CHAPTER 5

Antennas: General, Terms, Definitions

Lew Gordon, K4VX, needs no introduction to antenna designers and builders, nor to the contest community. I first met Lew through his excellent and still-popular *YagiMax* modeling software. A few years ago, when I evolved from an avid low-band DXer into an even more avid contester, Lew's contesting multi-op station in Missouri was an outstanding example of station and antenna design. It ranked with stations like W3LPL and K3LR. When I met Lew for the first time during WRTC (World Radio Team Championship) in San Francisco in the summer of 1996, I met a fine gentleman. When I asked Lew to godfather a few chapters of my new book, he immediately and enthusiastically accepted. Lew took care of Chapters 5 and 6 in this new book.

Lew graduated from Purdue University with a physics major. His professional career was as an RF systems engineer with the US Government. First licensed as W9APY in 1947, he has also held the calls WA4RPK and W4ZCY. Lew's antenna systems near Hannibal, Missouri, utilize a total of ten towers ranging from 50 to 170 feet in height. Although he professes to be mainly a contester instead of a DXer, his DXCC total stands at 349 confirmed.

Thank you, Lew, for your help and encouragement.

Agreeing on terms and definitions is important. Too many technical discussions seem to take place in the tower of Babble. First make sure you speak the same language; then speak. Before we get involved in a debate on what's the best antenna for the low bands (that must be the key question for most), we define what we want an antenna to do for us and how we will measure its performance.

Making antennas for the low bands is one area in Amateur Radio where home building can yield results that can substantially outperform most of what can be obtained commercially. All my antennas are homemade. Visitors often ask me, "Where do you buy the parts?" Or, "Do you have a machine shop to do all the mechanical work?" Very often I don't buy parts. And no, I don't have a machine shop, just run-of-the-mill hand tools. But my friends who are antenna builders and I keep our eyes open all the time for goodies that might be useful for our next antenna project. There is a very active swap activity between us. Among friends we have access to certain facilities that make antenna building easier. It's almost like we are a team, where each one of us has his own specialty.

Don't look at low-band antenna designing and building as a "kit project." You need some know-how, a good deal of imagination and inventiveness and often some organizational talent. But unlike the area of receivers and transmitters, where we homebuilders do not usually have access to custom-designed integrated circuits and other very specialized parts, we can build antennas and antenna systems using materials found locally.

A number of successful major low-band antennas are described in this book. These are not meant to be kits with step-by-step instructions, but are there to stimulate thinking and to put the newcomer to antenna building on the right track.

The antenna chapters of *Low-Band DXing* emphasize typical aspects of low-band antennas, and explain how and why some of the popular antennas work and what we can do to get the best results, given typical constraints. *The ARRL Antenna Book* (Ref 697) contains a wealth of excellent and accurate information on antennas.

1. THE PURPOSE OF AN ANTENNA

1.1. Transmitting Antennas

A transmitting antenna should radiate all the RF energy supplied to it in the desired direction, at the required elevation angle (directivity). We want to be loud; the issue is *gain*. We can do this by concentrating our RF in a given direction (in both the vertical and the horizontal planes).

1.1.1. Wanted direction

1.1.1.1 Horizontal directivity.

We learned in Chapter 1 (Propagation) that on the low bands, paths quite frequently deviate from the theoretical great-circle direction. This is especially so for paths going through or very near the auroral oval (such as West Coast or Mid-West USA to Europe). This is a fact we have to take into consideration for a fixed-direction antenna. For paths near the antipodes, signal direction can change as much as 180º (with every direction in-between) depending on the season. All this must be taken into account when designing an antenna system. Rotary systems, of course, provide the ultimate in flexibility so far as horizontal directivity is concerned.

I want to emphasize that the term *horizontal directivity* is really meaningless without further definition. Azimuthal directivity at a takeoff angle of 0º (perfectly parallel to the horizon) is of very little use, since practical antennas produce very little signal at a 0º wave angle over real ground. This issue is important when designing or modeling an antenna. It would be ideal to design an antenna that concentrates transmitted energy at a relatively low angle, while exhibiting the highest rejection off the back at a much higher angle (to achieve maximum rejection of stronger local signals, which as a rule come in at a much higher wave angle. Horizontal directivity should always be specified at a given elevation angle. An antenna can have quite different azimuthal directional properties at different elevation angles.

We will see further that a very low dipole radiates most of its energy directly overhead at 90° (zenith angle), and shows no directivity at high wave angles (60° to 90°). The same antenna, at the same height, shows a pronounced directivity (hardly any signal off the ends of the dipole) at very low wave angles, but hardly radiates at all at very low elevation angles. These issues must be very clear in our minds if we want to understand radiation patterns of antennas.

1.1.1.2. Vertical directivity

In the last few years a lot of modeling has been done using various propagation software packages. At ARRL HQ, D. Straw, N6BV, used *IONCAP* (Ionospheric Propagation Analysis and Prediction System) and *VOACAP* (a version of *IONCAP* upgraded by the Voice of America) to calculate elevation angles for various paths on the different amateur bands. *IONCAP* is based on a mass of propagation data collected over more than 35 years. **Table 5-1** shows the distribution of elevation angles on 40 and 80 meters for some typical DX paths, as does **Fig 5-1** in graphical form. This elevation-angle statistical information is derived from the data on the CD-ROM included with the 20th Edition of *The ARRL Antenna Book* (Ref 697).

Just after the 3rd Edition of *ON4UN's Low-Band DXing* went to press in 1999, N6BV discovered a bug in his elevation-statistics parsing software. Besides fixing the bug (which tended to emphasize medium-angle elevation angles), N6BV also elected to standardize on isotropic antennas (instead of dipoles and Yagis) in *VOACAP* so that the full range of possible elevation angles could be explored. This was done even though the lower angles (such as a 1º takeoff angle) would be very difficult to achieve with most real-world antennas (Ref 182).

The net result is that the range of elevation angles shown in Table 5-1 and Fig 5-1 are now generally lower than the values shown in the 3rd Edition of *Low-Band DXing*. "No Data" means that there are no data available from the model. This does *not* mean that there is *no* possibility of propagation. On 80 and 40 meters propagation is possible from any point of the world to any other point of the world—given the right moment of the year and the right time of the day, under good propagation conditions —even though such propagation may not be statistically "significant." After all, low-band hams thrive on adversity and they love to pursue openings that are not shown in the statistics!

Table 5-1

Range of Radiation Angles for 40 and 80 Meters for Various Paths

The values are averages across the complete sunspot cycle and across the seasons. The value between parentheses is the most common radiation angle (peak value in the distribution).

From	*Path to*	*40 Meters*	*80 Meters*
W. Europe (Belgium)	Southern Africa	1-18 (5)	1-17 (5)
	Japan	1-19 (3)	2-17 (3)
	Oceania	1-4 (1)	No Data
	South Asia	1-17 (4)	3-5 (4)
	USA (W1-W6)	2-33 (5)	1-35 (4)
	South America	1-17 (1)	1-12 (1)
USA East Coast	Southern Africa	1-16 (3)	3-4 (4)
	Japan	1-15 (1)	1-12 (5)
	Oceania	1-9 (1)	No Data
	South Asia	1-9 (1)	No Data
	South America	1-23 (5)	1-21 (10)
	Europe	1-38 (6)	1-31 (13)
USA Midwest	Southern Africa	1-8 (4)	No Data
	Japan	1-17 (2)	1-17 (1)
	Oceania	1-12 (3)	No Data
	South Asia	No Data	No Data
	South America	2-21 (4)	1-16 (4)
	Europe	1-29 (1)	1-34 (13)
USA West Coast	Southern Africa	1-4 (1)	No Data
	Japan	1-27 (5)	2-27 (10)
	Oceania	1-17 (2)	No Data
	South Asia	1-16 (4)	No Data
	South America	1-16 (6)	1-8 (1)
	Europe	1-21 (5)	1-23 (4)

The elevation-angle distributions are based on statistical figures for various levels of solar activity over an entire solar cycle, and for various times and months. These distributions assume undisturbed geomagnetic conditions. There is anecdotal evidence that the prevailing elevation angles go higher during disturbed conditions. You will note that there is no statistical information for 160 meters, mainly because *IONCAP* and its derivatives do not explicitly take into account the Earth's magnetic field, which is crucially important on Top Band.

Because of the use of isotropic radiators in *IONCAP*, the range of elevation angles is limited only by the all the propagation "possibilities" and *not* by the antenna used at either the transmitting or receiving site. In other words, the charts assume a hypothetical antenna transmits and receives equally well at a 1º wave angle as it does at 10º, 20º or 30º angles. An isotropic antenna, of course, does not actually exist, although

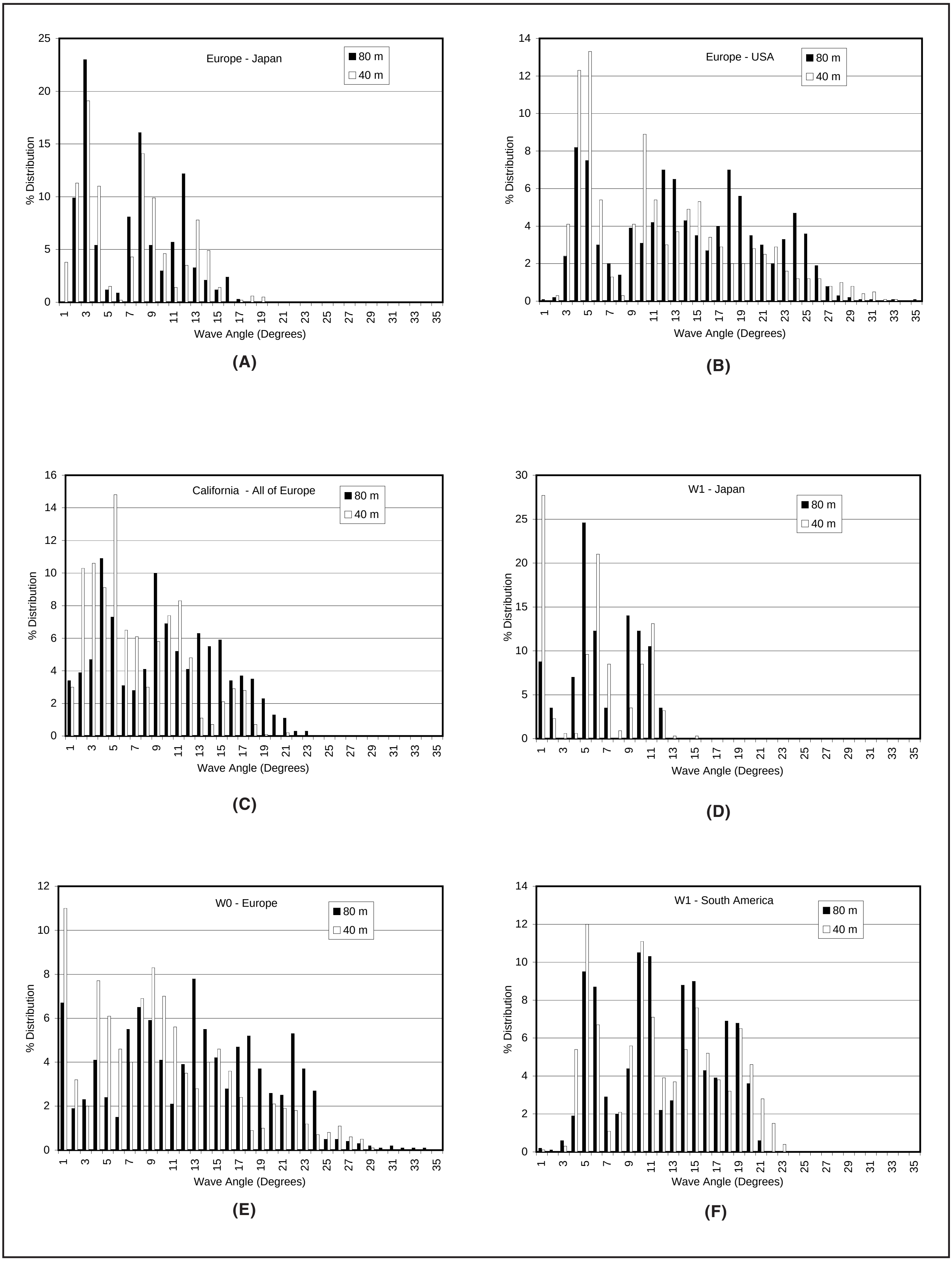


Fig 5-1—Distribution of wave angles (elevation angles) for a few common paths on 80 and 40 meters. Notice that the distribution is not a Gaussian one. This is because many mechanisms are involved that are totally unrelated.

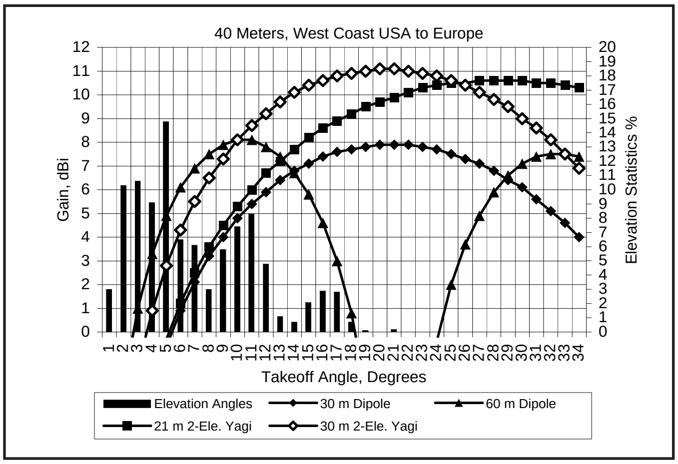


Fig 5-2—The statistical distribution of elevation angles for the 40-meter path from Europe to the US West Coast (San Francisco), compared with the elevation responses for horizontally polarized antennas at several heights over flat ground.

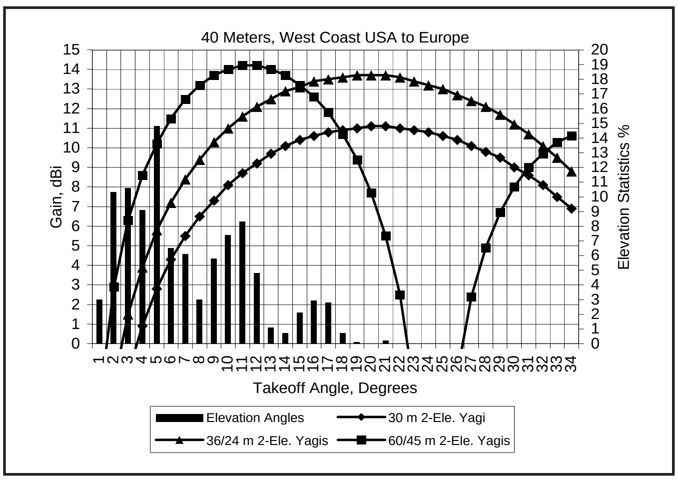


Fig 5-3—A comparison of the elevation responses versus elevation-angle statistics for the same path as Fig 5-2, but for more ambitious antennas mounted over flat ground. At very low angles (2° to 4°), you gain approximately 8 dB going from a single 30-meter high 2-element Yagi to a very high stack of identical Yagis at 60 and 45 meters. Ambitious, indeed!

a vertical over salt water or a high horizontal antenna over a sloping terrain can approach such performance.

1.1.1.3. 40 Meters

Now that we know the range of angles we need to cover, let's have a look at how we could do this. Wave angles of 1º to 20º (except for the path from the US East Coast to Europe, where the range extends to 30º) seem to be most common on 40 meters. Let's analyze how we might achieve this range over *flat terrain*. We'll take a look at three common types of antennas: A dipole, a 2-element Yagi and a λ/4 vertical over average ground.

To work at the lower angles, you need an impressively high horizontal antenna to match the wave angle distribution. In **Fig 5-2**, only the 60-meter high dipole comes relatively close to matching the statistics for the path from the US West

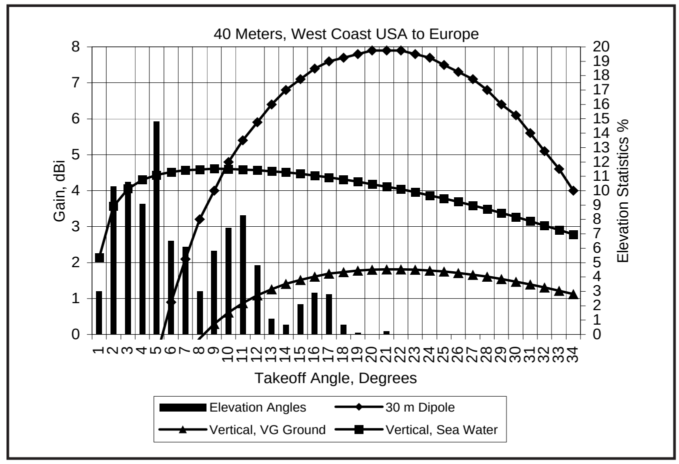


Fig 5-4—A comparison of horizontal versus vertical antennas for the 40-meter path from Europe to the US West Coast. At very low angles (less than about 10°) a quarter-wave vertical over saltwater would have a decided advantage over a horizontal dipole that is 30 meters high over flat ground. A quarter-wave vertical mounted over "very good" ground (typical of farmland in Belgium) would be stronger than the 30-meter high dipole at elevation angles below about 4°.

Coast to all of Europe on 40 meters. **Fig 5-3** shows even better matches, but look at the heights involved. The stack of 2-element Yagis at 45 and 60 meters is at least 12 dB better than our 30-meter high dipole for wave angles of 5º and less!

What about verticals? **Fig 5-4** shows a single quarter-wave vertical, over very good ground (such as at ON4UN) with 100 λ/4 radials. This is still a poor match to the wave-angle distribution. Now, place that same vertical over salt water and see what happens. An almost perfect match results, even better than the stack of 2-element Yagis at 45 and 60 meters!

1.1.1.4. 80 Meters

Let's have a look at 80 meters. From Table 5-1 and Fig 5-1 you can see there is little difference in the overall range of elevation angles between 40 and 80 meters. Let us analyze the US East Coast to Europe path, where elevation angles extend up to approximately 35º on 80 meters.

The horizontal dipoles in **Fig 5-5** are relatively poor performers for this range of elevation angles, even for antennas at a height of 45 meters! Only a giant 2-element 80-meter Yagi at that height covers the low wave angles reasonably well down to about 5º. On this band verticals fare much better than on 40 meters (**Fig 5-6**). The single vertical over very good ground is better than the horizontal dipole at 24 meters, and covers the elevation angles almost as well as the 2-element Yagi at 45 meters. The λ/4 vertical over salt-water is unbeatable!

1.1.1.5. 160 meters

On Top Band most of us have the choice between an antenna that shoots straight up (a horizontal dipole or inverted-V dipole even at 30 meters in height will produce a 90° takeoff angle), and a vertical (it may be shortened or in the form of an inverted-L or T-antenna) that produces a good low radiation angle (20° to 40° depending on the ground quality). This means we have little chance to experience the differences in signal strength between different radiation angles. The

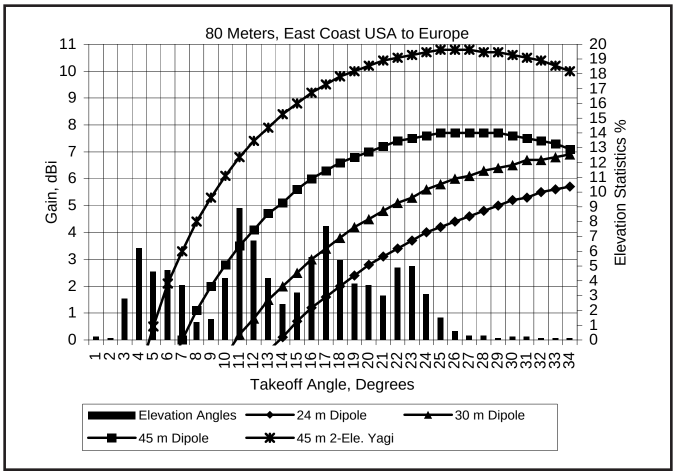


Fig 5-5— A comparison of the elevation responses versus elevation-angle statistics for the 80-meter path from Washington, DC, on the US East Coast, to Europe. Note the response for a gigantic 2-element 80-meter Yagi at 45 meters, a truly heroic antenna!

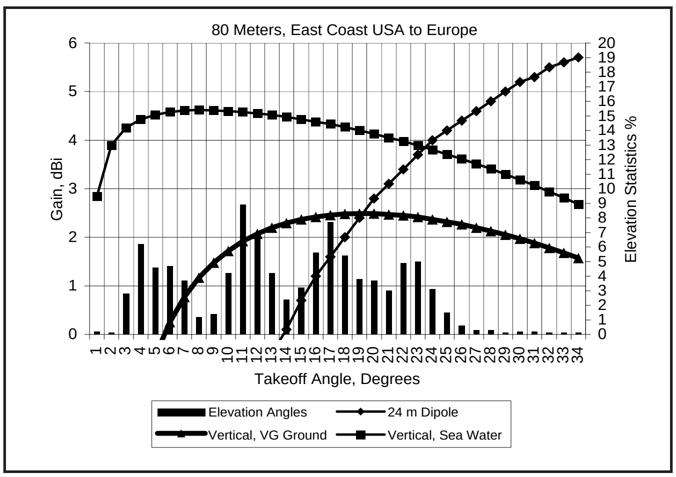


Fig 5-6—A comparison of horizontal and vertical antennas on 80 meters from the US East Coast to Europe. A quarter-wave vertical over saltwater is virtually unbeatable for angles lower than about 20°.

antenna with a low wave angle would be the best in maybe 99% of the cases. Again, there are (even more than on 80 meters) exceptional cases where a high radiation angle is required to launch into a ducting mechanism, which around sunset or sunrise can produce much stronger signals than can be achieved using a low wave-angle antenna at these times.

Even if you have a very high horizontally polarized antenna (as does Tom, W8JI, with his 100-meter high inverted V), this does not mean it will perform as well as a vertical on 160 meters. The reason for that is explained in Chapter 1 (Section 3.4 and 3.5). Tom confirms that his very high dipole almost never equals his 4-square array, which uses quarter-wave verticals. The suspected mechanism only applies to 160 meters, because of the proximity of 1.8 MHz to the electron gyro frequency.

1.1.1.6. Conclusion, elevation angles

For 40 and 80 meters we have elevation-angle statistics generated using a mathematical model, based on long-term observed propagation data. The wave angles are averages over many sunspot cycles, throughout the different seasons of the years and throughout the night (darkness path). Looking at the California-to-Europe angle distribution on 80 meters, we see that there is 3% chance that the angle is 1º and 1% chance as well that the angle is 20º. But what will the exact wave angle be tonight? The models give us good insight on the range of what is possible. They do not tell us anything about "when" a particular angle will occur. Fortunately our real-life antennas are not radiating at just one wave angle, but rather over a range of angles. The trick is to have an antenna or antennas where the range of actual radiating angles matches the range of statistically available wave angles as closely as possible. That way you cover all the possibilities.

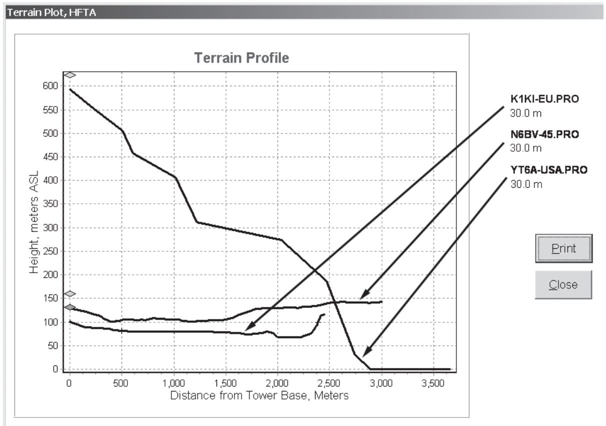
What we also learn from the model is that propagation angles above 35º are rarely present on 40 and 80 meters under normal geomagnetic conditions, and that there is usually some sort of mechanism that supports propagation at very low wave angles. Does this come as a surprise? No. We all have heard, time after time, that vertical antennas on the beach radiating over salt water produce astonishingly strong signals on the low bands (Ref 183). There is also a lot of evidence about high-angle propagation near sunrise/sunset, where a high wave angle appears to be required to initiate ducting (see Chapter 1). Such "anomalies," which are by definition of short duration, are not included in the statistical data on which *IONCAP* and *VOACAP* are based.

1.1.2. The influence of sloping terrain

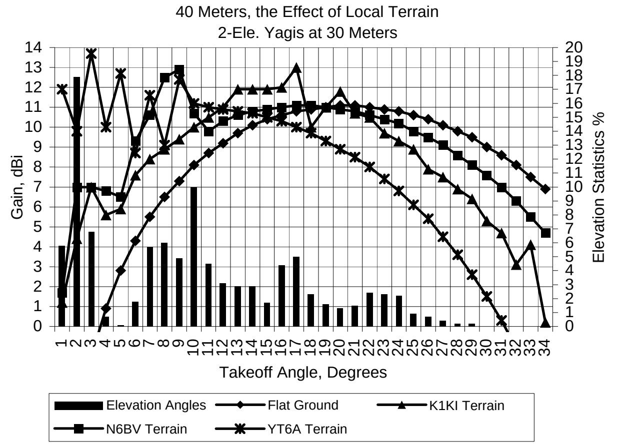
Where I live in Belgium, it's really, really flat. About 65 km from the coast, my QTH is 30 meters above sea level. It's flat as a pancake! But many low-band DXers live in hill country or even on mountaintops. It's not only saltwater locations that can do wonders—A mountaintop with the right slope and the right type of terrain pattern in the far field can also work wonders. In the mid 1980s I wrote a simple software program that could evaluate simple sloping terrains. That program is still part of the YAGI DESIGN SOFTWARE (see Chapter 4). Years later K6STI developed *TA* (Terrain Analysis) and N6BV developed *YT* (Yagi Terrain analysis) that ray trace over complex terrain using diffraction methods. The 20th Edition of *The ARRL Antenna Book* (Ref 697) now includes a full-blown Windows program called *HFTA* (High Frequency Terrain Analysis) by N6BV.

Let's have a look at some 40 and 80-meter antennas on "hilly terrains." **Fig 5-7A** shows the terrain for several prominent contest and DX stations. K1KI's QTH in Connecticut has a gentle slope that drops about 12 meters over the first 300 meters distance from the tower towards Europe. The impact of this downslope is nevertheless quite substantial and low takeoff angles are covered much better than over flat terrain, as shown in Fig 5-7B.

When he was in New Hampshire, N6BV's terrain sloped down 20 meters in the first 300 meters from the tower base and this too yielded a good improvement at low angles. The third example is the spectacular mountaintop QTH of YT6A, which features a very steep slope of almost 600 meters all the way down to the sea, some 2800 meters from his tower. The low-angle fill-in is quite spectacular! Ranko can hear signals arriving at 1º some 3 or 4 S units better than I can from my flat-terrain QTH.



(A)



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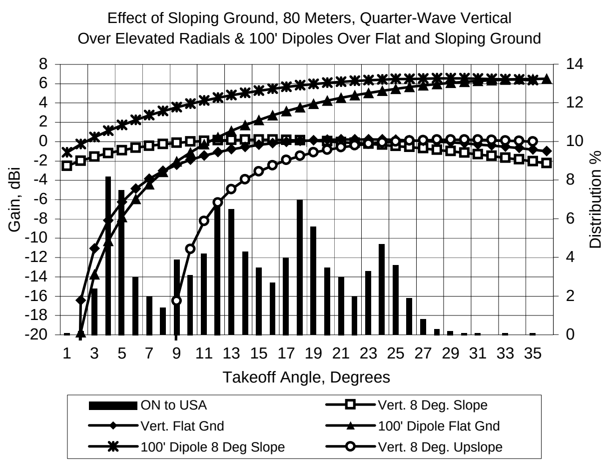

(C)

Fig 5-7—At A, the Terrain Profiles from ARRL's *HFTA* (HF Terrain Assessment) program for several contesting stations. The drop-off from YT6A's mountain-top QTH is breathtaking! At B, the elevation responses for each of these three QTHs for a horizontally polarized 2-element Yagi at a height of 30 meters. For reference, the response for the same antenna over flat ground is shown also. At C, elevation responses for quarter-wave verticals and horizontal dipoles over flat and sloping ground (downwards, and upwards for a vertical antenna at 8°) on 80 meters.

Fig 5-7C compares quarter-wave verticals with horizontal dipoles on 80 meters. In each case the terrain is either flat ground or ground with an 8º downslope, which is close to the YT6A terrain. A downslope in the direction of interest can materially aid low elevation angles for verticals as well as horizontals. One trace in Fig 5-7C is for a vertical antenna with ground sloping upwards at 8°, effectively blocking really low takeoff angles.

If you do live in a hilly country, you really should use terrain-modeling software to see the effects that real-world terrain has on the launch of HF signals into the ionosphere. You will have to make terrain data files for your particular QTH for all directions of interest. You can do this manually: Buy a detailed paper topographic map and note the terrain height at intervals (usually corresponding to the height contours on the topo map) along the direction of interest. You can also use *MicroDEM* (**www.nadn.navy.mil/Users/oceano/pguth/website/microdem.htm**), a sophisticated mapping and terrain-profiling program from the US Naval Academy. *MicroDEM* is supplied on the CD-ROM that comes with the 20th Edition of *The ARRL Antenna Book*. For the USA you can get the required electronic topographic maps from the USGS (US Geologic Survey) at **seamless.usgs.gov/**. All details can be found in the exhaustive manual that comes with the *HFTA* software program.

HFTA only models terrains for horizontally polarized antennas (for dipoles and 2 to 8-element Yagis). If you want to include a vertical over flat ground, you can model it (for example, with *EZNEC*). This is how the vertical patterns in Figs 5-4 and 5-6 were made.

1.2. Receiving Antennas

For a receiving antenna, the requirements are very different on the lower bands (80 and 160 meters). We expect the antenna to receive only signals from a given direction and at a given wave angle (directivity), and we expect the antenna to produce signals that are substantially stronger than the internally generated noise of the receiver, taking into account losses in matching networks and feeders. This means that the efficiency (see Section 2.5) of a receiving antenna is really not a requirement. The important asset of a good receiving antenna system is its *directivity*—the ability to be aimed in desired directions and to be switched in different directions rapidly. The ability to direct a null in a particular direction is often crucial.

In most amateur applications on the higher bands the transmitting antenna is used as the receiving antenna, and the transmitting requirements of the antenna outweigh typical receiving requirements. On the low bands, however, successful DXers most often use specialized receiving antennas, as we will see in Chapter 7 on Special Receiving Antennas. This is because most hams cannot build very directive (and efficient) transmit antennas, which are very large. It is possible, however, to build very effective directive receiving antennas that have poor efficiency, making them unsuitable for transmitting.

2. DEFINITIONS

2.1. The Isotropic Antenna

An *isotropic* antenna is a theoretical antenna of infinitely small dimensions that radiates equally well in all directions. This concept can be illustrated by a tiny light bulb placed in the center of a large sphere (see **Fig 5-8).** The lamp illuminates

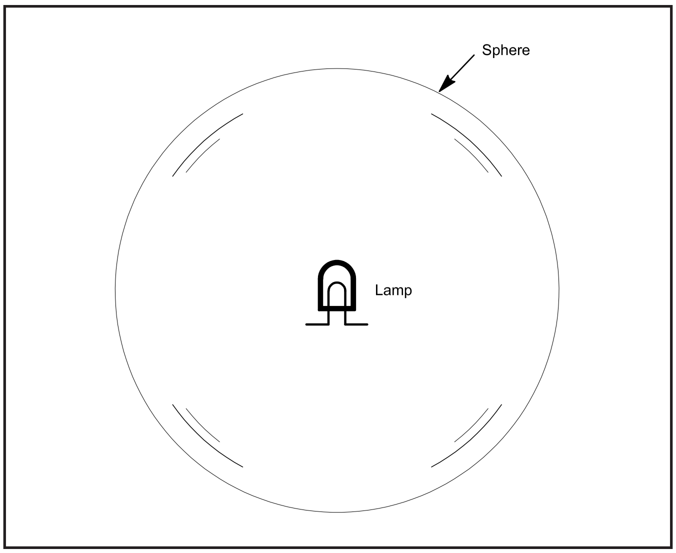

Fig 5-8—In this drawing the isotropic antenna is simulated by a small lamp in the center of a large sphere. The lamp illuminates the sphere equally well at all points.

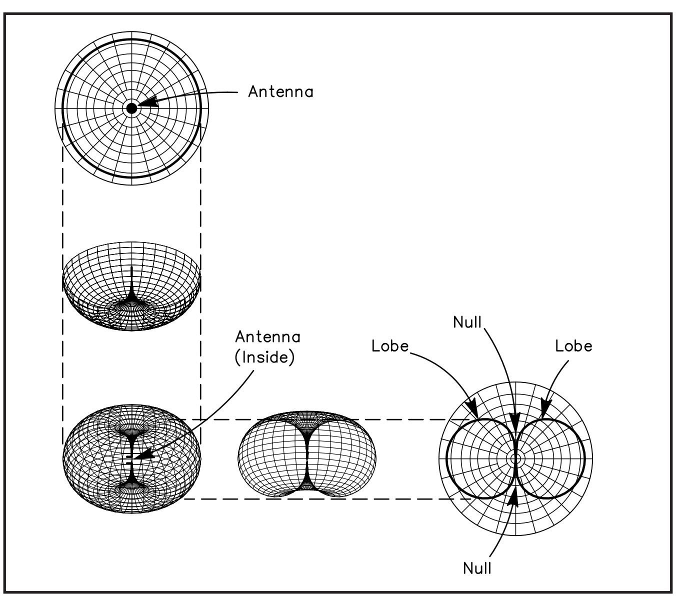

Fig 5-9—Vertical (left) and horizontal (right) radiation patterns as developed from the three-dimensional pattern of a horizontal dipole.

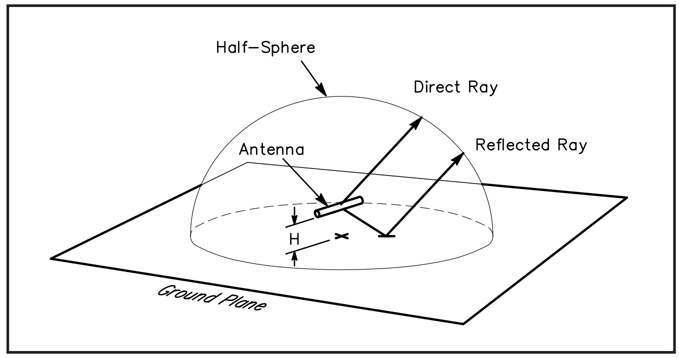

Fig 5-10—The effect of ground is simulated in a sphere by putting a plate (the reflecting ground plane) through the center of the sphere. Since the power in the antenna is now radiated in half the sphere's volume, the total radiated field in the half sphere is doubled. The ground reflection can add up to 6 dB of signal increase compared to free space. A smaller total gain is caused in practice, since part of the RF energy is absorbed in the poorly reflecting, lossy ground.

the interior of the sphere equally at all points. The isotropic antenna is often used as a reference antenna for gain comparison, expressed in decibels over isotropic (dBi). The radiation pattern of an isotropic antenna is a sphere, by definition. A dBi is no more and no less than a convenient abbreviation for power per unit area over the volume of a sphere.

2.2. Antennas in Free Space

Free space is a condition where no ground or any other conductor interacts with the radiation from the antenna. In practice, such conditions are approached only at VHF and UHF, where very high antennas (in wavelengths) are common. Also every real-life antenna has some degree of directivity. If is placed in the center of a large sphere, it will illuminate certain portions better than others. In antenna terms, the antenna radiates energy better in certain directions. A half-wave dipole has maximum radiation at right angles to the wire and minimum radiation off the ends. A half-wave dipole, in free space, has a gain of 2.15 dB over isotropic (2.15 dBi).

Radiation patterns are collections of all points in a given plane, having equal field strength. **Fig 5-9** shows the radiation pattern of a dipole in free space, as seen three dimensions and in two planes, the plane through the wire and the plane perpendicular to the wire.

2.3. Antennas over Ground

In real life, antennas are near the ground. We can best visualize this situation by cutting the sphere in Fig 5-8 in half, with a metal plate going through the center of the sphere. This plate represents the ground, a perfect electrical mirror. **Fig 5-10** shows what happens with an antenna near the ground: Direct and reflected waves combine and illuminate the sphere unequally at different points at different angles. For certain angles the direct and reflected waves are in phase and reinforce one another. The field is doubled, which means a power gain of 3 dB. In addition, we have only a half sphere to illuminate with the same power, and that provides another 3 dB of gain. This means that a dipole over perfect ground will have 6 dB of gain over a dipole in free space.

Over ground, radiation patterns are often identified as vertical (cutting plane perpendicular to the ground) or horizontal (cutting plane parallel to the ground). The latter is of very little use, since practical antennas over real ground produce no signal at a 0º wave angle. The so-called horizontal directivity should in all practical cases be specified as directivity in a plane making a given angle with the horizon, usually at the main takeoff angle.

Low-band antennas always involve real ground. With real ground, the above-mentioned gain of 6 dB will be lowered, since part of the RF is dissipated in the lossy ground. For evaluation purposes, we often specify *perfect ground*, a ground consisting of an infinitely large, perfect reflector.

Real grounds have varying properties, in both conductivity and dielectric constant. In this book, frequent reference will be made to different qualities of real grounds, as shown in **Table 5-2**.

2.4. Radiation Resistance

Radiation resistance (referred to a certain point in an antenna system) is the resistance, which if inserted at that point, would dissipate the same energy as is actually radiated from the antenna. In other words, radiation resistance is the total power radiated as electromagnetic radiation divided by the square of the current at some defined point in the system. This definition does not state where the antenna is being fed, however. There are two common ways of specifying radiation resistance:

- The antenna is fed at the current maximum: $R_{rad\ (I)}$
- The antenna is fed at the base, between the antenna lower end and ground: $R_{rad\ (B)}$

$R_{rad\ (I)} = R_{rad\ (B)}$ for verticals of $^1/_2$ wavelength or shorter. $R_{rad\ (B)}$ is the radiation resistance used in all efficiency calculations for vertical antennas. Fig 9-10 in Chapter 9 shows the radiation resistance according to both definitions for four types of vertical antennas:

- A short vertical (< 90º high)
- A quarter-wave vertical
- A $^3/_8$- wave vertical (135º high)
- A $^1/_2$-wave vertical

Radiation resistance is not the same as the feed-point impedance, since feed-point impedance consists of both radiation resistance and loss resistances, plus any reactance at the feed point.

2.5. Antenna Efficiency

The *antenna efficiency* of an antenna by itself located in free space is simply the ratio of power radiated from that antenna to the power applied to it. Any energy that is not radiated will be converted into heat in the lossy parts of the antenna. For a transmitting antenna, radiation efficiency is an important parameter. The efficiency of an antenna is expressed as follows:

$$\text{Efficiency} = R_{rad} / (R_{rad\ (B)} + R_{loss}) \qquad \text{(Eq 1)}$$

where $R_{rad\ (B)}$ is the radiation resistance of the antenna as defined in Section 2.4, and R_{loss} is the total equivalent loss resistance of all elements of the antenna (resistance losses, dielectric losses, loading coils, etc). Loss resistance is normalized to the same point where R_{rad} was defined.

The *total efficiency* of an antenna setup is a rather different story. While antenna efficiency only considers the lossy parts of the antenna itself, total efficiency includes losses in its environment, including the ground. In other words, total efficiency takes into account all losses in the near field as well as in the far field (see Sections 2.6, 2.7 and 2.8).

2.6. Near Field

Depending on the physical dimension of the antenna the *radiating near field* (also called the *Fresnel* field) reaches out typically one or two wavelengths from simple wire antennas to many wavelengths in the case of long-boom Yagis on VHF and UHF. The relationship between magnetic and electric fields is a complex one in the near field. This is one of the reasons that we must not make antenna pattern measurements too close to the antenna. Antennas field-strength measurements should be done no less than a few wavelengths from the antenna.

Table 5-2
Conductivities and Dielectric Constants for Common Types of Earth

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

With low-band antennas the ground will always be in the near field of our antennas, and losses in the near field will have to be considered. These losses will be discussed in detail in Chapter 9.

2.7. Induction Field

The *reactive near field* or *induction field* is a part of the near field, very close to the antenna where mutual coupling exists between conductors. This happens typically within a maximum of 0.5 wavelengths around the antenna.

2.8. Far Field

The *radiating far field* (or *Fraunhöfer* field) is the area around the antenna beyond the near field. This is where ground reflections for low-angle signals occur, which greatly interest us low-band operators. In the far field the power density is inversely proportional to the square of the distance from the antenna. Total energy is equally divided between electric and magnetic fields, and the relation is defined by: $E/H = Z_0 = 377\ \Omega$, the free-space impedance. See Chapter 9 for further discussion of far-field reflection losses.

2.9. Antenna Gain

The *gain* of an antenna is a measure of its ability to concentrate radiated energy in a desired direction (minus any losses in the antenna). Antenna gain is expressed in decibels, abbreviated dB. It tells us how much the antenna in question is better than a reference antenna, under defined circumstances. And that's where we enter the antenna-gain "jungle." Commonly, both the theoretical isotropic, as well as a real-world dipole, are used as reference antennas. In the former case the gain is expressed as dBi and in the latter as dBd.

But that's only part of the story. We can do a comparison in free space, or over perfect ground or over real ground. The only situation that makes a generic comparison possible is to compare antennas in free space. Gain in dBi in free space is what can always be compared; there is no inflation of gain figures by reflection. Very often manufacturers of commercial antennas will calculate gains including ground reflections—and often they will not mention this fact.

You might argue, "Why not use a real antenna, such as a dipole, as a reference, since the isotropic antenna is a theoretical antenna that does not exist, while a half-wave dipole does?" Comparing gains is really comparing the field strength of an antenna under investigation with that of our reference antenna. With an isotropic antenna the situation is clear. It radiates equally well in all directions and the three-dimensional radiation pattern is a sphere. What about the dipole as a reference? The gain of a half-wave, lossless half-wave dipole in free space over an isotropic is 2.15 dBi. But that does not mean that a real dipole has a gain of 2.15 dBi. It only means that the gain of a lossless dipole in free space (that's a theoretical condition as well, because nothing is really in free space) is 2.15 dB over an isotropic radiator. If we put the dipole over a perfect ground, it suddenly shows a gain of 8.15 dBi! You pick up 6 dB by radiating the power in half a hemisphere instead of a whole hemisphere, as in the theoretical case of free space. With less-than-perfect ground, part of the power will be absorbed in the ground and the ground-reflection gain will be less than 6 dB. It is clear that the only generic way of comparing antenna gains is in dBi, using an isotropic antenna as the only generic reference antenna not influenced by height or ground conditions. In this publication we will always quote gain figures in dBi—that is, referenced to an isotropic antenna in free space. (Ref 688).

2.10. Front-to-Back Ratio

Being a ratio (just like gain), we would expect front-to-back ratio to be expressed in decibels, which it is. The front-to-back ratio (F/B) is a measure expressing an antenna's ability to radiate a minimum of energy in the direction directly in the back of the antenna.

Free-space front-to-back ratio is always measured at a 0º wave angle. Over ground the F/B depends on the vertical radiation angle being considered. In most cases a horizontal radiation pattern over real ground is not really the pattern in the horizontal plane, but in a plane that corresponds to the main wave angle. If we look at the back lobe at that angle, it may be okay, but at the same time there may be a significant back lobe at a much different angle.

With the advent and the widespread use of modeling programs, especially some of the optimizer programs, the rat race started for the most ludicrous F/B figure. Let's not forget that mathematics is one thing, while antenna physics is another thing. It is possible to calculate an antenna exhibiting a F/B of 70 dB in a given direction, at a given wave angle. But that's all there is to it. One degree away the rejection may be down 40 or 50 dB. When you understand the physics behind all of this, it will be clear that F/B above a certain level (maybe 35 dB) is rather meaningless.

2.10.1 Geometric front-to-back ratio

In the past, front-to-back ratios were usually defined in the sense of a geometric front-to-back—the radiation 180º directly behind the front (0º lobe) of the antenna. We thus compare the "forward" power at the main forward radiation angle to the "backward" power radiated at the same wave angle in the backward direction.

The pattern of an antenna discriminates against unwanted signals coming from directions other than the front of the antenna. It is very unlikely that unwanted signals will be generated exactly 180º off the beam direction or at a radiation angle that is the same as the main forward lobe's radiation angle. Therefore, geometric F/B can be ruled out immediately as a meaningful way of defining the antenna's ability to discriminate against unwanted signals.

2.10.2 Average front-to-back (integrated front-to-back) ratio

The *average front-to-back ratio* can be defined as the average value of the front-to-back as measured (or computed) over a given back angle (both in the horizontal as well as the vertical plane). In the chapter on special receiving antennas (Chapter 7, Section 1.8 and 1.9) I use this concept for evaluating different antennas.

2.10.3. Worst-case front-to-rear ratio (F/R)

Another meaningful way to quantify the F/B ratio of an antenna is to measure the ratio of the forward power to the power in the "worst" lobe in the entire back of the antenna (from 90º to 270º azimuth). This is the standard used for example in *The ARRL Antenna Book* for Yagis and quads.

2.10.4. Front-to-back ratio and gain

Is there a link between gain and the front-to-back ratio of an antenna? Let's visualize a three-dimensional radiation pattern of a simple Yagi. The front lobe resembles a long stretched pear, while the back lobe (let's assume for the time we have a single back lobe) is a much smaller pear. The antenna sits where the stems of the two pears touch. The volume of the two pears (the total volume of the three-dimensional radiation pattern) is determined only by the power fed to the antenna. If you increase the power, the volume of the large as well as the small pear will increase in the same proportion. Let's take for definition of front-to-back ratio the ratio of the power radiated in the back versus the power radiated in the front. This means that the F/B ratio is proportional to the ratio of the volume of the two pears.

By changing the design of the Yagi (by changing element lengths or element positions), we change the size and the shape of the two pears. But so long as we feed the same power to it, the sum of the volumes of the two pears remains unchanged. It's as if the two pear-shaped bodies are connected with a tube, and are filled with a liquid. By changing the design of the antenna, we merely push liquid from one pear into the other. If the antenna were isotropic, the radiation body would be a sphere having the volume of the sum of the two pears.

Assume we have 100 W of power with 10% of this power applied to the antenna in the back-lobe. The F/B will be 10 × log (10 / 1) = 10 dB. Ninety percent of the applied power is available to produce the forward lobe.

Let's take a second case, where only 0.1% of the applied power is in the back lobe. The F/B ratio will be 10 × log (100 / 0.1) = 30 dB. Now we have 99.9% of the power available in the front lobe.

The antenna gain realized by having 99.9 watts instead of 90 watts in the forward lobe is 10 × log (99.9 / 90) = 0.45 dB. Pruning an antenna with a modest F/B pattern (10 dB) to an exceptional 30-dB value, gives us 0.45 dB more forward gain, provided that the extra liquid is used to lengthen the cone of the big pear.

The mechanism for obtaining gain and F/B is much more complicated than that described above. I am only trying to explain that optimizing an antenna for F/B does not necessarily mean that it will be optimized for gain. What is always true, however, is that a high-gain antenna will have a narrow forward lobe. You cannot concentrate energy in one direction without taking it away from other directions! We will see later that maximum-gain Yagis show a narrow forward lobe, but often a poor front-to-back ratio. This is the case with very high-Q, gain-optimized 3-element Yagis, for example.

Conclusion: There is no simple relationship between front-to-back ratio and gain of an antenna.

2.10.5. The importance of directivity

Directivity can be important for two very different reasons: With *transmit antennas* we want to have directivity because directivity is invariably linked to gain. What you take away in certain directions is added in other directions. We want gain because we want to be heard (to be strong), and that also implies the notion of efficiency.

With *receiving antennas* the story is different. We want to hear well above the noise (manmade, atmospherics, QRM, etc). The issue is one of signal-to-noise ratio, not just signal strength. While antenna efficiency is a secondary issue with receiving antennas, directivity is primary. That's why the concept of quantifying the directivity of an antenna was developed.

2.11. Directivity Merit Figure and Directivity Factor

For a receiving antenna directivity is the main concern. The average front-to-back (the peak forward lobe versus what happens in the back 180º degrees over the entire elevation angle range) gives a good indication of directivity. I used it in the Third Edition of this book to quantify some of the special receiving antennas in Chapter 7. I call the difference between the forward gain (at the desired wave angle, such as 20º) and the average gain in the back of the antenna, the *Directivity Merit Figure* (see Chapter 7, Section 1.10).

Tom, W8JI, (**www.w8ji.com/**) goes a step further and compares the forward-lobe gain to the average gain of the antenna in all directions (both azimuth and elevation). This figure does tells you not only how good the average front-to-back ratio is, but also how narrow your forward (wanted) lobe is (see Chapter 7, Section 1.11 on Special receiving antennas for more details). His merit figure is called *RDF* (Receiving Directivity Factor).

2.12. Standing-Wave Ratio

SWR is *not* a performance measure of an antenna! SWR is only a measure of how well the feed-point impedance of the antenna is matched to the characteristic impedance of the feed line. If a 50-Ω feed line is terminated in a 50-Ω load, then the impedance at any point on any length of the cable is 50 Ω.

If the same feed line is terminated in an impedance different from 50 Ω, the impedance will vary along the line. The SWR is a measure of the match between the line and the load. Changing the length of a feed line does not change the SWR on the line (apart from minute changes due to feed-line loss with longer lengths of line). What changes is the impedance at the input end of the line.

If changing the line length slightly changes the SWR reading on your SWR meter, then your SWR meter is not measuring correctly (many SWR meters fall into this category) or else you have stray common-mode current flowing on the shield of your feed line. A good test for an SWR meter is to insert short cable lengths between the end of the antenna feed line and the SWR meter (a few feet at a time). If the SWR reading changes significantly, don't expect correct SWR values.

If there are stray currents on the outside of the coaxial cable shield, a change in position on the line can indeed change the SWR reading (see Chapter 6). That's why we use a *balun* (*bal*anced-to-*un*balanced transformer) when feeding balanced feed points with a coaxial cable. In fact, current baluns (choke baluns) are a good idea to install on any coaxial feed line. You can insert a current balun (eg, a short length of coax equipped with a stack of 50 to 100 ferrite cores) at the SWR meter. If this balun changes the SWR value, RF currents are flowing on the outside of the coaxial cable.

Changing the feed-line length doesn't change the performance of the antenna. A feed line is an element that is *not* supposed to radiate. SWR on a feed line has no relation whatsoever to the radiation characteristics of an antenna. A perfect match between the line and the antenna results in a 1:1 SWR. What are the reasons we like a 1:1 SWR or the lowest possible SWR value?

- Showing a convenient 50-Ω impedance: Unless we want to use a transmission line as an impedance transformer, we would like all feed lines to show a 1:1 SWR. This would present the design load impedance of 50 Ω for solid-state transceivers.
- Minimizing losses: All feed lines have inherent losses. This loss is minimal when the feed line is operated as a flat line (SWR = 1:1) and increases when the SWR rises. On the low bands this will seldom be a criterion for desiring a very low SWR, because the nominal losses on the low frequencies are quite negligible, unless very long lengths are used.

For many hams, SWR is the only property they can measure. Measuring gain and F/B with any degree of accuracy is beyond the capability of most. That is why most hams pay attention only to SWR properties. The amount of SWR that can be tolerated on a line depends on:

- Additional loss caused by SWR—determined by the quality of the feed line. A high quality feed line can tolerate more SWR from an additional-loss point of view than a mediocre quality line.
- How much SWR the transceiver or linear amplifier can live with.
- How much power we will run into a line of given physical dimensions (for a given power, a larger coax will withstand a higher SWR without damage than a smaller one).

It must be said that a poor-quality line (a small-diameter cable with high intrinsic losses), when terminated in a load different from its characteristic impedance, will show at its input end a lower SWR value than if a good (low-loss, large-diameter) cable is used. Remember that a very long, poor (having high losses) coaxial cable (whether terminated, open or shorted at the end) will exhibit a 1:1 SWR at the input (a perfect dummy load) because of those losses.

From a practical point of view an SWR limit of 2:1 is usually sought after. From a loss point of view, it is clear that higher values can easily be tolerated on the low bands. Coaxial feed lines used in the feed systems of multi-element low-band arrays sometimes work with an SWR of 10:1!

You can always use an antenna tuner if the SWR is higher than the transceiver or the amplifier needs to work into (usually less than 2:1). Remember that the antenna tuner will not change the SWR on the line itself; it will merely transform the impedance existing at the line input and present the transceiver (linear) with a reasonable and more convenient SWR value. While this approach is valid on the low bands, I strongly suggest not using it on the higher frequencies, since the additional line losses caused by the SWR can become quite significant.

2.13. Bandwidth

The *bandwidth* of an antenna is the difference between the highest and the lowest frequency on which a given property exceeds or meets a given performance mark. This can be gain, front-to-back ratio or SWR. In this book, "bandwidth" refers to SWR bandwidth, unless otherwise specified. In most cases the SWR bandwidth is determined by the 2:1 SWR points on the SWR curve. In this text the SWR limits will be specified when dealing with antenna bandwidths. Many amateurs only think of SWR bandwidth when the term bandwidth is used. In actual practice, the bandwidth can refer to other properties at least as important, if not more important. Consider a dummy load, which has an excellent SWR bandwidth, but a very poor gain figure, since it does not radiate at all!

Bandwidth is an important performance criterion on the low bands. The relative bandwidth of the low bands is large compared to the higher HF bands. Special attention must be given to all bandwidth aspects, not only SWR bandwidth.

2.14. Q-Factor

2.14.1. The tuned circuit equivalent

An antenna can be compared to a tuned LCR circuit. The *Q factor* of an antenna is a measure of the SWR bandwidth of an antenna. The Q factor is directly proportional to the difference in reactance on two frequencies around the frequency of analysis, and inversely proportional to the radiation resistance and relative frequency change.

$$Q = \frac{F_0 \times (X1 - X2)}{2 \times R \times \Delta F} \qquad \text{(Eq 2)}$$

where

X1 = reactance at the lower frequency
X2 = reactance at the higher frequency
R = average value of resistive part of feed-point imped ance at frequencies of analysis ($R_{rad} + R_{losses}$)
ΔF = relative frequency change between the higher and the lower frequency of analysis

Example:

F_{low} = 3.5 MHz

F_{high} = 3.6 MHz

F_0 = 3.55

ΔF = 3.6 – 3.5 = 0.1

$R_{feed\ (Ave)}$ = 50 Ω

X1 = –20 Ω

X2 = +20 Ω

$$Q = \frac{3.55 \times (20 - (-20))}{2 \times 50 \times 0.1} = 14.2$$

It is clear that a low Q can be obtained through:

- A high value of radiation resistance
- High loss resistance
- A flat reactance curve.

An antenna with a low Q will have a large SWR bandwidth, and an antenna with a high Q will have a narrow SWR bandwidth. Antenna Q factors are used mainly to compare the (SWR) bandwidth characteristics of antennas.

2.14.2. The transmission-line equivalent

A single-conductor antenna (vertical or dipole) with sinusoidal current distribution can be considered as a single-wire transmission line for which a number of calculations can be done, just as for a transmission line.

2.14.2.1 Surge Impedance

The characteristic impedance of the antenna seen as a transmission line is called the *surge impedance* of the antenna.

The surge impedance of a vertical is given by:

$$Z_{surge} = 60 \times \ln\left[\frac{4h}{d} - 1\right] \quad \text{(Eq 3)}$$

where

h = antenna height (length of equivalent transmission line)

d = antenna diameter (same units).

The surge impedance of a dipole is:

$$Z_{surge} = 276 \times \log\left[\frac{S}{d \times \sqrt{1 + \frac{S}{4h}}}\right] \quad \text{(Eq 4)}$$

where

S = length of antenna

d = diameter of antenna

h = height of antenna above ground.

2.14.2.2 Q-factor

The Q-factor of the transmission-line equivalent of the antenna is given by:

$$Q = \frac{Z_{surge}}{R_{rad} + R_{loss}} \quad \text{(Eq 5)}$$

Example 1:

A 20-meter (66-foot) vertical with OD = 5 cm (1.6 inches), and $R_{rad} + R_{loss}$ = 45 Ω.

$$Z_{surge} = 60 \times \ln\left[\frac{4 \times 2000}{5} - 1\right] = 443\,\Omega$$

Q = 443/45 = 9.8

Example 2:

A 40-meter (131-foot) long dipole, at 20 meters (66 feet) height is made of 2 mm OD wire (AWG 12). The feed-point impedance is 75 Ω.

$$Z_{surge} = 276 \times \log\left[\frac{4000}{0.2 \times \sqrt{1 + \frac{4000}{4 \times 2000}}}\right] = 1163\,\Omega$$

Q = 1163 / 75 = 16.