# What Can We Expect from a 2-Element Beam?

## Part 1
## Method, Units of Measure, and the Dipole Standard of Reference

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### Method

A 2-element Yagi can be configured either as a director and driven element or as a driven element and reflector. We shall concentrate on the latter, because it is the most common and perhaps the most versatile configuration used.

Developing a basic understanding of 2-element Yagis requires a consistent method. My method will be computer antenna modeling, using a variety of software: MININEC, NEC-2, and NEC-4. The advantage of the latter two engines is the availability of the Sommerfeld-Norton ground equations for more accurate modeling of antennas over real ground. However, some results will be crosschecked with MININEC in order to understand any differences that may arise. Models are convergence tested and use more than the minimum recommended number of segments per half-wavelength. Ground parameters will be average earth throughout.

*Frequency*: All models will be for 10-meters, with a design center of 29 MHz. Although this frequency is well up the band from the region of greatest activity, it allows an examination of performance curves that cover maximum gain, maximum front-to-back ratio, and feedpoint impedance while trying to stay within the ham band. However, what applies to 10 meters also applies to all other ham bands with suitable adjustments.

*Element Diameter*: The 10-meter models will employ single diameter aluminum elements. (Real elements may use stepped-diamet4er elements or a "tapered-diameter schedule." Such elements are a special topic all unto itself. In general, if we taper the diameter as we move away from the element center, then the element will be longer than an element using a uniform diameter, *even if the average tapered element diameter is somewhat larger than the uniform-diameter element*. In fact, changing the taper schedule may call for a change in some element lengths to return a design to its original performance specifications.) I have chosen 0.375" (3/8") elements because they scale well to other bands. The equivalencies from band to band for element diameter appear in **Table 1**:

| Approximate Scaled | | Table 1 |
|---|---|---|
| Diameters by Band | | |
| Band m | Dia. " | Dia. " |
| 10 | 0.375 | 3/8 |
| 15 | 0.5625 | 9/16 |
| 20 | 0.75 | 3/4 |
| 30 | 1.125 | 1-1/8 |
| 40 | 1.5 | 1-1/2 |

In fact, all antennas for 10 meters noted below have been scaled for each of the ham bands mentioned, and--as expected--give identical performance figures. When scaling an antenna, the diameter changes slowly within any ham band, so picking the closest real value to a calculated size usually does no harm to a design. However, picking a random value can create problems. In the table, each diameter is about the same fraction of a wavelength for each band.

*Scaling*. The idea of scaling an antenna from one band to another often creates a bit of confusion for newcomers. If we wish to scale the dimensions of an antenna for 10 meters to 20 meters, let's first take the ratio of the old frequency to the new frequency--and use some precision in the process. For example, if the 10-meter design is for 29.0 MHz and the new or scaled design is for 14.2 MHz, then the ratio of old to new is 29.5/14.2 or 2.077.

Next, lets multiply all dimensions by the scaling ratio. The dimensions include the length of each element, the spacing between elements, and the diameter of the element. Most casual builders forget this last factor. Indeed, it is common for newcomers to see a magazines article and think that they can build the antenna from whatever materials may be convenient. If we are dealing with very thin wire (for example, AWG #12 wire is very thin as a function of a wavelength on 40 meters), then no great harm occurs. However, for fatter elements, such as the tubing used in beams, changing the element diameter will throw the design off frequency and out of its original design specifications.

The bottom line is simple: if you cannot scale all of the dimensions to a new frequency, then you will have to adjust the complete dimension set for the new frequency. That task is not a casual one.

*Antenna Height above Ground*: When we work with antennas and take the ground into consideration, we add another factor into the analysis. Antenna heights will be given in fractions of a wavelength as well as feet. This procedure will permit more ready scaling of results to antennas designed for other bands. As a reference, the **Table 2** lists the heights of an antenna at 29 MHz in terms of both feet and fractions of a wavelength. Heights in feet are rounded to the nearest tenth of a foot.

| Height above | | Table 2 |
|---|---|---|
| Ground at 29 MHz | | |
| Ht wl | | Ht feet |
| 1/8 | 0.125 | 4.2 |
| 1/4 | 0.25 | 8.5 |
| 3/8 | 0.375 | 12.7 |
| 1/2 | 0.5 | 17 |
| 5/8 | 0.625 | 21.2 |
| 3/4 | 0.75 | 25.4 |
| 7/8 | 0.875 | 29.7 |
| 1 | 1 | 33.9 |

Scaling for lower ham bands by up to a factor of 8 should introduce no significant errors in results. Note that although heights of antennas for 10 meters would rarely be placed at a 4' level, antenna heights for the lowest amateur bands are often forced to correspondingly low heights. An 80-meter dipole at 35' is very close to 1/8 wavelength above ground.

MININEC models of antennas at a height of 1/8 wavelength are not reliable, since the program only begins to approach reliability at antenna heights of 0.2 wavelength or greater. (One highly corrected MININEC program, Antenna Model, has grafted the NEC ground system to its MININEC core with very good results.) NEC with Sommerfeld-Norton (S-N) ground implemented is reliable at the lower heights.

None of the models will press any of the other internal modeling limitations. All elements will be of a single diameter and linear, thus assuring easy convergence of results. Indeed, NEC-2 and NEC-4 should provide identical results, +/-1 digit in the last decimal place of the output.

Models do have other limitations. Modeling programs assume level uniform terrain. Local variations can change some performance figures, such as the elevation angle of maximum radiation and feedpoint impedance. However, they do not change the basic expectation limits for any given design when related to other designs, since each design will be equally affected by the local terrain variations.

## Units of Measure

One of the most confusing aspects of antenna performance figures lies in the units of measure. Therefore, let me explain the units used here, working from the least confusing to the most confusing.

**SWR (standing wave ratio)**. SWR, wherever apt to produce a curve, will be given relative to the resonate impedance of the test model at the design frequency. Hence, all antennas modeled will show close to 1:1 SWR at or close to the design center frequency. Curves will assume that appropriate matching is employed, wherever applicable, to the user's desired feedline impedance, with no examination of matching circuit losses. For certain models, a 50-ohm reference may also be used, since some common designs can be developed specifically for 50-ohm cable use.

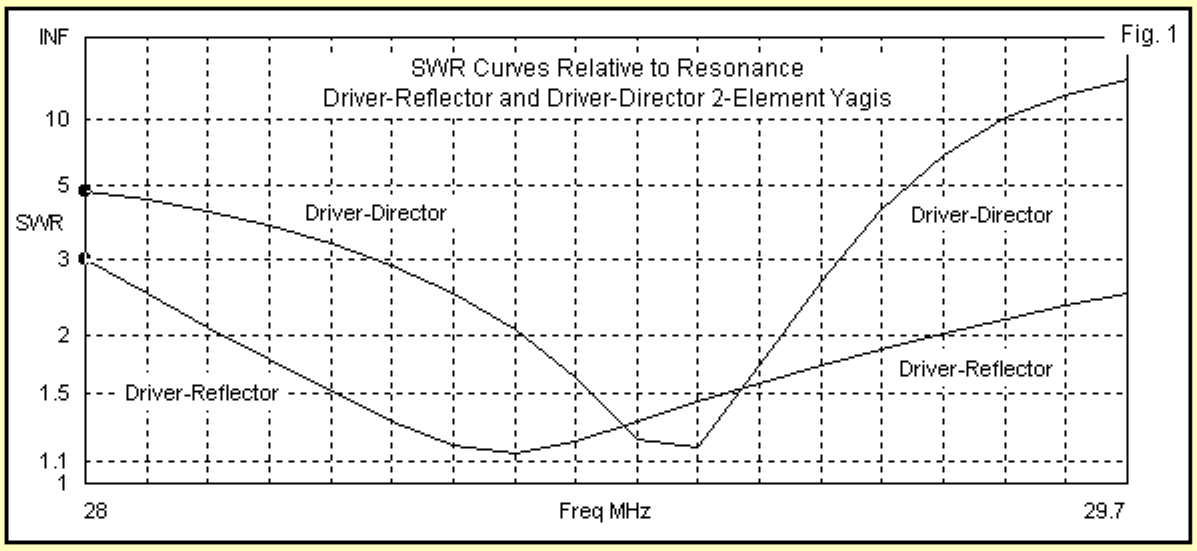
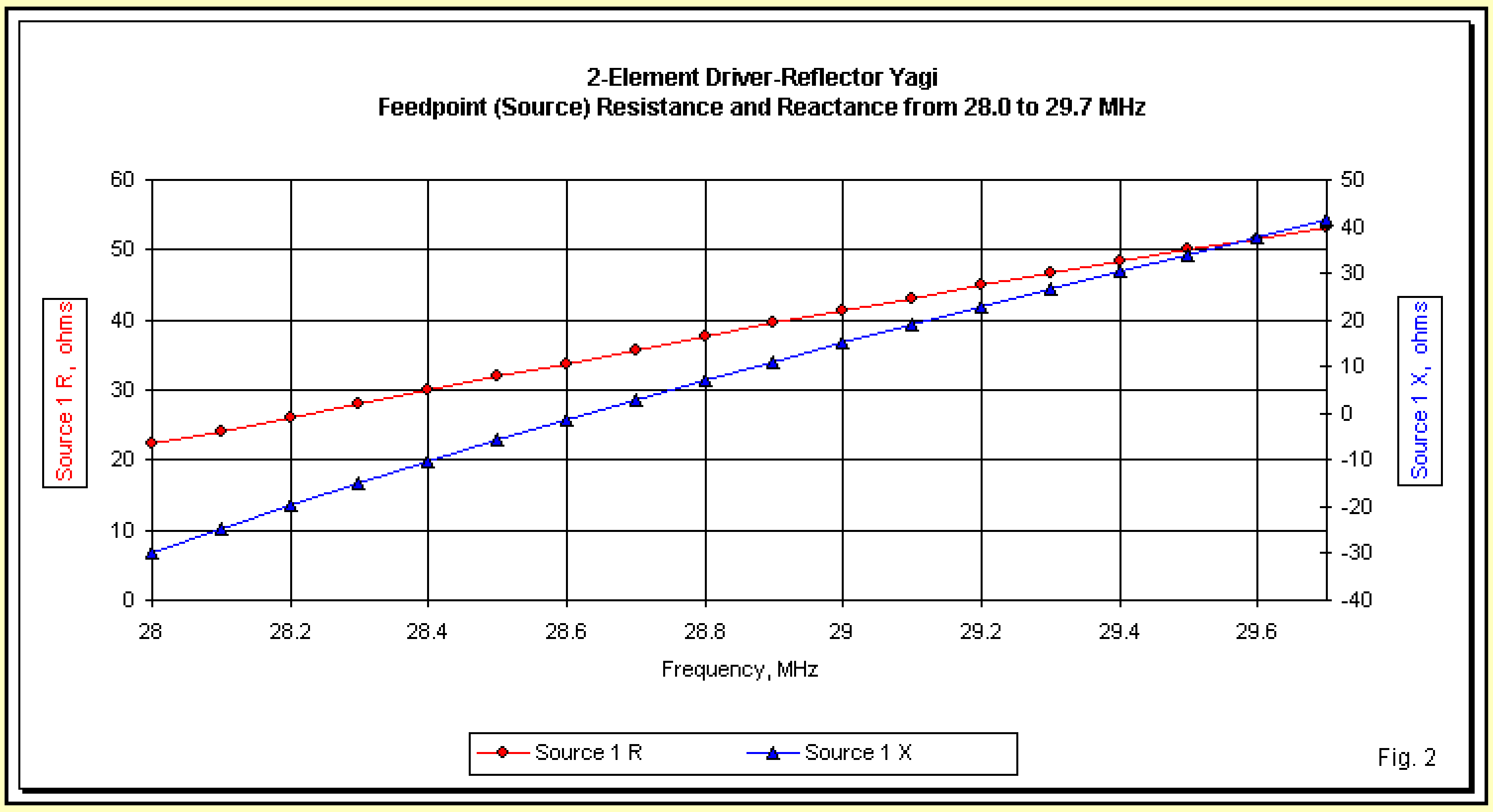



**Fig. 1** compares sample SWR curves from 2 kinds of 2-element Yagis. Each curve is relative to the resonant feedpoint resistive impedance. The driver-reflector Yagi uses a 40-Ohm reference, while the driver-director array uses a 17-Ohm standard. The fact that the driver-reflector Yagi has a much wider frequency span between the points at which it crosses the 2:1 SWR line is one reason why this general design is more widely used than the driver-director version of the antenna.

**Feedpoint Impedance (Z)**. Feed point impedance will always be given as a complex number involving resistance and reactance (R +/- jX) in Ohms. Resonance will be defined as a reactance less than +/-1 Ohm.

Both the resistance and the reactance of any antenna vary across any stretch of frequencies we might use for operation. **Fig. 2** shows a sample graph of the changes in both resistance and reactance on 10 meters for the driver-reflector Yagi used for the SWR curve in **Fig. 1**.




Note that the reactance crosses the 0-line (right Y-axis) at about the point where the SWR curve shows its lowest value. Although the resistance is also change with frequency, the reactance is changing faster, and so reactance is often (but not always) the limiting factor in SWR curves.

**Front-to-Back Ratio (F-B)**. Front-to-back ratio will be given in dB below the maximum gain of the forward lobe. Front-to-back ratio is taken at a 180-degree angle from the forward lobe. One may also employ a notion of front-to-rear ratio, using the simple or complex mean of values in the quadrant extending for 180 degrees (or some other number of degrees) to the rear of the forward lobe. For the present enterprise, this procedure is unnecessary, since the rear lobe of a 2-element beam is usually geometrically simple. Hence, front-to-back ratio is a sufficient performance indicator for these tests.

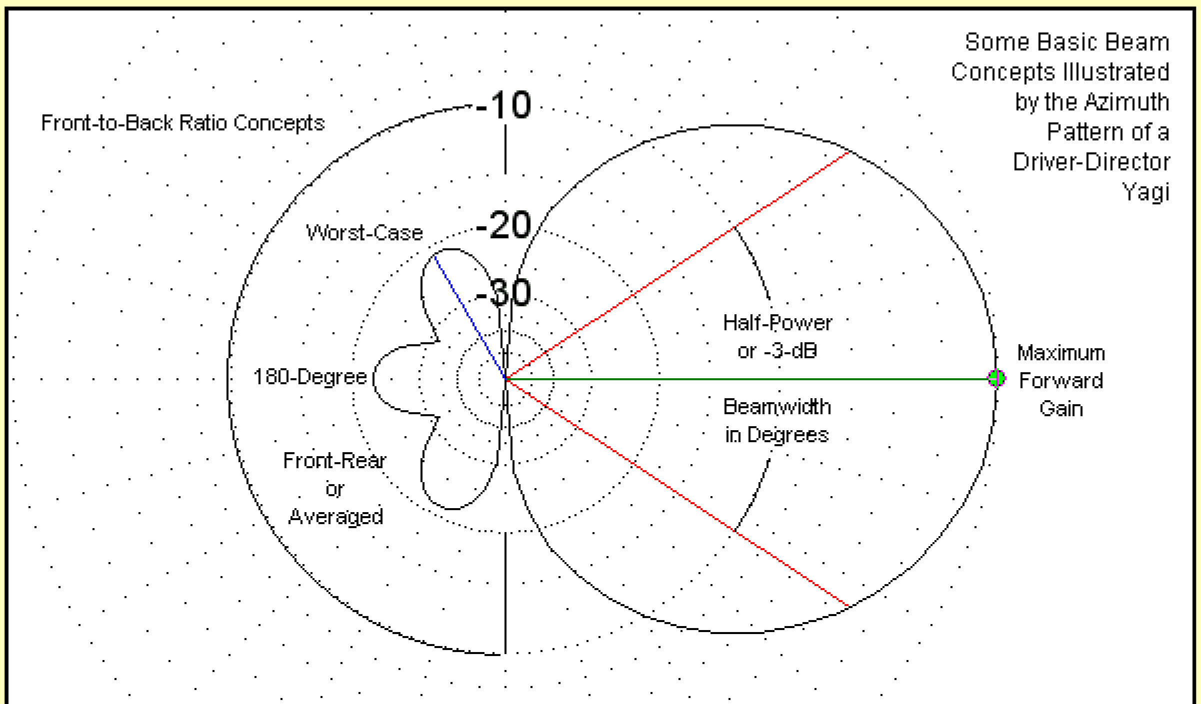


Fig. 3

*Special Note on Front-to-Back Ratios*. **Fig. 3** uses the azimuth pattern of a driver-director Yagi to illustrate the variety of front-to-back ratio concepts that you may find in both articles and manufacturer specification sheets. The 180-degree ratio uses a straight line to the rear opposite the heading of maximum forward gain and compares the two gain readings. The worst-case ratio (sometimes called the front-to-rear ratio) compares the maximum forward gain to the gain of the strongest rearward lobe. The front-to-rear ratio (sometimes called the average front-to-back ratio) averages the gain across the entire rearward quadrants and compares that value to the maximum forward gain. When reading about beams, always try to determine which front-to-back ratio calculation that the author is using.

**Forward gain**: The most complex question for the selection of units of measure is a proper characterization of gain. In **Fig. 3**, we can easily determine the direction of maximum forward gain, but the pattern does not tell us how to quantify that gain.

The most universal standard is gain in **dBi**, or dB over an isotropic source. An isotropic source is a hypothetical concept that one can approximate with various types of real antennas (but only in free space). It radiates equally well in any direction: up, down, left, right, etc. Hence, it is a universal comparator. Whenever two antennas require comparison, one simply subtracts one dBi-gain figure from the other to find the relative gain advantage or disadvantage.

A second common gain figure is dBd, dB relative to a dipole. The dipole standard arose in connection with horizontal antennas, since horizontal dipoles were in common use from the earliest days of radio. However, when gain is registered in dBd, at least 2 different measures may be indicated:

**dBd(i)**: Gain in dBd(i) is gain relative to a free space dipole composed of lossless wire of infinitely thin diameter. This idea of a dipole is as hypothetical as a true isotropic source, and real dipoles only approximate the ideal. We may easily relate this notion of dBd to the notion of dBi by the following equation: Gain dBi = Gain dBd(i) + 2.15. This notion of dBd has limited utility, but appear in some tables.

**dBd(r)**: Gain in dBd(r) is gain relative to a real dipole in the same defined situation as the test antenna. For modeling purposes, the dipole should be made from the same materials as the test antenna or from some predefined (and stated) set of materials. For these tests, the dipole will use the same material and element diameter as the test Yagi.

The notion of dBd(r) may also be used where gain figures result from range measurements. Whenever the notion is so employed, the complete set of test conditions for both the test antenna and the reference dipole should be explained. Otherwise, the figures cannot be meaningful, since replication of the test would not be possible. Range measurements will not be included in these notes. Therefore, dBd(r) will always refer to the gain of a full-length dipole of similar materials as the test antenna, and situated within the same parameters of height and ground specification.

However, a further complication arises in the use of dBd(r). Even 2-element Yagi antennas exhibit for the same antenna height, a (usually slightly) lower elevation angle of maximum radiation than a dipole, especially for antenna height less than 1 wavelength. Therefore, simple gain figures must be accompanied by the elevation angle for those figures if a reasonable comparison is to be made.

**Beamwidth**: We think of a vertical antenna as omni-directional, radiating equally well in all azimuth or compass directions. By comparison, even a dipole is directional, although it shows lobes that are identical in two directions. Hence, it falls in the group of antennas that we think of as bi-directional. When we use the term "directional" without a qualifier, we usually mean an antenna--like our sample Yagis--that shows very strong radiation in only one direction, with considerably weaker radiation in all other directions.

However, bi-directional and directional antennas do not radiate on a single compass heading. Rather, the gain slowly grows weaker as we move away from the heading of maximum forward gain. At a certain angular distance in either direction from the heading of maximum forward gain, we would find that the transmitted energy has half the power that it has in the direction of maximum power. These half-power points will show 3-dB less gain than in the maximum forward gain direction. We use these points as a convenient measure of an antenna's beamwidth, as measured in degrees between the two points. The pattern in **Fig. 3** shows a beamwidth of about 67 degrees from one limit to the other.

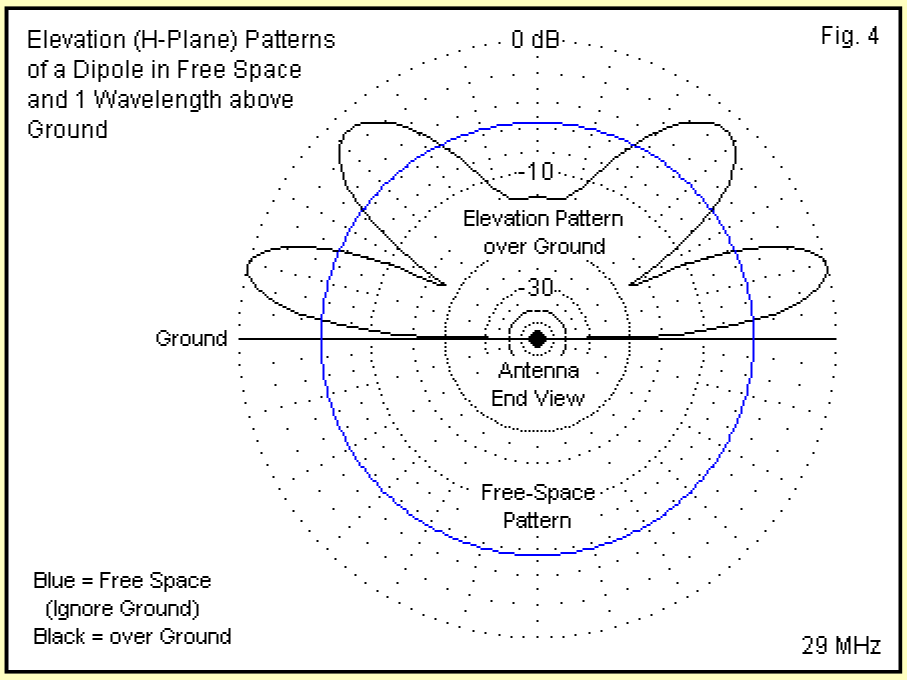
These notes on basic beam specification concepts all presume that the antenna we are using is oriented horizontally relative to the ground. When we place beams above ground and orient them vertically, the azimuth pattern shape changes, and so too does the maximum forward gain at the heights we use in the HF range. However, the meanings of terms like forward gain, front-to-back ratio, and beamwidth will not change. Since we will normally use a 2-element beam horizontally on 80 through 10 meters, we shall bypass the vertical orientation in these notes. However, if you decide to build a VHF beam for repeater serve, remember that the horizontal patterns and numbers will not be applicable.

## Where Does Beam Gain Come From?

A beam derives its gain from 3 main sources: ground reflection, directionality, and beamwidth. The total radiated energy from a beam can never be greater than from a dipole or an isotropic source (ignoring element resistances). Any directional antenna acquires gain by re-directing energy in a desired (or usable) direction.

Free space is equivalent to outer space with no population of particles or waves other than those produced by an antenna under study. In free space, there is no up or down to define azimuth and elevation. So we generally (but not always) consider radiation in the plane of a wire to be the E-plane or electrical plane. At right angles to the plane of the linear elements in the antenna, we have the H-plane or the magnetic plane. If we place the same array of linear element over ground with the elements parallel to the ground, this plane becomes the elevation pattern. (For convenience, modeling software will call any pattern taken in the +/-Z-plane an elevation pattern. Any plot taken in the X-Y-plane becomes an azimuth pattern.)

Antennas in free space show a maximum gain that less than the value we find when we place the antenna over a ground surface. In free space, the radiation can equally go "up" and "down." However, the moment that we introduce the ground, we ultimately have only the "up" direction. What initially starts downward reflects (with some loss) back upward. Compare the free-space and over-ground patterns for a simple dipole, looking along the length of the element.



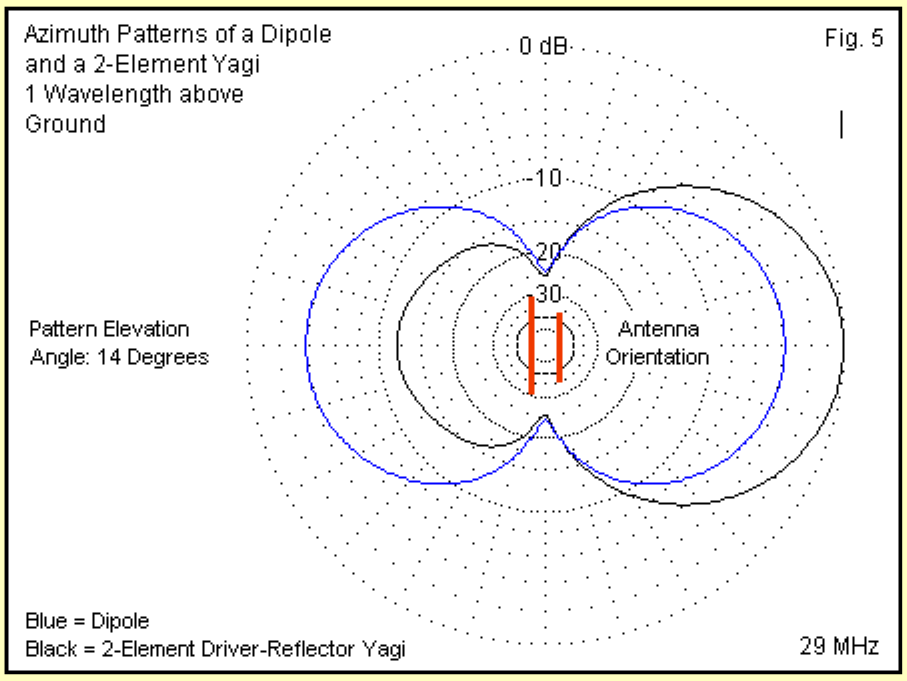

The energy the goes "downward" in free space becomes reflected upward by the ground. However, the angle of the downward energy, once reflected, determines whether the waves will mutually add, mutually subtract, or something in between the two. Hence, the elevation pattern of an antenna over ground may show both lobes and nulls. The test antenna is 1 wavelength above ground. In general and subject to some modification for long-boom antennas, we can estimate the angle of any lobe (or null) from a horizontal (but not a vertical) antenna by using a simple equation.

$$\mathbf{A_{LN} = \arcsin(N / 4h)}$$

$A_{LN}$ is the angle of the lobe or null above the horizon. The term h is the height of the antenna above ground measured in wavelengths or fractions thereof. N is the lobe or null number. We give lobes odd numbers, so that the first lobe is 1, the second lobe is 3, etc. Nulls receive even numbers. Most often, we are concerned with the first lobe. In this case, for N=1, and h=1, we want the arcsin (or $\sin^{-1}$) of 0.25. On any calculator, we take the inverse sin function of .25 and get a little over 14 degrees for the value of $A_{LN}$.

The peak gain at 14 degrees elevation for the sample dipole is about 7.6 dBi, compared to a gain value of 2.1 dBi in free space. If the ground did not have any losses, we would see a 6-dB difference. However, over real ground, we find a 5.5-dB gain differential.

The second way in which a beam acquires gain is in developing a pattern that favors a single direction. The dipole is already directional, but in two directions. We can further increase gain in a single favored direction by arranging the elements so that we have one large main (forward) lobe with only one or more minor lobes in other directions. Compare the overlaid azimuth patterns for a dipole and a 2-element driver-reflector Yagi in **Fig. 5**.




Note that, relative to the dipole, the 2-element Yagi shifts energy to the right in the pattern and removes energy toward the left. In free space, this particular sample beam has a maximum forward gain of about 6.0 dBi. Over ground, the maximum gain at 14 degrees elevation is about 11.4 dBi. The ground provides 5.4 dB of gain relative to free space. The gain of this beam is about 3.8 to 3.9 dB higher than the gain of a dipole--in the favored direction only.

The beamwidth of the beam is about 69 degrees. Although we shall not examine them closely, we may want to ask here how longer Yagis with more elements obtain higher gain levels in the favored direction. The answer is both simple and complex at once. The simple part is the general statement that the longer Yagis reduce their beamwidth in order to produce a higher gain in the favored direction. **Fig. 6** shows both independent and overlaid patterns for our sample 2-element Yagi and for a sample 6-element Yagi.

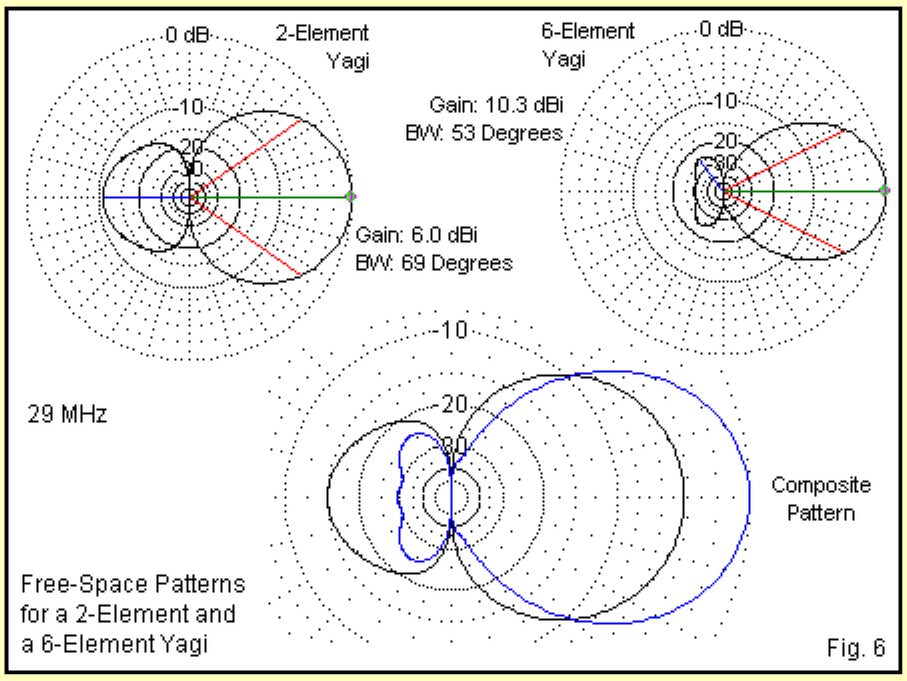


Fig. 6

The 6-element Yagi has somewhat less rearward radiation, and so it acquires a bit of gain from that source. But only a little. The main source of the increased forward energy and gain comes from the narrowing of the beamwidth--from 69 down to 53 degrees in this example.

The picture given by these plots is incomplete, which is why the answer is more complex than it may initially seem. Not only does the longer Yagi decrease the horizontal beamwidth, it also decreases the vertical beamwidth. This 3-dimensional beamwidth reduction shows up well when we start with free-space patterns, but for now we can simply use the azimuth patterns as an indicator of how beamwidth reduction becomes a source of additional gain in long Yagis and certain other kinds of horizontal beam antennas. However, **Fig. 7** shows the relationship between E-plane and H-plane patterns in free space and between elevation and azimuth patterns over ground for our sample 2-element driver-reflector Yagi.

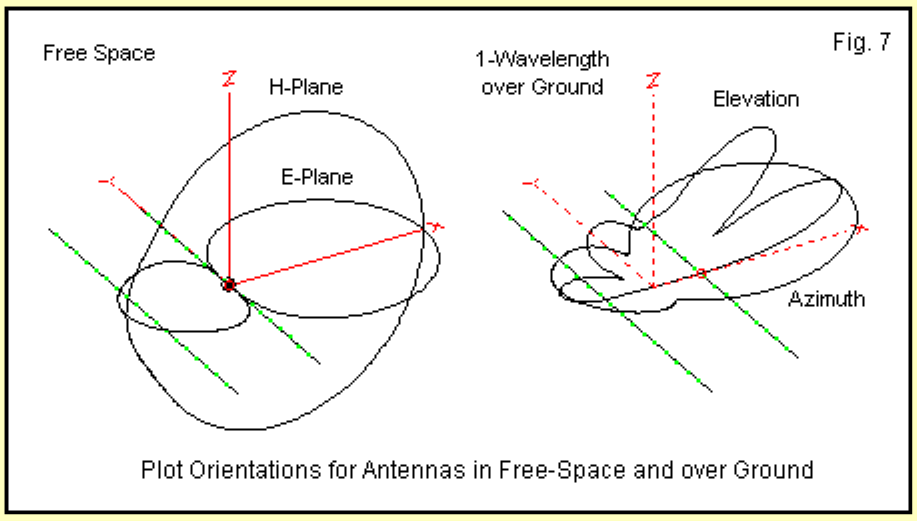


Fig. 7
Plot Orientations for Antennas in Free-Space and over Ground

Before we grow too attached to the 2-element Yagi, we need to understand a bit more about the behavior of a simple dipole over ground.

## The Dipole Standard of Reference

All Yagis ultimately rest on the linear dipole. The elements relate to a resonant 1/2-wavelength dipole, with reflectors being slightly longer and directors slightly shorter. Therefore, understanding the behavior of a dipole over ground is a crucial factor in appreciating the behavior of 2-element beams.

**Table 3** present some interesting data for a full-size 3/8" aluminum dipole for various heights from 1/8 to 1-1/4 wavelength using 1/16-wavelength increments. Gain values use both dBi and dBd to familiarize you with the differences in the gain recording systems. El. Angle refers to the elevation angle of maximum radiation at which the gain figure is taken. Feed R and Feed X refer to the resistance and reactance at the feedpoint.

| 29-MHz Dipole at Various Heights above Average Ground | | | | | | Table 3 |
|---|---|---|---|---|---|---|
| Height wl | Len feet | Feed R | Feed X | Gain dBi | Gain dBd | El Angle |
| 0.0625 | 16.14 | 59 | 0.2 | 0.49 | -1.66 | 90 |
| 0.125 | 16.01 | 55.2 | 0 | 4.64 | 2.49 | 88 |
| 0.1875 | 15.94 | 65.8 | -0.3 | 5.78 | 3.63 | 87 |
| 0.25 | 16.02 | 77.9 | 0.3 | 5.73 | 3.58 | 62 |
| 0.3125 | 16.17 | 85 | 0.1 | 5.75 | 3.6 | 46 |
| 0.375 | 16.32 | 84.7 | 0 | 6.07 | 3.92 | 37 |
| 0.4375 | 16.4 | 78.4 | 0.3 | 6.62 | 4.47 | 32 |
| 0.5 | 16.38 | 70.2 | 0.2 | 7.23 | 5.08 | 28 |
| 0.5625 | 16.29 | 64.5 | -0.1 | 7.66 | 5.51 | 25 |
| 0.625 | 16.18 | 63.8 | -0.2 | 7.75 | 5.6 | 22 |
| 0.6875 | 16.13 | 67.4 | 0.3 | 7.56 | 5.41 | 20 |
| 0.75 | 16.13 | 72.8 | 0.1 | 7.28 | 5.13 | 18 |
| 0.8125 | 16.18 | 77.1 | 0 | 7.12 | 4.97 | 17 |
| 0.875 | 16.26 | 78.1 | 0.1 | 7.15 | 5 | 16 |
| 0.9375 | 16.31 | 75.7 | -0.1 | 7.34 | 5.19 | 15 |
| 1 | 16.31 | 71.6 | -0.2 | 7.63 | 5.48 | 14 |
| 1.0625 | 16.27 | 68.2 | 0.2 | 7.85 | 5.7 | 13 |
| 1.125 | 16.21 | 67.2 | 0 | 7.9 | 5.75 | 12 |
| 1.1875 | 16.17 | 69 | 0.1 | 7.81 | 5.66 | 12 |
| 1.25 | 16.17 | 72.3 | 0.3 | 7.63 | 5.48 | 11 |
| See text for explanation of column labels. | | | | | | |

**Fig. 8** shows the gain values and the elevation angle of maximum radiation (also called the take-off or TO angle) for the sequence of models. The gain values are significant in several respects. First, note the very low gain at very low antenna heights. MININEC users may see very different results below about 0.2-wavelength heights, because the ground system used by that program is very unreliable at low antenna heights. Next, note that the gain of a dipole does not rise and level off smoothly. Although the differences are not operationally significant, they do undulate as we raise the antenna, change its length to arrive at resonance, and then check the gain. We find small gain peaks at heights of 3/16, 5/8, and 1-

1/8 wavelength. We also find dips at 1/4, and 13/16 wavelengths, with the curve headed toward another dip at the end of the model sequence. (In a future episode, we shall show you a handy marketing trick that you can play if you should ever desire.) Perhaps the only consistent curve is the one for the elevation angle of maximum radiation. It decreases as we increase height, and the progression is very orderly.

It should be clear from the table that, except in the most unusual circumstance, the concept of dBd adds nothing to the analysis not already contained in the notion of dBi. For purposes of determining gain relative to a dipole with respect to test antennas, we shall simply subtract the appropriate value of gain in dBi for the dipole from the value of gain in dBi for the test antenna at the same height. However, it is wise to keep the 2 notions of dBd (that is, dBd(i) and dBd(r)) in the back of your mind because some antenna manufacturers use one or the other to portray the performance of their offerings. dBd remains popular among European antenna builders.

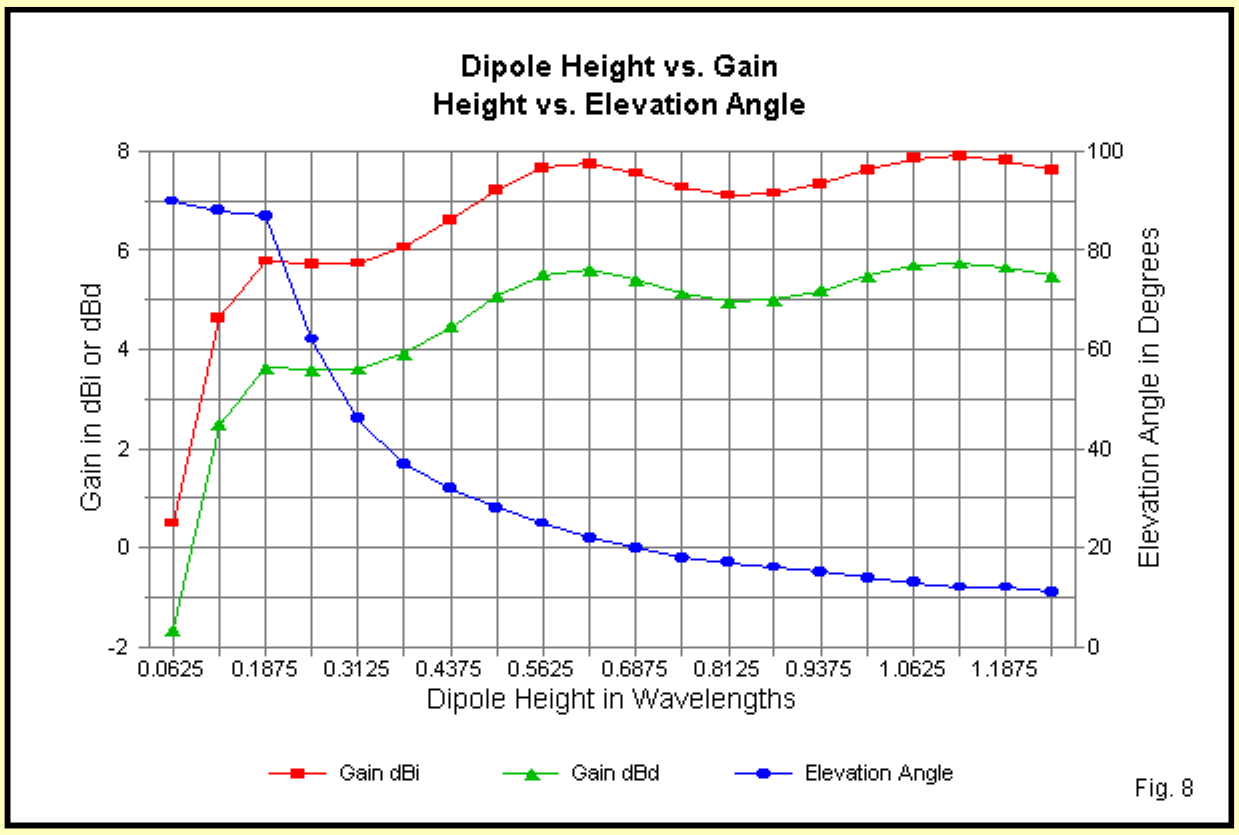


Fig. 8

As shown in the table and in **Fig. 9**, the required length of the dipole to achieve resonance varied from 15.9' to 16.4' but not in a linear progression. Short lengths appear at heights of 3/16, 3/4, and 1-1/4 wavelength, a progression that does not quite correspond to the peaks or dips in gain. Likewise, long lengths appear at heights of 7/16 and 1 wavelength, again without coincidence with the gain curve.

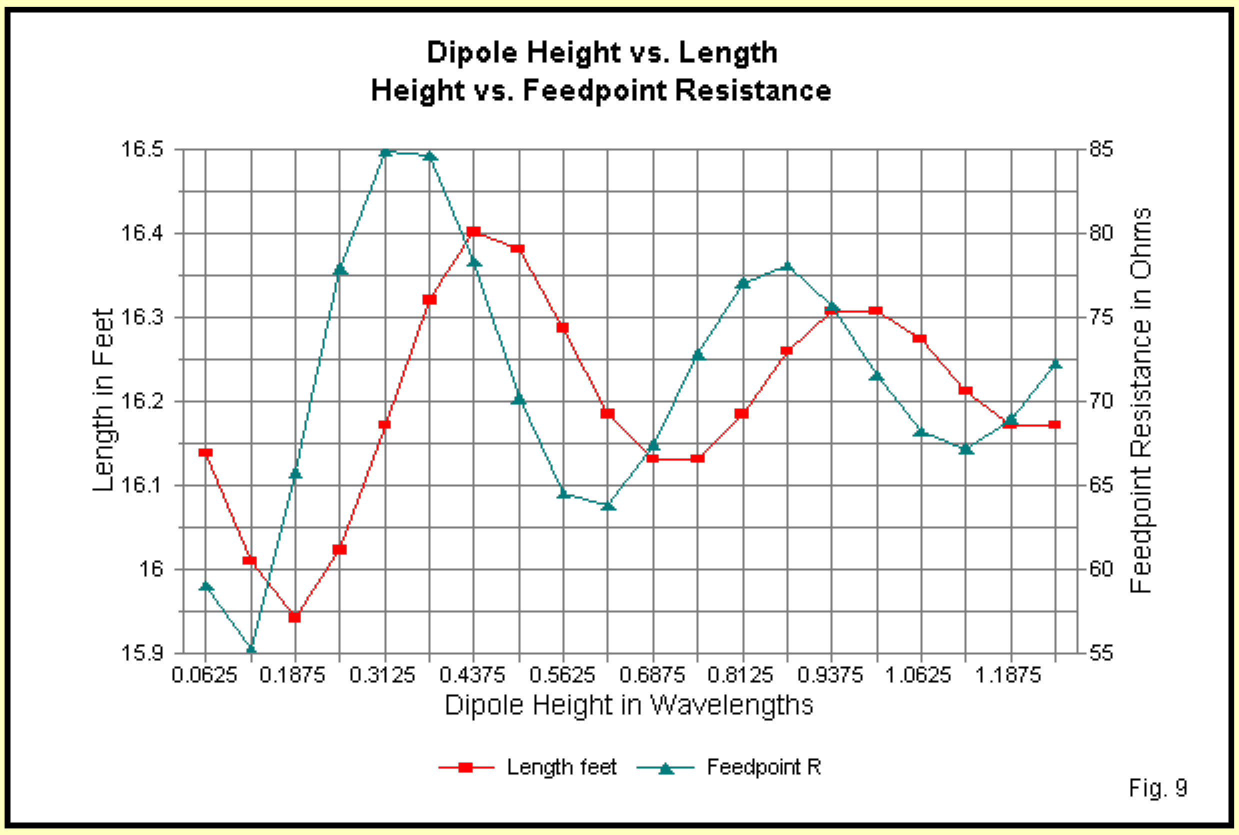
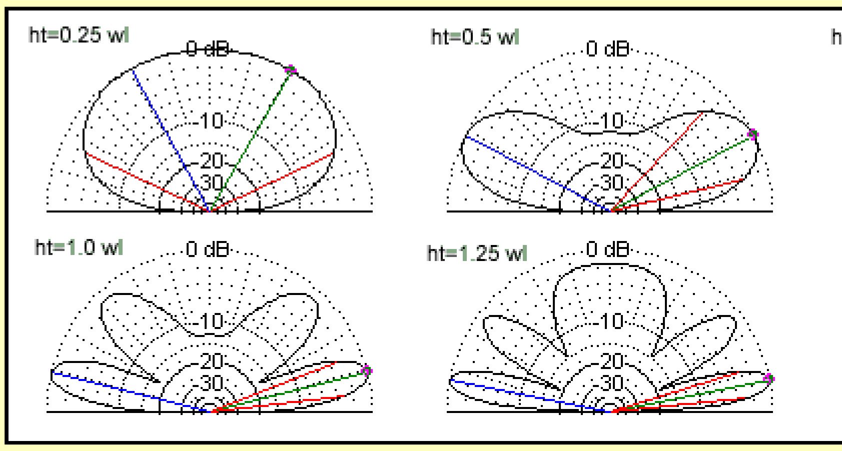


Fig. 9

The feedpoint impedance also varies with height, but not in a pattern that corresponds to the variance in length. However, the feedpoint resistance values tend to coincide with the changes in gain. Low feedpoint resistance values appear at 1/8, 5/8, and 1-1/8 wavelength heights, roughly corresponding to the gain peaks. High feedpoint values occur at heights of 5/16 and 7/8 wavelength, roughly corresponding to the gain dips.

One factor, but not the only factor, that plays a role in the undulations of gain is the changing spread of elevation lobes as we raise the antenna higher. **Fig. 10** provides only a few elevation patterns to illustrate how lobes emerge and change with changing antenna height.



Elevation Patterns of a 29 MHz Dipole at Various Heights above Average Ground

Fig. 10

As we increase the height of an antenna, new lobes do not simply appear. Rather, they make their first appearance as vertical or near-vertical lobes. (The pattern for a height of 1/4-wavelength makes it clear why those who pursue Near-Vertical Incidence Skywave (NVIS) operations favor a relatively low horizontal antenna.) As we raise the antenna, the nearly vertical lobe splits and gradually lowers its angle of maximum radiation. At certain heights, we find almost no radiation straight up, and the lower lobes contain all of the radiated energy. Further increases in height show the emergence of a new upward lobe, which then undergoes the same transformation as we continue the upward trend in antenna height. In general, we acquire a new lobe with each 1/2-wavelength addition to the antenna height. For most purposes, we are only concerned with the lowest and strongest elevation lobe, since it usually comes closest to matching the favored radiation angles for long-distance HF communications.

### A Final Question about Gain

Before we leave the subject of antenna gain, let's look at an all-too-typical claim. Suppose someone says that a certain antenna at a height of 7/8 wavelengths has a gain of 5 dBd. How are we to understand this claim without further and full specification of what the idea of dBd means in this context? If we interpret the claim to mean dBd(i), then the assertion is that the antenna has only the gain of a dipole, since a dipole at 7/8 wavelength has a gain of 5.00 dBi (assuming similar materials). If the antenna is an array, that would be a disappointing result.

If the claim is that the antenna has a gain of 5 dBd(r) (as applicable to modeling), then we would expect the antenna to have a gain of 12.15 dBi, since the gain of a dipole in dBi at 7/8 wavelength (assuming similar materials) is 7.15 dBi. Our next question is whether this claim is reasonable. To make such a judgment, we need to have some clear expectations of 2-element Yagi performance capabilities and limitations. That is the next stop on this road towqard understanding 2-element beams.

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