for DXing. You can then choose the antenna that performs best for a given set of conditions. A low dipole will generally work better for shorter-range communications, while the vertical will generally be the better performer over longer distances.

Consider the azimuthal pattern of fixed antennas. You'll want to orient any fixed antennas to favor the directions of greatest interest to you.

BUILDING THE SYSTEM

When the planning is completed, it is time to begin construction of the antenna system. Chances are that you can divide that construction into a series of *phases* or steps. Say, for example, that you have lots of room and that your long-range plan calls for a pair of towers, one 100-feet high, and the other 70-feet high, to support monoband Yagi antennas. The towers will also support a horizontal 3.5-MHz dipole, for DX work. On your map you've located them so the 80-meter dipole will be broadside to Europe. You decide to build the 70-foot tower with a "triband" beam and 80- and 40-meter inverted-V dipoles to begin the project.

In your master plan you design the guys, anchors and all hardware for the 70-foot tower to support the load of stacked 4-element 10- and 15-meter monobanders Yagis. So you make sure you buy a heavy-duty rotator and the stout mast needed for the monoband antennas later. Thus you avoid having to buy, and then sell, a medium-duty rotator and lighter weight tower equipment later on when you upgrade the station. You could have saved money in the long run by putting up a monoband beam for your favorite band, but you decided that for now it is more important to have a beam on 14, 21 and 28 MHz, so you choose a commercial triband Yagi.

The second step of your plan calls for installing the second tower and stacking a 2-element 40-meter and a 4-element 20-meter monoband Yagi on it. You also plan to replace the tribander on the 70-foot tower with stacked 4-element 10- and 15-meter monoband Yagis. Although this is still a "dream system" you can now apply some of the modeling techniques discussed earlier in this chapter to determine the overall system performance.

Modeling Interactions at Your Dream Station

In this analysis we're going to assume that you have sufficient real estate to separate the 70- and 100-foot towers by 150 feet so that you can easily support an 80-meter dipole between them. We'll also assume that you want the 80-meter dipole to have its maximum response at a heading of 45° into Europe from your location in Newington, Connecticut. The dipole will also have a lobe

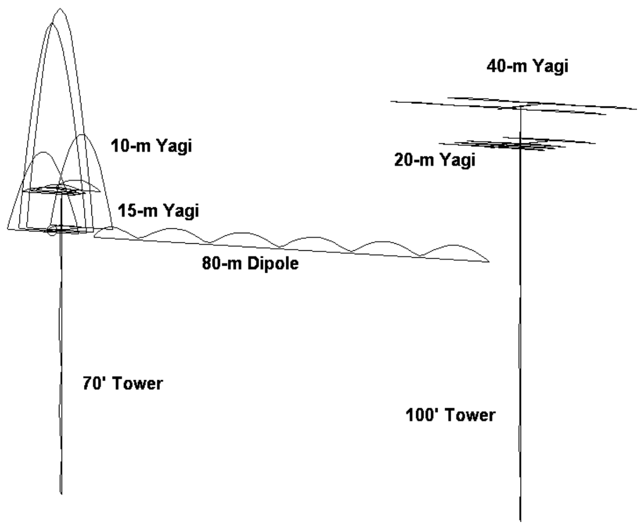


Fig 22—Layout for two-tower antenna system, at 70 and 100 feet high and 150 feet apart. The 70-foot tower has a 4-element 10-meter Yagi at 80 feet on a 10-foot rotating mast and a 4-element 15-meter Yagi at 70 feet. An 80-meter dipole goes from the 70-foot tower to the 100-foot tower, which holds a 2-element 40-meter Yagi at 110 feet and a 4-element 20-meter Yagi at 100 feet. In this figure all the rotatable Yagis are facing the direction of Europe and the currents on the 15-meter Yagi are shown. Note the significant amount of current re-radiated by the nearby 80-meter dipole.

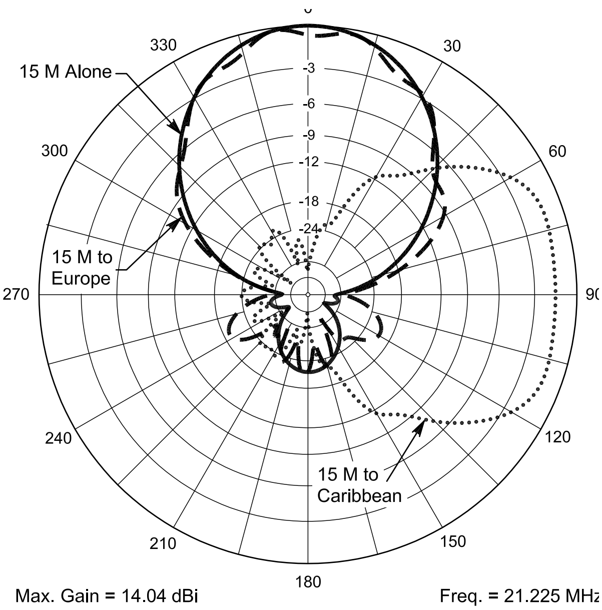


Fig 23—An overlay of azimuth patterns. The solid line is the radiation pattern for the 15-meter Yagi all by itself. The dashed line is the pattern for the 15-meter Yagi, as affected by all the other antennas. The dotted line is the pattern for the 15-meter Yagi when it is pointed toward the Caribbean, with the Yagis on the 100-foot tower pointed toward the 70-foot tower. The peak response of the 15-meter Yagi has dropped by about 1.5 dB.

facing 225° towards the USA and New Zealand, making it a good antenna for both domestic contacts and DX work.

Let's examine the interactions that occur between the rotatable Yagis for 10, 15, 20 and 40 meters. See **Fig 22**, which purposely exaggerates the magnitude of the currents on the 4-element 15-meter Yagi mounted at 70 feet. Here, both sets of Yagis have been rotated so that they are pointing into Europe. There is a small amount of current radiated onto the 10-meter antenna but virtually no current is radiated onto the 40- and 20-meter Yagis. This is good.

However, significant current is radiated onto, and then re-radiated, by the 80-meter dipole. This undesired current affects the radiation pattern of the 15-meter antenna, as shown in **Fig 23**, which overlays the pattern of the 4-element 15-meter Yagi by itself with that of the Yagi interacting with the other antennas. You can see "ripples" in the azimuthal response of the 15-meter Yagi due to the effects of the 80-meter dipole's re-radiation. The magnitude of the ripples is about 1 dB at worst, so they don't seriously affect the forward pattern (into Europe), but the rearward lobes are degraded somewhat, to just below 20 dB.

Fig 23 also shows the worst-case situation for the 15-meter Yagi. Here, the 15- and 10-meter stack has been turned clockwise 90°, facing the Caribbean, while the 40- and 20-meter Yagis on the 100-foot tower have been turned counter-clockwise 90° (in the direction of Japan) to face the 70-foot tower holding the 10/15-meter Yagis. You can see the layout and the currents in **Fig 24**. Now the 40- and 20-meter Yagis re-radiate some 15-meter

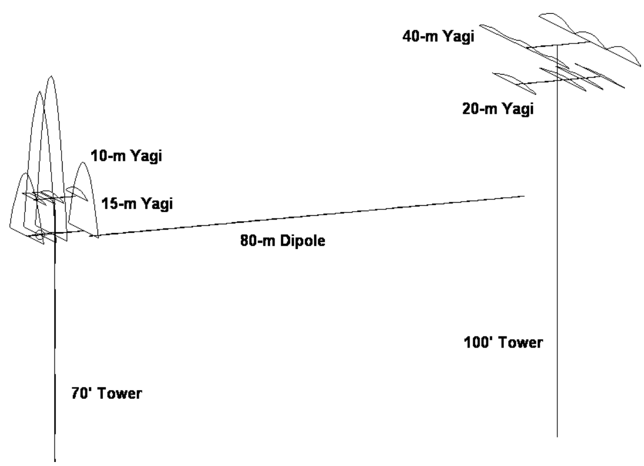


Fig 24—The layout and 15-meter currents when the Yagis on the 100-foot tower are pointed toward the 70-foot tower. The 15-meter Yagi has been rotated to face the direction of the 100-foot tower (toward the Caribbean).

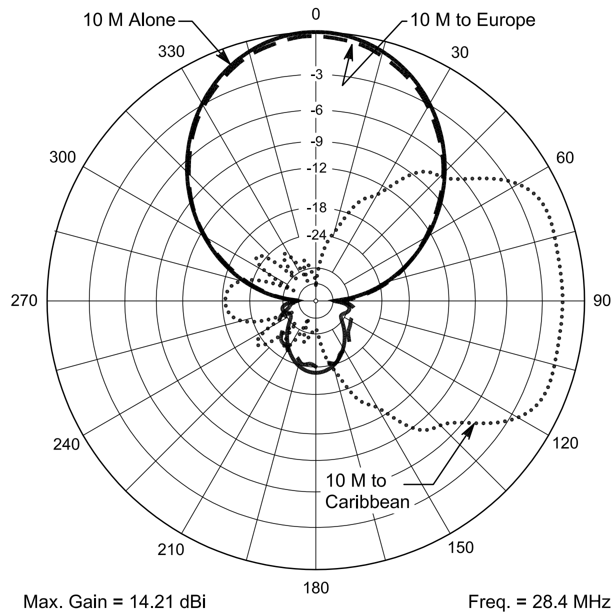


Fig 25—The radiation patterns for the 10-meter Yagi. The solid line is the 10-meter Yagi by itself. The dashed line is for the same Yagi, with all other antenna interactions. The dotted line shows the worst-case pattern, with the stacked Yagis on the 100-foot tower facing the 70-foot tower and the 10-meter Yagi pointed toward the Caribbean. Again, the peak response of the 10-meter Yagi has dropped about 1.5 dB in the worst-case situation.

energy and reduce the maximum gain by about 1.5 dB. Note that in this direction the 80-meter dipole no longer has 15-meter energy radiated onto it by the 15-meter Yagi.

The shape of the patterns will change depending on whether you specify "current" or "voltage" sources in the models for the other antennas, since this effectively opens up or shorts the feed points at the other antennas so far as 15-meter energy is concerned. In practice, this means that the interaction between antennas will vary somewhat depending on the length of the feed lines going to each antenna and whether each feed line is open-circuited or short-circuited when it is not in use.

You can now see that interactions between various antennas pointing in different directions can be significant in a real-world antenna system. In general, higher-frequency antennas are affected by re-radiation from lower-frequency antennas, rather than the other way around. Thus the presence of a 10- or 15-meter stack does not affect the 20-meter Yagi at all.

Modeling can also help determine the minimum stacking distance required between monoband Yagis on the same rotating mast. In this case, stacking the 10- and 15-meter monobanders 10 feet apart holds down interaction between them so that the pattern and gain of the 10-meter Yagi is not impacted adversely. **Fig 25** demonstrates this in the European direction, where the patterns for the 10-meter beam by itself looks very clean compared to the same Yagi separated by 10 feet from the 15-meter Yagi below it. The worst-case situation is pointing towards the Caribbean, when the 40- and 20-meter stack is facing the 70-foot tower. This drops the 10-meter gain down about 1.5 dB from maximum, indicating significant interaction is occurring.

In this situation you might find it best to place the 70-foot tower in the direction closest to the Caribbean if this direction is very important to you. Doing so will, however, cause the pattern in the direction of the Far East to be affected on 10 and 15 meters. You have the modeling tools necessary to evaluate various configurations to achieve whatever is most important to you.

COMPROMISES

Because of limitations, most amateurs are never able to build their dream antenna system. This means that some compromises must be made. Do not, under any circumstances, compromise the *safety* of an antenna installation. Follow the manufacturer's recommendations for tower assembly, installation and accessories. Make sure that all hardware is being used within its ratings.

Guyed towers are frequently used by radio amateurs because they cost less than more complicated unguyed or freestanding towers with similar ratings. Guyed towers are fine for those who can climb, or those with a friend who is willing to climb. But you may want to consider an antenna tower that folds over, or one that cranks up (and down). Some towers crank up (and down) and fold over too. See **Fig 26**. That makes for convenient access to antennas for adjustments and maintenance without climbing. Crank-up towers also offer another advantage. They allow antennas to be lowered during periods of no operation, such as for aesthetic reasons or during periods of high winds.

A well-designed monoband Yagi should outperform a multiband Yagi. In a monoband design the best adjustments can be made for gain, front-to-rear ratio (F/R) and matching, *but only for a single band*. In a multiband design, there are always tradeoffs in these properties for the ability to operate on more than one band. Nevertheless, a multiband antenna has many advantages over two or more single band antennas. A multiband antenna requires less heavy-duty hardware, requires only one feed line, takes up less space and it costs less.

Apartment dwellers face much greater limitations in their choice of antennas. For most, the possibility of a tower is only a dream. (One enterprising ham made arrangements to purchase a top-floor condominium from a developer. The arrangements were made before construction began, and the plans were altered to include a roof-top tower installation.) For apartment and condominium dwellers, the situation is still far from hopeless. A later section presents ideas for consideration.

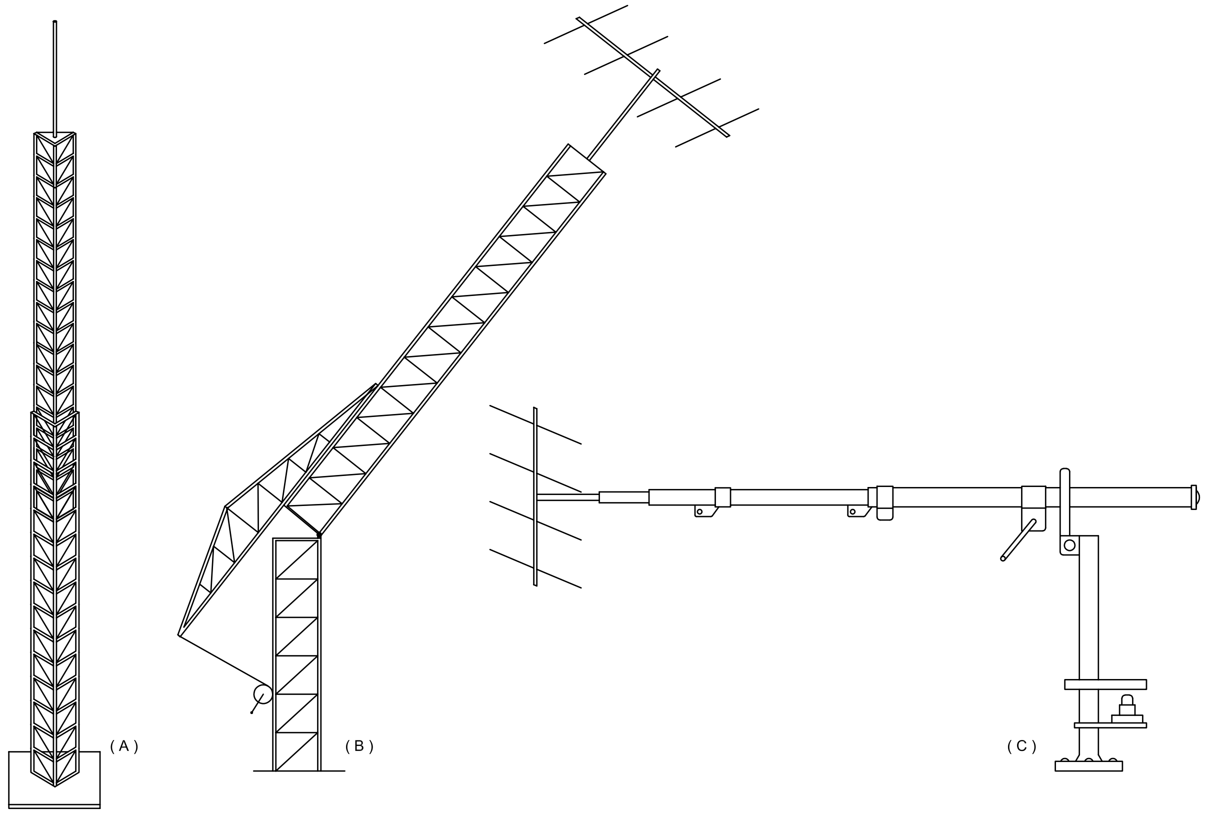


Fig 26—Alternatives to a guyed tower are shown here. At A, the crank-up tower permits working on antennas at reduced height. It also allows antennas to be lowered during periods of no operation. Motor-driven versions are available. The fold-over tower at B and the combination at C permit working on antennas at ground level.

EXAMPLES

You can follow the procedure previously outlined to put together modest or very large antenna systems. What might a ham put together for antennas when he or she wants to try a little of everything, and has a modest budget? Let's suppose that the goals are (1) low cost, (2) no tower, (3) coverage of all HF bands and the repeater portion of one VHF band, and (4) the possibility of working some DX.

After studying the pages of this book, the station owner decides to first put up a 135-foot center-fed antenna. High trees in the back yard will serve as supports to about 50 feet. This antenna will cover all the HF bands by using a balanced feeder and an antenna tuner. It should be good for DX contacts on 10 MHz and above, and will probably work okay for DX contacts on the lower bands. However, her plan calls for a vertical for 3.5 and 7 MHz to enhance the DX possibilities on those bands. For VHF, a chimney-mounted vertical is included.

ANOTHER EXAMPLE

A licensed couple has bigger ambitions. Goals for their station are (1) a good setup for DX on 14, 21 and 28 MHz, (2) moderate cost, (3) one tower, (4) ability to work some DX on 1.8, 3.5 and 7 MHz, and (5) no need to cover the CW portion of the bands.

After considering the options, the couple decides to install a 65-foot guyed tower. A large commercial triband Yagi will be mounted on top of the tower. The center of a trap dipole tuned for the phone portion of the 3.5- and 7-MHz bands will be supported by a wooden yardarm installed at the 60-foot level of the tower, with ends drooping down to form an inverted V. An inverted L for 1.8 MHz starts near ground level and goes up to a similar yardarm on the opposite side of the tower. The horizontal portion of the inverted L runs away from the tower at right angles to the trap dipole. Later, the husband will experiment with sloping antennas for 3.5 MHz. If those experiments are not successful, a $\lambda/4$ vertical will be used on that band.

Apartment Possibilities

A complete and accurate assessment of antenna types, antenna placement and feed-line placement is very important for the apartment dweller. Among the many possibilities for types are balcony antennas, *invisible* ones (made of fine wire), vertical antennas disguised as flag poles or as masts with a TV antenna on top, and indoor antennas.

A number of amateurs have been successful negotiating with the apartment owner or manager for permission to install a short mast on the roof of the building. Coaxial lines and rotator control cables might be routed through conduit troughs or through ductwork. If you live in one of the upper stories of the building, routing the cables over the edge of the roof and in through a window might be the way to go. There is a story about one amateur who owns a triband beam mounted on a 10-foot mast. But even with such a short mast, he is the envy of all his amateur friends because of his superb antenna height. His mast stands on top of a 22-story apartment building.

Usually the challenge is to find ways to install antennas that are unobtrusive. That means searching out antenna locations such as balconies, eaves, nearby trees, etc. For example, a simple but effective balcony antenna is a dangling vertical. Attach a thin wire to the tip of a mobile whip or a length of metal rod or tubing. Then mount the rigid part of the antenna horizontally on the balcony rail, dangling the wire over the edge. The antenna is operated against the balcony railing or other metallic framework. A matching network is usually required at the antenna feed point. Metal in the building will likely give a directivity effect, but this may be of little consequence and perhaps even an advantage. The antenna may be removed and stored when not in use.

Frequently, the task of finding an inconspicuous route for a feed line is more difficult than the antenna installation itself. When Al Francisco, K7NHV, lived in an apartment, he used a tree-mounted vertical antenna. The coax feeder exited his apartment through a window and ran down the wall to the ground. Al buried the section of line that went from under the window to a nearby tree. At the tree, a section of enameled wire was connected to the coax center conductor. He ran the wire up the side of the tree away from foot traffic. A few short radials completed the installation. The antenna worked fine, and was never noticed by the neighbors.

See Chapters 6, Low-Frequency Antennas, and Chapter 15, Portable Antennas, for ideas about low-frequency and portable antennas that might fit into your available space. Your options are limited as much by your imagination and ingenuity as by your pocketbook. Another option for apartment dwellers is to operate away from home. Some hams concentrate on mobile operation as an alternative to a fixed station. It is possible to make a lot of contacts on HF mobile. Some have worked DXCC that way.

Suppose that you like VHF contests. Because of other activities, you are not particularly interested in operating VHF outside the contests. Why not take your equipment and antennas to a hilltop for the contests? Many hams combine a love for camping or hiking with their interest in radio.

Antennas for Limited Space

It is not always practical to erect full-size antennas for the HF bands. Those who live in apartment buildings may be restricted to the use of minuscule radiators because of house rules, or simply because the required space for full-size antennas is unavailable. Other amateurs may desire small antennas for aesthetic reasons, perhaps to keep peace with neighbors who do not share their enthusiasm about high towers and big antennas. There are many reasons why some amateurs prefer to use physically-shortened antennas. This section discusses proven designs and various ways of building and using them effectively. You will find that modeling antennas by computer, even compromised "stealth antennas," can help you determine the most practical system possible for your particular circumstances—before you go through the effort of stringing up wires.

Few compromise antennas are capable of delivering the performance you can expect from the full-size variety. But the patient and skillful operator can often do as well as some who are equipped with high power and full-size antennas. Someone with a reduced-size antenna may not be able to "bore a hole" in the bands as often and with the commanding dispatch enjoyed by those who are better equipped, but DX can be worked successfully when band conditions are suitable.

INVISIBLE ANTENNAS

We amateurs don't regard our antennas as eyesores; in fact, we almost always regard them as works of art! But there are occasions when having an outdoor or visible antenna can present problems.

When we are confronted with restrictions—self-imposed or otherwise—we can take advantage of a number of options toward getting on the air and radiating at least a moderately effective signal. In this context, a poor antenna is certainly better than no antenna at all! This section describes a number of techniques that enable us to use indoor antennas or "invisible" antennas outdoors.

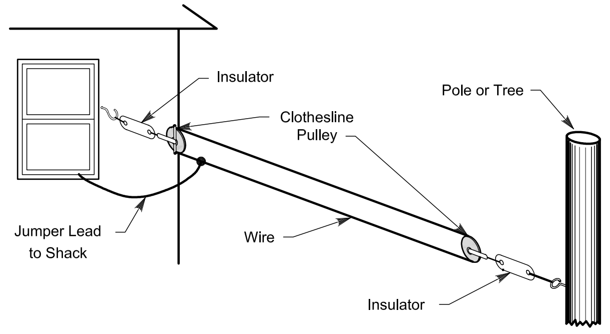


Fig 27—The clothesline antenna is more than it appears to be.

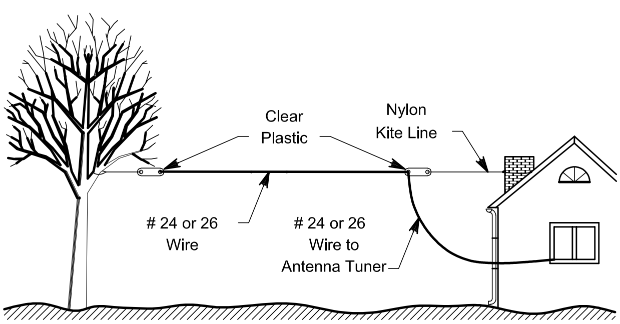


Fig 28—The "invisible" end-fed antenna.

Many of these systems will yield good-to-excellent results for local and DX contacts, depending on band conditions at any given time. *The most important consideration is that of not erecting any antenna that can present a hazard (physical or electrical) to humans, animals and buildings. Safety first!*

Clothesline Antenna

Clotheslines are sometimes attached to pulleys (**Fig 27**) so that the user can load the line and retrieve the laundry from a back porch. Laundry lines of this variety are accepted parts of the neighborhood "scenery," and can be used handily as amateur antennas by simply insulating the pulleys from their support points. This calls for the use of a conducting type of clothesline, such as heavy gauge stranded electrical wire with Teflon or vinyl insulation. A high quality, flexible steel cable (stranded) is suitable as a substitute if you don't mind cleaning it before clothing is hung on it.

A jumper wire can be brought from one end of the line to the ham shack when the station is being operated. If a good electrical connection exists between the wire clothesline and the pulley, a permanent connection can be made by connecting the lead-in wire between the pulley and its insulator. An antenna tuner can be used to match the "invisible" random-length wire to the transmitter and receiver.

Invisible Long Wire

A wire antenna is not actually a "long wire" unless it is one wavelength or greater in length. Yet many amateurs refer to (relatively) long physical spans of conductor as *long wires*. For the purpose of this discussion we will assume we have a fairly long span of wire, and refer to it as an *end-fed* wire antenna.

If we use small-diameter enameled wire for our end-fed antenna, chances are that it will be very difficult to see against the sky and neighborhood scenery. The smaller the wire, the more invisible the antenna will be. The limiting factor with small wire is fragility. A good compromise is #24 or #26 magnet wire for spans up to 130 feet; lighter-gauge wire can be used for shorter spans, such as 30 or 60 feet. The major threat to the longevity of fine wire is icing. Also, birds may fly into the wire and break it. Therefore, this style of antenna may require frequent service or replacement.

Fig 28 illustrates how you might install an invisible end-fed wire. It is important that the insulators also be lacking in prominence. Tiny Plexiglas blocks perform this function well. Small-diameter clear plastic medical vials are suitable also. Some amateurs simply use rubber bands for end insulators, but they will deteriorate rapidly from sun and air pollutants. They are entirely adequate for short-term operation with an invisible antenna, however.

Rain Gutter and TV Antennas

A great number of amateurs have taken advantage of standard house fixtures when contriving inconspicuous antennas. A very old technique is the use of the gutter and downspout system on the building. This is shown in **Fig 29**, where a lead wire is routed to the operating room

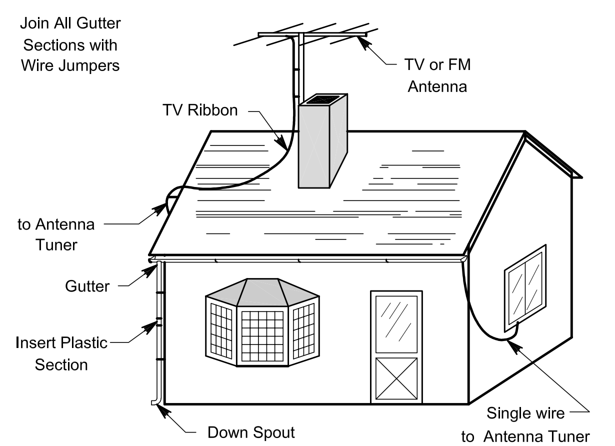


Fig 29—Rain gutters and TV antenna installations can be used as inconspicuous Amateur Radio antennas.

from one end of the gutter trough. We must assume that the wood to which the gutter is affixed is dry and of good quality to provide reasonable electrical insulation. The rain gutter antenna may perform quite poorly during wet weather or when there is ice and snow on it and the house roof.

All joints between gutter and downspout sections must be bonded electrically with straps of braid or flashing copper to provide good continuity in the system. Poor joints can permit rectification of RF and subsequently cause TVI and other harmonic interference. Also, it is prudent to insert a section of plastic downspout about 8 feet above ground to prevent RF shocks or burns to passersby while the antenna is being used. Improved performance may result if you join the front and back gutters of the house with a jumper wire to increase the area of the antenna.

Fig 29 also shows a TV or FM antenna that can be employed as an invisible amateur antenna. Many of these antennas can be modified easily to accommodate the 144- or 222-MHz bands, thereby permitting the use of the 300-Ω line as a feeder system. Some FM antennas can be used on 6 meters by adding #10 bus wire extensions to the ends of the elements, and adjusting the match for an SWR of 1:1. If 300-Ω line is used it will require a balun or antenna tuner to interface the line with the station equipment.

For operation in the HF bands, the TV or FM antenna feeders can be tied together at the transmitter end of the span and the system treated as a random length wire. If this is done, the 300-Ω line will have to be on TV standoff insulators and spaced well away from phone and power company service entrance lines. Naturally, the TV or FM radio must be disconnected from the system when it is used for amateur work! Similarly, masthead amplifiers and splitters must be removed from the line if the system is to be used for amateur operation. If the system is mostly vertical, a good RF ground system with many radials around the base of the house should be used to improve performance.

A very nice top-loaded vertical can be made from a length of TV mast with a large TV antenna on the top. Radials can be placed on the roof or at ground level with the TV "feed line" acting as part of the vertical. There is an extensive discussion of loaded verticals and radial systems in Chapter 6, Low-Frequency Antennas.

Flagpole Antennas

We can exhibit our patriotism and have an invisible amateur antenna at the same time by disguising our antenna as shown in **Fig 30**. The vertical antenna is a wire that has been placed inside a plastic or fiberglass pole.

The flagpole antenna shown is structured for a single amateur band, and it is assumed that the height of the pole corresponds to a quarter wavelength for the chosen band. The radials and feed line can be buried in the ground

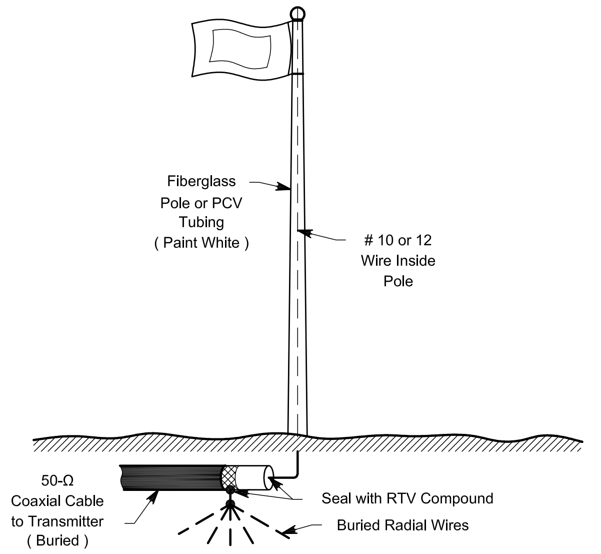


Fig 30—A flagpole antenna.

as shown. In a practical installation, the sealed end of the coax cable would protrude slightly into the lower end of the plastic pole.

If a large-diameter fiberglass pole were available, a multiband trap vertical may be concealed inside it. Or you might use a metal pole and bury a water-tight box at its base, containing fixed-tuned matching networks for the bands of interest. The networks could then be selected remotely by means of relays inside the box. A 30-foot flagpole would provide good results in this kind of system, provided it was used in conjunction with a buried radial system.

Still another technique is one that employs a wooden flagpole. A small diameter wire can be stapled to the pole and routed to the coax feeder or matching network. The halyard could by itself constitute the antenna wire if it were made from heavy-duty insulated hookup wire. There are countless variations for this type of antenna, and they are limited only by the imagination of the amateur.

Other Invisible Antennas

Some amateurs have used the metal fence on apartment verandas as antennas, and have had good results on the upper HF bands (14, 21 and 28 MHz). We must presume that the fences were not connected to the steel framework of the building, but rather were insulated by the concrete floor to which they were affixed. These verandah fences have also been used effectively as ground systems (counterpoises) for HF-band vertical antennas put in place temporarily after dark.

One amateur in New York City uses the fire escape on his apartment building as a 7-MHz antenna, and he reports good success working DX stations with it. Another apartment dweller makes use of the aluminum frame on his living room picture window as an antenna for 21 and 28 MHz. He works it against the metal conductors of the baseboard heater in the same room.

Many jokes have been told over the years about *bed-spring antennas*. The idea is by no means absurd. Bed-springs and metal end boards have been used to advantage as antennas by many apartment dwellers as 14, 21 and 28 MHz radiators. A counterpoise ground can be routed along the baseboard of the room and used in combination with the bedspring. It is important to remember that any independent (insulated) metal object of reasonable size can serve as an antenna if the transmitter can be matched to it. An amateur in Detroit once used his Shopsmith craft machine (about 5 feet tall) as a 28 MHz antenna. He worked a number of DX stations with it when band conditions were good.

A number of operators have used metal curtain rods and window screens for VHF work, and found them to be acceptable for local communications. Best results with any of these makeshift antennas will be had when the "antennas" are kept well away from house wiring and other conductive objects.

INDOOR ANTENNAS

Without question, the best place for your antenna is outdoors, and as high and in the clear as possible. Some of us, however, for legal, social, neighborhood, family or landlord reasons, are restricted to indoor antennas. Having to settle for an indoor antenna is certainly a handicap for the amateur seeking effective radio communication, but that is not enough reason to abandon all operation in despair.

First, we should be aware of the reasons why indoor antennas do not work well. Principal faults are:

- Low height above ground—the antenna cannot be placed higher than the highest peak of the roof, a point usually low in terms of wavelength at HF
- The antenna must function in a lossy RF environment involving close coupling to electrical wiring, guttering, plumbing and other parasitic conductors, besides dielectric losses in such nonconductors as wood, plaster and masonry
- Sometimes the antenna must be made small in terms of a wavelength
- Usually it cannot be rotated.

These are appreciable handicaps. Nevertheless, global communication with an indoor antenna is still possible, although you must be sure that you are not exposing anyone in your family or nearby neighbors to excessive radiation. See Chapter 1, Safety, in this book.

Some practical points in favor of the indoor antenna include:

- Freedom from weathering effects and damage caused by wind, ice, rain and sunlight (the SWR of an attic antenna, however, can be affected somewhat by a wet or snow-covered roof).
- Indoor antennas can be made from materials that would be altogether impractical outdoors, such as aluminum foil and thread (the antenna need support only its own weight).
- The supporting structure is already in place, eliminating the need for antenna masts.
- The antenna is readily accessible in all weather conditions, simplifying pruning or tuning, which can be accomplished without climbing or tilting over a tower.

Empiricism

A typical house or apartment presents such a complex electromagnetic environment that it is impossible to predict theoretically which location or orientation of the indoor antenna will work best. This is where good old fashioned cut-and-try, use-what-works-best *empiricism* pays off. But to properly determine what really is most suitable requires an understanding of some antenna measuring fundamentals.

Unfortunately, many amateurs do not know how to evaluate performance scientifically or compare one antenna with another. Typically, they will put up one antenna and try it out on the air to see how it "gets out" in comparison with a previous antenna. This is obviously a very poor evaluation method because there is no way to know if the better or worse reports are caused by changing band conditions, different S-meter characteristics or any of several other factors that could influence the reports received.

Many times the difference between two antennas or between two different locations for identical antennas amounts to only a few decibels, a difference that is hard to discern unless instantaneous switching between the two is possible. Those few decibels are not important under strong signal conditions, of course, but when the going gets rough, as is often the case with an indoor antenna, a few dB can make the difference between solid copy and no possibility of real communication.

Very little in the way of test equipment is needed for casual antenna evaluation, other than a communications receiver. You can even do a qualitative comparison by ear, if you can switch antennas instantaneously. Differences of less than 2 dB, however, are still hard to discern. The same is true of S-meters. Signal strength differences of less than a decibel are usually difficult to see. If you want to measure that last fraction of a decibel, you should use a good ac voltmeter at the receiver audio output (with the AGC turned off).

In order to compare two antennas, switching the coaxial transmission line from one to the other is necessary. No elaborate coaxial switch is needed; even a simple double-throw toggle or slide switch will provide more than 40 dB of isolation at HF. See **Fig 31**. Switching by means of manually connecting and disconnecting coaxial lines is not recommended because that takes too long.

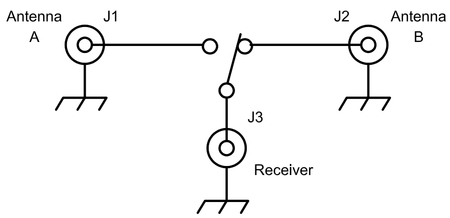


Fig 31—When antennas are compared on fading signals, the time delay involved in disconnecting and reconnecting coaxial cables is too long for accurate measurements. A simple slide switch will do well for switching coaxial lines at HF. The four components can be mounted in a tin can or any small metal box. Leads should be short and direct. J1 through J3 are coaxial connectors.

Fading can cause signal-strength changes during the changeover interval.

Whatever difference shows up in the strength of the received signal will be the difference in performance between the two antennas in the direction of that signal. For this test to be valid, both antennas must have nearly the same feed-point impedance, a condition that is reasonably well met if the SWR is below 2:1 on both antennas.

On ionospheric propagated signals (sky wave) there will be constant fading, and for a valid comparison it will be necessary to take an average of the difference between the two antennas. Occasionally, the inferior antenna will deliver a stronger signal to the receiver, but in the long run the law of averages will put the better antenna ahead.

Of course with a ground-wave signal, such as that from a station across town, there will be no fading problems. A ground-wave signal will enable the operator to properly evaluate the antenna under test in the direction of the source. The results will be valid for ionospheric-propagated signals at low elevation angles in that direction. On 28 MHz, all sky-wave signals arrive and leave at low angles. But on the lower bands, particularly 3.5 and 7 MHz, we often use signals propagated at high elevation angles, almost up to the zenith. For these angles a ground-wave test between local stations may not provide a proper evaluation of the antenna, and use of sky wave signals becomes necessary.

Dipoles

At HF the most practical indoor antenna is usually the dipole. Attempts to get more gain with parasitic elements will usually fail because of close proximity to the ground or coupling to house wiring. Beam antenna dimensions determined outdoors will not usually be valid for an attic antenna because the roof structure will cause dielectric loading of the parasitic elements. It is usually more worthwhile to spend time optimizing the location and performance of a dipole than to try to improve results with parasitic elements.

Most attics are not long enough to accommodate half-wave dipoles for 7 MHz and below. If this is the case, some folding of the dipole will be necessary. The final shape of the antenna will depend on the dimensions and configuration of the attic. Remember that the center of the dipole carries the most current and therefore does most of the radiating. This part should be as high and unfolded as possible. Because the dipole ends radiate less energy than the center, their orientation is not as important. They do carry the maximum voltage, nevertheless, so care should be taken to position the ends far enough from other conductors to avoid arcing.

The dipole may end up being L-shaped, Z-shaped, U-shaped or some indescribable corkscrew shape, depending on what space is available, but reasonable performance can often be had even with such a non-straight arrangement. **Fig 32** shows some possible configurations. Multiband operation is possible with the use of open-wire feeders and an antenna tuner.

One alternative not shown here is the aluminum-foil dipole, which was conceived by Rudy Stork, KA5FSB. He suggests mounting the dipole behind wallpaper or in the attic, with portability, ease of construction and adjustment, and economy in design among its desirable features. This antenna should also display reasonably good bandwidth resulting from the large area of its conductor material. If coaxial feed is used, some pruning of an attic antenna to establish minimum SWR at the band center will be required. Tuning the antenna outdoors and then installing it inside is usually not feasible since the behavior of the antenna will not be the same when placed in the attic. Resonance will be affected somewhat if the antenna is bent.

Even if the antenna is placed in a straight line, parasitic conductors and dielectric loading by nearby wood structures can affect the impedance. Trap and loaded dipoles are shorter than the full-sized versions, but are comparable performers. Trap dipoles are discussed in Chapter 7, Multiband Antennas, and loaded dipoles in Chapter 6, Low-Frequency Antennas.

Dipole Orientation

Theoretically a vertical dipole is most effective at low radiation angles, but practical experience shows that the horizontal dipole is usually a better indoor antenna. A high horizontal dipole does exhibit directional effects at low radiation angles, but you will not be likely to see much, if any, directivity with an attic-mounted dipole. Some operators place two dipoles at right angles to each other with provisions at the operating position for switching between the two. Their reasoning is the radiation patterns will inevitably be distorted in an unpredictable manner by nearby parasitic conductors. There will be little coupling between the dipoles if they are oriented a right

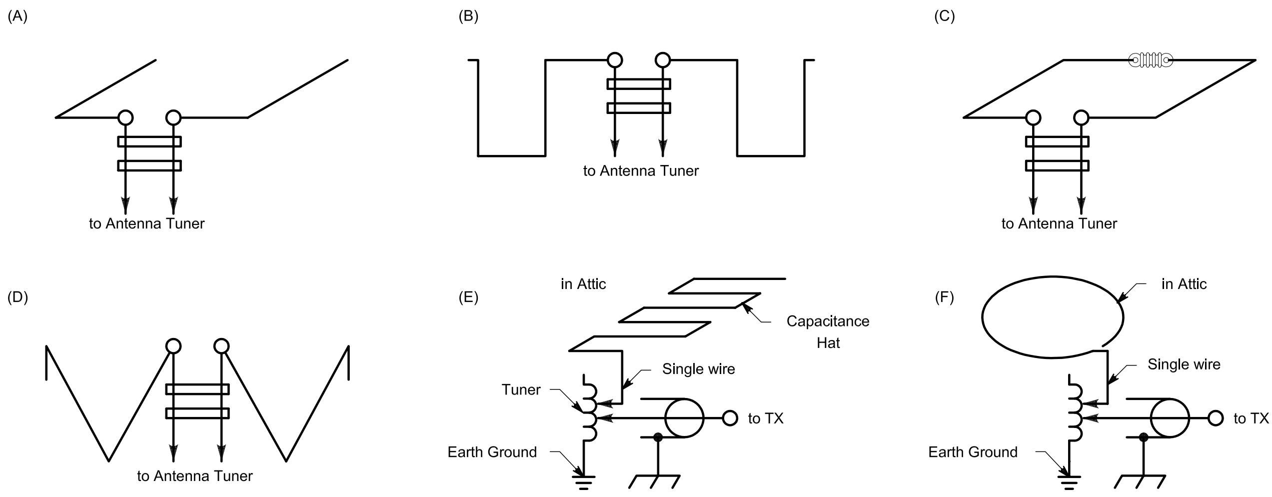


Fig 32—Various configurations for small indoor antennas. See text for discussion.

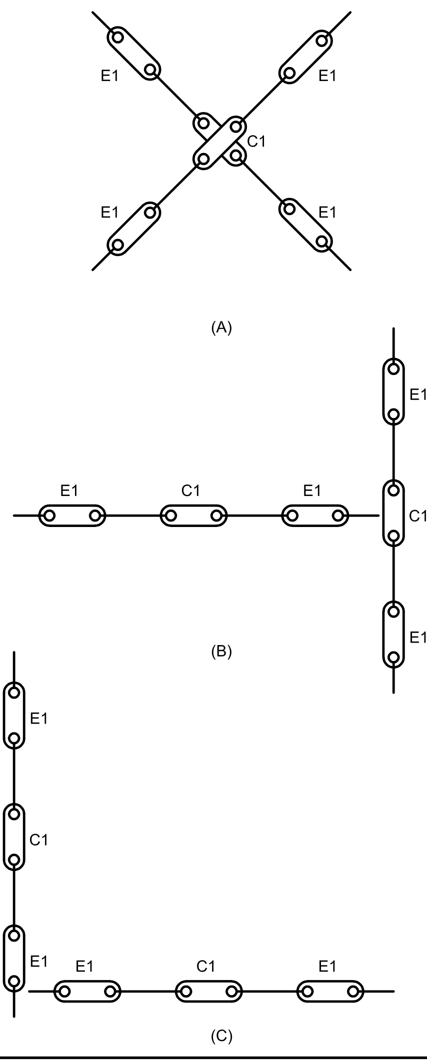


Fig 33—Ways to orient a pair of perpendicular dipoles. The orientation at A and B will result in no mutual coupling between the two dipoles, but there will be some coupling in the configuration shown at C. End (El) and center (Cl) insulators are shown.

angles to each other as shown in **Figs 33A** and 33B. There will be some coupling with the arrangement shown in Fig 33C, but even this orientation is preferable to a single dipole.

With two antennas mounted 90° apart, you may find that one dipole is consistently better in nearly all directions, in which case you will want to remove the inferior dipole, perhaps placing it someplace else. In this manner the best spots in the house or attic can be determined experimentally.

Parasitic Conductors

Inevitably, any conductor in your house near a quarter wave in length or longer at the operating frequency will be parasitically coupled to your antenna. The word *parasitic* is particularly appropriate in this case because these conductors usually introduce losses and leave less energy for radiation into space. Unlike the parasitic elements in a beam antenna, conductors such as house wiring and plumbing are usually connected to lossy objects such as earth, electrical appliances, masonry or other objects that dissipate energy. Even where this energy is reradiated, it is not likely to be in the right phase in the desired direction; it is, in fact, likely to be a source of RFI.

There are, however, some things that can be done about parasitic conductors. The most obvious is to reroute them at right angles to the antenna or close to the ground, or even underground—procedures that are usually not feasible in a finished home. Where these conductors cannot be rerouted, other measures can be taken. Electrical wiring can be broken up with RF chokes to prevent the flow of radio-frequency currents while permitting 60-Hz current (or audio, in the case of telephone wires) to flow unimpeded. A typical RF choke for a power line can be 100 turns of #10 insulated wire close wound on a length of 1-inch diameter plastic pipe. Of course one choke will be needed for each conductor. A three-wire line calls for three chokes. The chokes can be simplified by winding them bifilar or trifilar on a single coil form.

THE RESONANT BREAKER

Obviously, RF chokes cannot be used on conductors such as metal conduit or water pipes. But it is still possible, surprising as it may seem, to obstruct RF currents on such conductors without breaking the metal. The resonant breaker was first described by Fred Brown, W6HPH, in Oct 1979 *QST*.

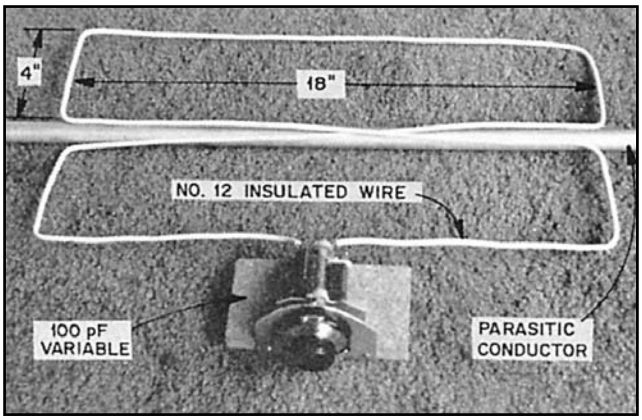


Fig 34—A "resonant breaker" such as shown here can be used to obstruct radio-frequency currents in a conductor without the need to break the conductor physically. A vernier dial is recommended for use with the variable capacitor because tuning is quite sharp. The 100-pF capacitor is in series with the loop. This resonant breaker tunes from 14 through 29.7 MHz. Larger models may be constructed for the lower frequency bands.

Fig 34 shows a method of accomplishing this. A figure-eight loop is inductively coupled to the parasitic conductor and is resonated to the desired frequency with a variable capacitor. The result is a very high impedance induced in series with the pipe, conduit or wire. This impedance will block the flow of radio-frequency currents. The figure-eight coil can be thought of as two turns of an air-core toroid and since the parasitic conductor threads through the hole of this core, there will be tight coupling between the two. Inasmuch as the figure-eight coil is parallel resonated, transformer action will reflect a high impedance in series with the linear conductor.

Before you bother with a *resonant breaker* of this type, be sure that there is a significant amount of RF current flowing in the parasitic conductor, and that you will therefore benefit from installing one. The relative magnitude of this current can be determined with an RF current probe of the type described in Chapter 27, Antenna and Transmission-Line Measurements. According to the rule of thumb regarding parasitic conductor current, if it measures less than $^1/_{10}$ of that measured near the center of the dipole, the parasitic current is generally not large enough to be of concern.

The current probe is also needed for resonating the breaker after it is installed. Normally, the resonant breaker will be placed on the parasitic conductor near the point of maximum current. When it is tuned through resonance, there will be a sharp dip in RF current, as indicated by the current probe. Of course, the resonant breaker will be effective only on one band. You will need one for each band where there is significant current indicated by the probe.

Power-Handling Capability

So far, our discussion have not considered the full power-handling capability of an indoor antenna. Any tendency to flash over must be determined by running full power or, preferably, somewhat more than the peak power you intend to use in regular operation. The antenna should be carefully checked for arcing or RF heating before you do any operating. Bear in mind that attics are indeed vulnerable to fire hazards. A potential of several hundred volts exists at the ends of a dipole fed by the typical Amateur Radio transmitter. If a power amplifier is used, there could be a few thousand volts at the ends of the dipole. Keep your antenna elements well away from other objects. *Safety first*!

Construction Details and Practical Considerations

Ultimately the success of an antenna project depends on the details of how the antenna is fabricated. A great deal of construction information is given in other chapters of this book. For example the construction of HF Yagis is discussed in Chapter 11, Quad arrays in Chapter 12, VHF antennas in Chapter 18, and in Chapter 20 there is an excellent discussion of antenna materials, particularly wire and tubing for elements. Here is still more helpful antenna construction information.

END EFFECT

If the standard expression $\lambda/2 \approx 491.8/f$ (MHz) is used for the length of a $\lambda/2$ wire antenna, the antenna will resonate at a somewhat lower frequency than is desired. The reason is that in addition to the effect of the conductor diameter and ground effects (Chapter 3, The Effects of Ground) an additional "loading" effect is caused by the insulators used at the ends of the wires to support the antenna. The insulators and the wire loops that tie the insulators to the antenna add a small amount of capacitance to the system. This capacitance helps to tune the antenna to a slightly lower frequency, in much the same way that additional capacitance in any tuned circuit lowers the resonant frequency. In an antenna this is called *end effect*. The current at the ends of the antenna does not quite reach zero because of the end effect, as there is some current flowing into the end capacitance. Note that the computations used to create Figs 2 through 7 in Chapter 2, Antenna Fundamentals, did not take into account any end effect.

End effect increases with frequency and varies slightly with different installations. However, at frequencies up to 30 MHz (the frequency range over which wire antennas are most commonly used), experience shows that the length of a practical $\lambda/2$ antenna, including the effect of diameter and end effect, is on the order of 5% less than the length of a half wave in space. As an average, then, the physical length of a resonant $\lambda/2$ wire antenna can be found from:

$$\lambda = \frac{491.8 \times 0.95}{f\,(\text{MHz})} \approx \frac{468}{f\,(\text{MHz})} \qquad \text{(Eq 1)}$$

Eq 1 is reasonably accurate for finding the physical length of a $\lambda/2$ antenna for a given frequency, but does not apply to antennas longer than a half wave in length. In the practical case, if the antenna length must be adjusted to exact frequency (not all antenna systems require it) the length should be "pruned" to resonance. Note that the use of plastic-insulated wire will typically lower the resonant frequency of a half-wave dipole about 3%.

INSULATORS

Wire antennas must be insulated at the ends. Commercially available insulators are made from ceramic, glass or plastic. Insulators are available from many Amateur Radio dealers. RadioShack and local hardware stores are other possible sources. Acceptable homemade insulators may be fashioned from a variety of material including (but not limited to) acrylic sheet or rod, PVC tubing, wood, fiberglass rod or even stiff plastic from a discarded container. **Fig 35** shows some homemade insulators. Ceramic or glass insulators will usually outlast the wire, so they are highly recommended for a safe, reliable, permanent installation. Other materials may tear under stress or break down in the presence of sunlight. Many types of plastic do not weather well.

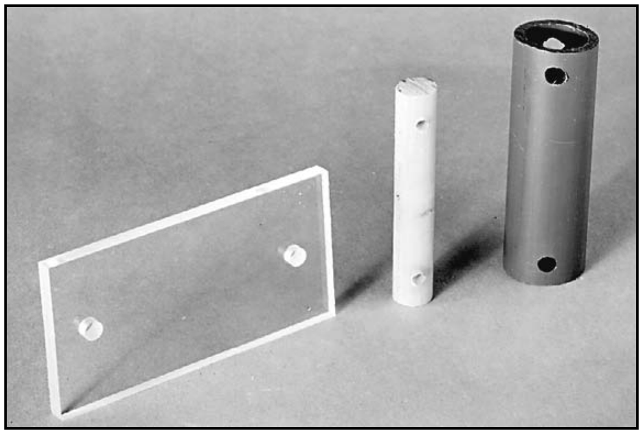


Fig 35—Some ideas for homemade antenna insulators.

INSTALLING TRANSMISSION LINES

Many wire antennas require an insulator at the feed point. Although there are many ways to connect the feed line, there are a few things to keep in mind. If you feed your antenna with coaxial cable, you have two choices. You can install an SO-239 connector on the center insu-

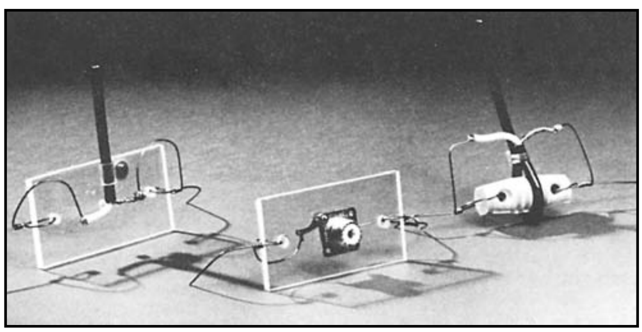


Fig 36—Some homemade dipole center insulators. The one in the center includes a built-in SO-239 connector. Others are designed for direct connection to the feed line.

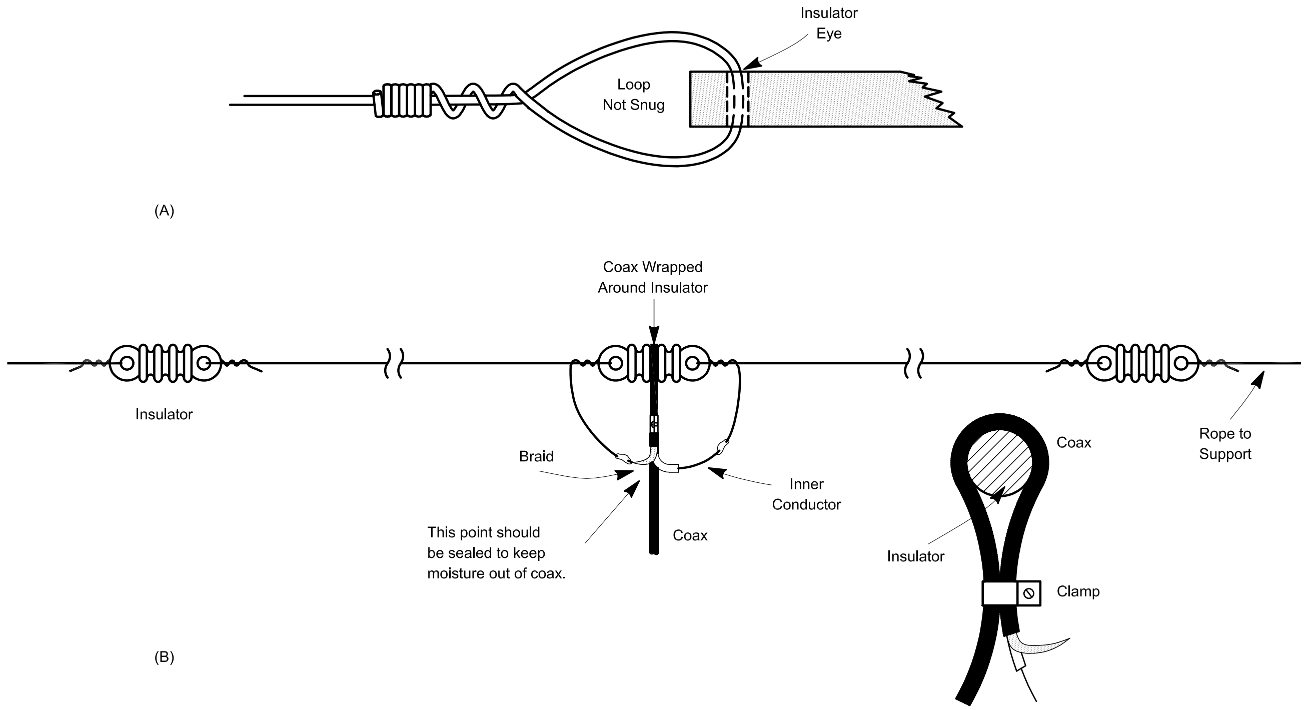


Fig 37—Details of dipole antenna construction. At A, the end insulator connection is shown. At B, the completed antenna is shown. A balun (not shown) is often used at the feed point, since this is a balanced antenna.

lator, as shown by the center example in **Fig 36,** and use a PL-259 on the end of your coax, or you can separate the center conductor from the braid and connect the feed line directly to the antenna wire as shown in the other two examples in Fig 36 and the example in **Fig 37**. Although it costs less to connect direct, the use of connectors offers several advantages. Coaxial cable braid soaks up water like a sponge unless it is very well waterproofed. If you do not adequately seal the antenna end of the feed line, water will find its way into the braid. Water in the feed line will lead to contamination, rendering the coax useless long before its normal lifetime is up. Many hams waterproof the coax, first with vinyl electrical tape, and then using a paint-on material called "PlastiDip," which is sold by RadioShack (part number 910-5166 for the white variety).

It is not uncommon for water to drip from the end of the coax inside the shack after a year or so of service if the antenna connection is not properly waterproofed. Use of a PL-259/SO-239 combination (or connector of your choice) makes the task of waterproofing connections much easier. Another advantage to using the PL-259/SO-239 combination is that feed-line replacement is much easier, should that become necessary.

Whether you use coaxial cable, ladder line, or twin lead to feed your antenna, an often overlooked consideration is the mechanical strength of the connection. Wire antennas and feed lines tend to move a lot in the breeze, and

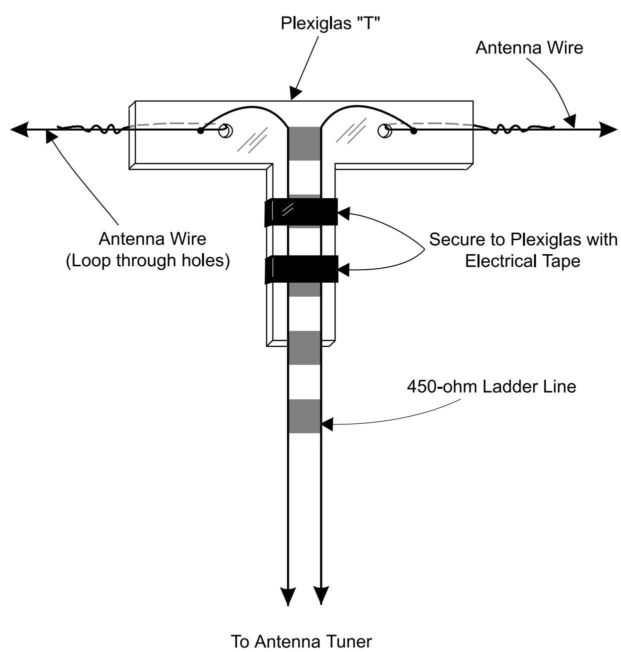


Fig 38—A piece of cut Plexiglas can be used as a center insulator and to support a ladder-line feeder. The Plexiglas acts to reduce the flexing of the wires where they connect to the antenna. Use thick Plexiglas in areas subject to high winds.

unless the feed line is attached securely, the connection will weaken with time. The resulting failure can range from a frustrating intermittent electrical connection to a complete separation of feed line and antenna. Fig 37 and **Fig 38** illustrate different ways of attaching either coax or ladder line to the antenna securely.

When open-wire feed line is used, the conductors of the line should be anchored to the insulator by threading them through the eyes of the insulator two or three times, and twisting the wire back on itself before soldering. A slack tie wire should then be used between the feeder conductor and the antenna, as shown in Fig 38. (The tie wires may be extensions of the line conductors themselves.) When window-type line is suspended from an antenna in a manner such as that shown in Fig 38, the line should be twisted—at several twists per foot—to prevent stress hardening of the wire because of constant flexing in the wind.

When using plastic-insulated open-wire line, the tendency of the line to twist and short out close to the antenna can be counteracted by making the center insulator of the antenna longer than the spacing of the line, as shown in Fig 38. In severe wind areas, it may be necessary to use ¼-inch thick Plexiglas for the center insulator rather than thinner material.

RUNNING THE FEED LINE FROM THE ANTENNA TO THE STATION

Chapter 24, Transmission Lines, contains some general guidelines for installing feed lines. More detailed information is contained in this section. Whenever possible, the transmission line should be lead away from the antenna at a 90° angle to minimize coupling from the antenna to the transmission line. This coupling can cause unequal currents on the transmission line, which will then radiate and it can detune the antenna.

Except for the portion of the line in close proximity to the antenna, coaxial cable requires no particular care in running from the antenna to the station entrance, other than protection from mechanical damage. If the antenna is not supported at the center, the line should be fastened to a post more than head high located under the center of the antenna, allowing enough slack between the post and the antenna to take care of any movement of the antenna in the wind. If the antenna feed point is supported by a tower or mast, the cable can be taped to the mast at intervals or to one leg of the tower.

Coaxial cable rated for direct burial can be buried a few inches in the ground to make the run from the antenna to the station. A deep slit can be cut by pushing a square-end spade full depth into the ground and moving the handle back and forth to widen the slit before removing the spade. After the cable has been pushed into the slit with a piece of 1-inch board 3 or 4 inches wide, the slit can be tamped closed. Many hams run coax cables through PVC pipe buried in the ground deeper than the frost line

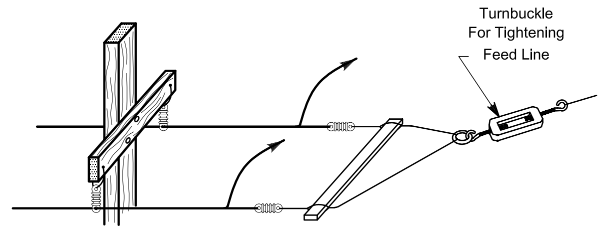


Fig 39—A support for open-wire line. The support at the antenna end of the line must be sufficiently rigid to stand the tension of the line.

and slanted downwards slightly so that water will drain, rather than pooling inside the length of the pipe.

Solid ribbon or the newer *window* types of line should be kept reasonably well spaced from other conductors running parallel to it for more than a few feet. TV-type standoff insulators with strap clamp mountings can be used for running this type of line down a mast or tower leg. Similar insulators of the screw-in type can be used in supporting the line on wooden poles for a long run.

Open-wire lines with bare conductors require frequent supports to keep the lines from twisting and shorting out, as well as to relieve the mechanical strain. One method of supporting a long horizontal run of heavy open-wire line is shown in **Fig 39**. The line must be anchored securely at a point under the feed point of the antenna. Window-type line can be supported similarly with wire links fastened to the insulators or with black cable ties (ones not affected by UV radiation from the sun).

To keep the line clear of pedestrians and vehicles, it is usually desirable to anchor the feed line at the eaves or rafter line of the station building (see **Fig 40**), and then drop it vertically to the point of entrance. The points of anchorage and entrance should be chosen to permit the vertical drop without crossing windows for aesthetic reasons.

If the station is located in a room on the ground floor, one way of bringing coax transmission line into the house is to go through the outside wall below floor level, feed it through the basement or crawl space and then up to the station through a hole in the floor. When making the entrance hole in the side of the building, suitable measurements should be made in advance to be sure the hole will go through the sill 2 or 3 inches above the foundation line (and between joists if the bore is parallel to the joists). The line should be allowed to sag below the entrance hole level outside the building to allow rain water to drip off.

Open-wire line can be fed in a similar manner, although it will require a separate hole for each conductor. Each hole should be insulated with a length of polystyrene or Lucite tubing. If available, ceramic tubes salvaged from old-fashioned *knob and tube* electrical

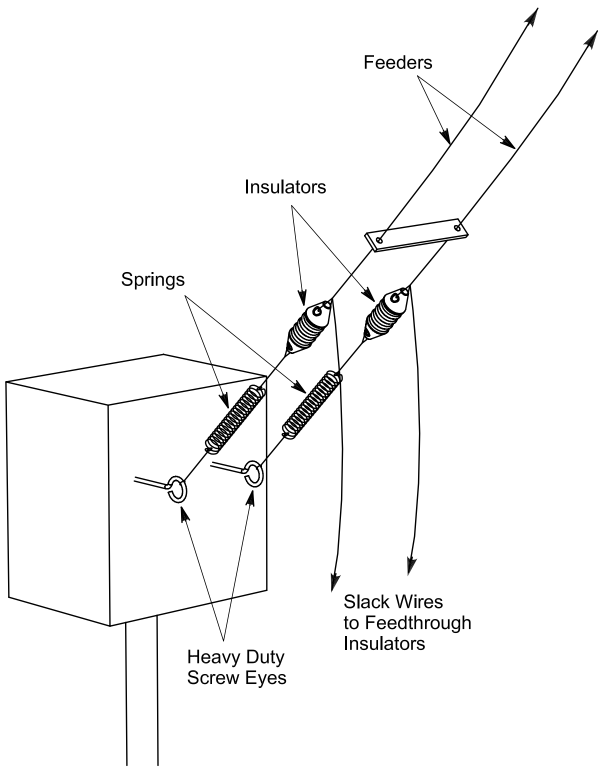


Fig 40—Anchoring open-wire line at the station end. The springs are especially desirable if the line is not supported between the antenna and the anchoring point.

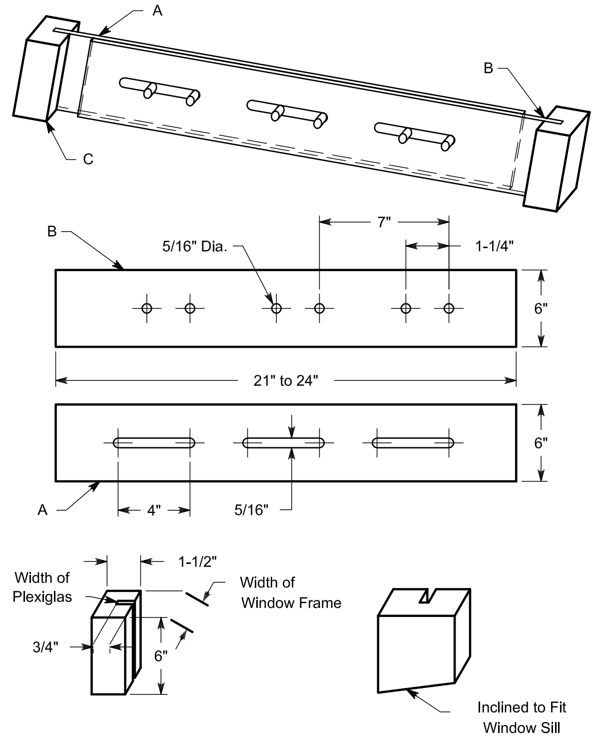


Fig 41—An adjustable window lead-in panel made up of two sheets of Lucite or Plexiglas. A feedthrough connector for coax line can be made as shown in Fig 28. Ceramic feedthrough insulators are suitable for open-wire line. (W1RVE)

installations, work very well for this purpose. Drill the holes with a slight downward slant toward the outside of the building to prevent rain seepage. With window ladder line, it will be necessary to remove a few of the spreader insulators, cut the line before passing through the holes (allowing enough length to reach the inside) and splice the remainder on the inside.

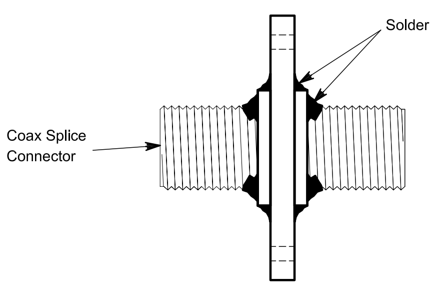


Fig 42—Feedthrough connector for coax line. An Amphenol 83-1J (PL-258) connector, the type used to splice sections of coax line together, is soldered into a hole cut in a brass mounting flange. An Amphenol bulkhead adapter 83-1F may be used instead.

If the station is located above ground level, or if there is other objection to the procedure described above, entrance can be made at a window, using the arrangement shown in **Fig 41**. An Amphenol type 83-1F (UG-363) connector can be used as shown in **Fig 42**; ceramic feedthrough insulators can be used for open-wire line. Ribbon line can be run through clearance holes in the panel, and secured by a winding of tape on either side of the panel, or by cutting the retaining rings and insulators from a pair of TV standoff insulators and clamping one on each side of the panel.

LIGHTNING PROTECTION

Two or three types of lightning arresters for coaxial cable are available on the market. If the antenna feed point is at the top of a well-grounded tower, the arrester can be fastened securely to the top of the tower for grounding purposes. A short length of cable, terminated in a coaxial plug, is then run from the antenna feed point to one receptacle of the arrester, while the transmission line is run from the other arrester receptacle to the station. Such arresters may also be placed at the entrance point to the station, if a suitable ground connection is available at that point (or arresters may be placed at both points for added insurance).

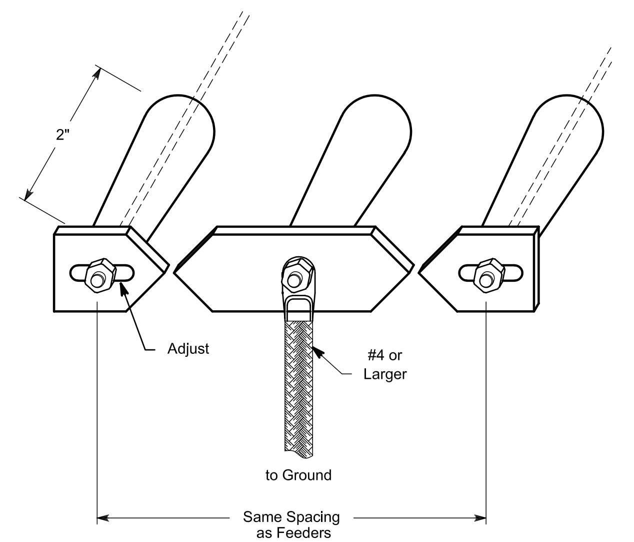


Fig 43—A simple lightning arrester for open-wire line made from three standoff or feedthrough insulators and sections of 1/8 × 1/2-inch brass or copper strap. It should be installed in the line at the point where the line enters the station. The heavy ground lead should be as short and as direct as possible. The gap setting should be adjusted to the minimum width that will prohibit arcing when the transmitter is operated.

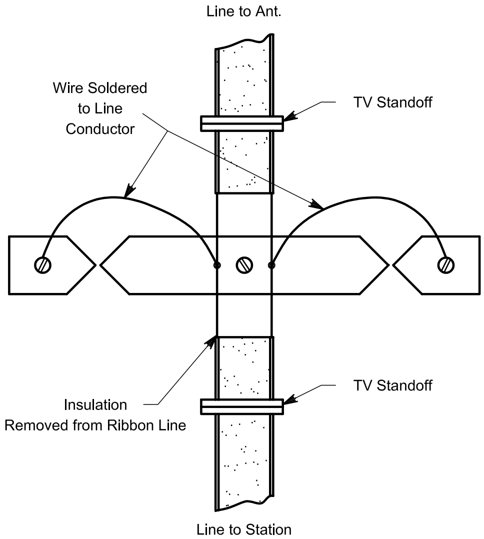


Fig 44—The lightning arrester of Fig 39 may be used with 300-Ω ribbon line in the manner shown here. The TV standoffs support the line an inch or so away from the grounded center member of the arrester

The construction of a homemade arrester for open-wire line is shown in **Fig 43**. This type of arrester can be adapted to ribbon line an inch or so away from the center member of the arrester, as shown in **Fig 44**. Sufficient insulation should be removed from the line where it crosses the arrester to permit soldering the arrester connecting leads.

Lightning Grounds

Lightning-ground connecting leads should be of conductor size equivalent to at least #10 wire. The #8 aluminum wire used for TV-antenna grounds is satisfactory. Copper braid 3/4-inch wide (Belden 8662-10) is also suitable. The conductor should run in a straight line to the grounding point. The ground connection may be made to a water pipe system (if the pipe is not plastic), the grounded metal frame of a building, or to one or more 5/8-inch ground rods driven to a depth of at least 8 feet. More detailed information on lightning protection is contained in Chapter 1, Safety.

A central grounding panel for coax cables coming into the house is highly recommended. See **Fig 45** for a photo of the homemade grounding panel installed by Chuck Hutchinson, K8CH, at his Michigan home. The coax cables screwed into dual-female feed-through UHF connectors. K8CH installed this aluminum panel under the outside grill for a duct that provided combustion air to an unused fireplace. He used ground strap to connect to ground rods located under the panel. See the ARRL book *Simple and Fun Antennas* for more information about ground panels.

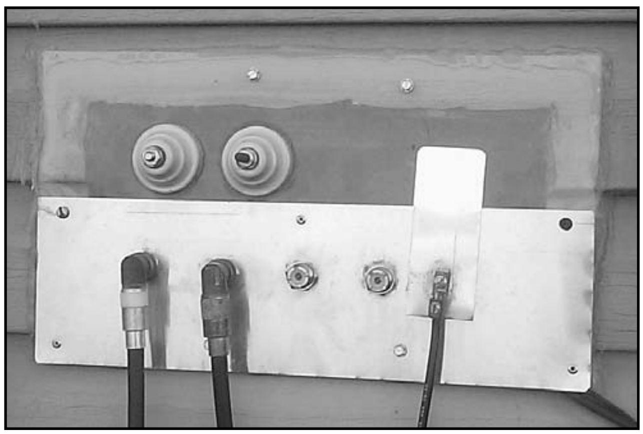


Fig 45—K8CH's coax entry panel mounted on exterior wall (later covered by grill that provides combustion to an unused fireplace). The ground braid goes to a ground rod located beneath the panel. (Photo courtesy: *Simple and Fun Antennas for Hams*)

Before a lightning storm approaches, a prudent ham will disconnect all feed lines, rotor lines and control lines inside the shack to prevent damage to sensitive electronics. When lightning is crashing about outside, you certainly don't want that lightning inside your shack!