GROUND-MOUNTED
VERTICAL ANTENNAS

A little history and some theory

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Vertical antennas date from the beginnings of radio. They were ground mounted with the exception of one highly successful and innovative system, the "Zepp." Its origin seems to have been forgotten, and the Zepp name has come to mean something quite unrelated to the original. In the twenties, when Amateurs were herded into the spectrum above 1.5 MHz ("200 meters and below"), the Zepp proved both practical and useful as a horizontal antenna. The originals, though, were often several thousand feet in length. They hung straight down from the gondola of a Zeppelin (hence the name) — vertically, of course!

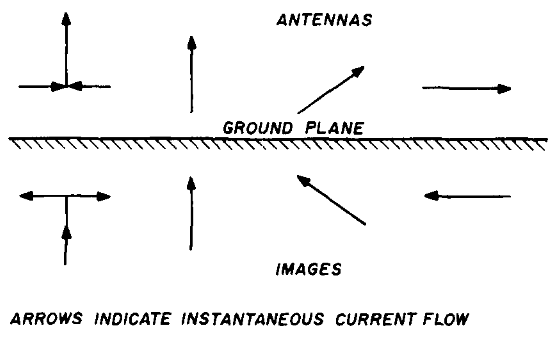
In those very early days, "spark" transmitters were used. They operated on enormous wavelengths (sometimes kilometers), and a number of them were run at many kilowatts with surprisingly high efficiencies — 80 percent was rather common. POZ, at Nauen, Germany operated at 150-kW output, 85-percent efficiency at the transmitter. Because of the extreme shortness of the antenna and the long wavelengths, antenna efficiency was probably less than 5 percent at most, resulting in an antenna current of over 1,000 amperes! There were also "arc" transmitters, and two different types of mechanically-generated radio frequency transmitters, but these appeared a decade or more later.[1]

Why vertical?

Vertical antennas were (and are) the only way to launch a low frequency radio field from a location on or near the ground. The techniques, practices, and experiences of earlier antenna pioneers are still germane today — especially when the subject is verticals. There's not much that's really new after all this time. Our instruments and some techniques have simply been upgraded.

There's a notable, fundamental difference between the behavior of verticals and horizontal antennas operated near ground. The "images" shown in **Figure 1** are in phase for the vertical, but they are opposing in the horizontal case.

FIGURE 1



Current filaments and their images over "perfect" ground.

Thus, while the vertical can be operated right on the ground, the horizontal can't because the image tends to cancel the antenna current. It would cancel completely if there were such a thing as "perfect earth." The perfect earth concept is used extensively for preliminary designs. Ground conditions, when known, aid in final designs.

Because the first transmitting antenna was made by Marconi (apologies to Tesla, Popov, and probably others who could have been first) the base-fed short vertical antenna is called (you guessed it) a "Marconi." It's defined as follows:

A Marconi is a current-fed antenna (usually vertical) whose overall length is a quarter-wave or less, and is loaded by various means so that it exhibits series (90 degree) resonance.

Those "various means" may include series inductors, capacitive top hats, or mixtures of both. Most of the early systems used a combination approach. There were two main reasons for this. The first was that erecting a quarter-wave high antenna for a wavelength of 5,000 meters was impossible then, and would be nearly so today. The second involves the "logarithmic decrement" of the antenna, about which there will be more later. Because it was related to the bandpass — those were *very* broad signals — it was of great importance to control (always to decrease) the value of the logarithmic decrement, hence the bandpass. In practical terms, this meant that inductance had to be added in order to decrease the log decrement, which was subject to government regulations. In 1919, the United States Department of Commerce limited the log decrement to 0.2 maximum.

Ever narrower bandpass

All spark transmitters functioned by the periodic discharging of a capacitor bank through a spark gap. The spark gap was either in series with an antenna which was the *only* frequency-determining element in the system (Marconi's early method), or coupled to a secondary circuit which contained the antenna and various resonating components — usually inductors. When a charge was delivered to either of these two basic types, the circuit plus antenna (or the antenna itself) would "ring," losing some of its energy with each cycle because of radiation and circuit losses. The decrease in amplitude was a constant fraction of the preceding cycle amplitude. That constant was the logarithmic decrement, and is related to what we now call the "Q" of an antenna — except that it is inverse. The larger the Q, the smaller the log decrement. The main factor controlling the log decrement was the amount of inductance in the system (as with Q, which is X_L/R), thus most of the early verticals were base loaded even though they had very large top hats. It was the only practical way to control the log decrement; the only place you could introduce inductance conveniently was at the base. The large (even by today's standards) top-loading capacitances were the smaller part of the total loading when the wavelength was several kilometers. Some of those early top-loading schemes resulted in 0.05-μF capacitance. The pioneers taught us something very important — how to construct base-loading inductors with an intrinsic Q of 5,000 or more. Such numbers are possible when the frequency is below, say, 100 kHz, where Litzendraht ("Litz") wire is practical. Litz wire loses its effectiveness above a few hundred kHz. Modern OMEGA antenna systems use Litz wire-loading coils; they are also combination base and top loaded.

An about-face

Nowadays we try to increase the bandwidth of a vertical, just to avoid having to retune when a rather large frequency shift is made. The signal bandwidth is *controlled by the modern design of both the transmitter and receiver.* It's a challenge to have a wide antenna bandwidth while maintaining high efficiency. It's especially difficult when the antenna is physically short, as is usually the case with vertical antennas for 80 and 160 meters. This is particularly true when they are placed over good ground systems.

We mentioned before that the antenna current for POZ was over 1,000 A (references exist which mention 1,200 A). Today, using more or less typical transmission line impedances of 50 or 75 ohms, a 1,000-A line current would represent 50 to 75 MW. But we know that the power was "only" 150 kW. Why the large current? Obviously, there were very low impedances involved. A characteristic of LF and VLF Marconi antennas is their low feedpoint impedances, given little ground loss. Their actual radiation resistances were extremely low, usually a fraction of an ohm. A resistance of 50 milliohms was rather common. That's because they were all physically very short.

How do we calculate radiation resistance?

The radiation resistance of a half-wave doublet constructed of "infinitely thin" wire (a necessity for the original derivation) is approximately 73.2 ohms.* That value has been known since the 1880s. Therefore, the radiation resistance of half a very thin doublet would be 36.6 ohms. This is the generally accepted value for a full length quarter-wave vertical antenna, unachievable though it is. We deal with values less than that because the length necessary for resonance is also a function of the length-to-diameter ratio of the element. The outcome is resonant lengths that are shorter than the equivalent "free space" lengths. The net result is an antenna that will always be of lower resistance than that achieved for the thin wire. **Figure 2** shows the manner in which it changes.[2]

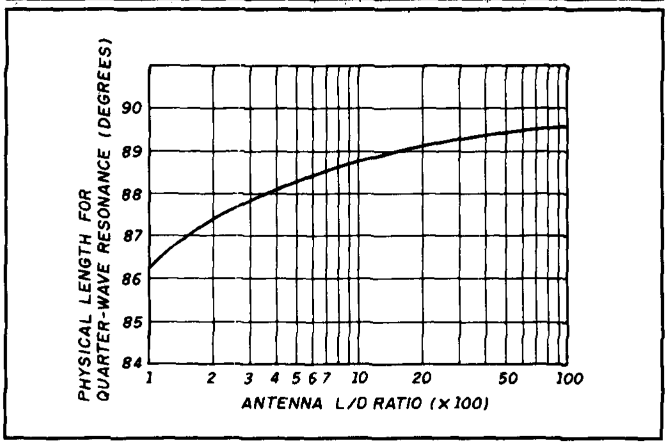
It has been difficult to determine the expected radiation resistances of variously loaded short verticals, although some complicated calculations do exist. Occasionally, a curve is published titled "Radiation Resistance of a Vertical Antenna versus Height," with no indication as to the form of antenna (or what length-to-diameter ratio) it relates to. It's usually presented on linear graph paper, though the function is a steep transcendental one which makes it hard to interpret at both ends of the curve. Typically it's been calculated for what we'll call the "base-loaded" case, and is of no use whatsoever for any other type of loading (like top, center, or combination).

Simple but workable derivations

Figures 3 through **6** illustrate methods for estimating the radiation resistances of various antennas with different forms of loading. Two of them were first presented in *Ham Radio* in 1983.[3] The derivation starts with one-half of the theoretically derived resistance of a free space half-wave dipole (36.6 ohms). If you assign 1 A as the value of the base current and assume that the current distributes itself sinusoidally, then the area of the profile will be 1 ampere-radian.

The rationale for the derivations is that by allowing for no

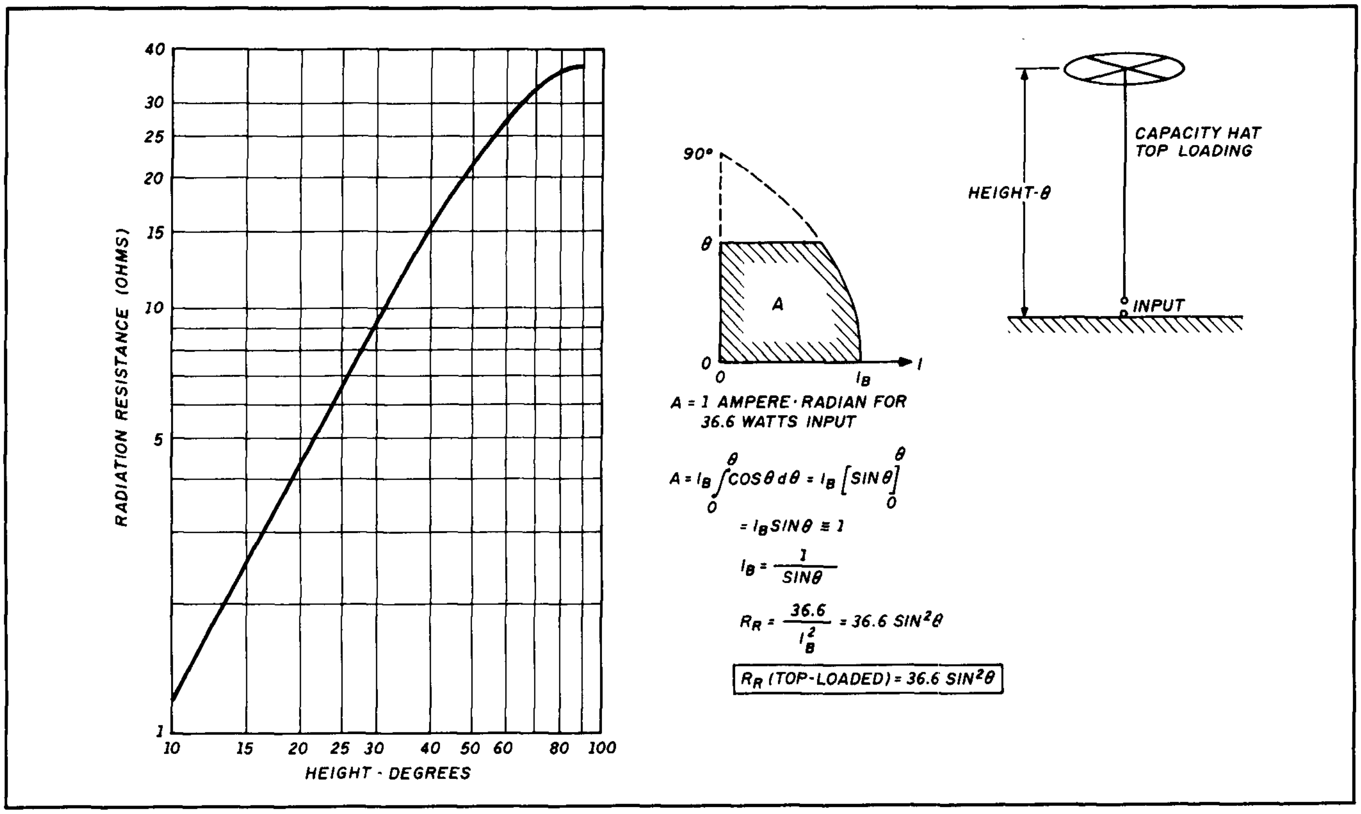
FIGURE 2



Graph of free-space length of quarter-wave resonance versus the ratio of the length-to-diameter of an element.

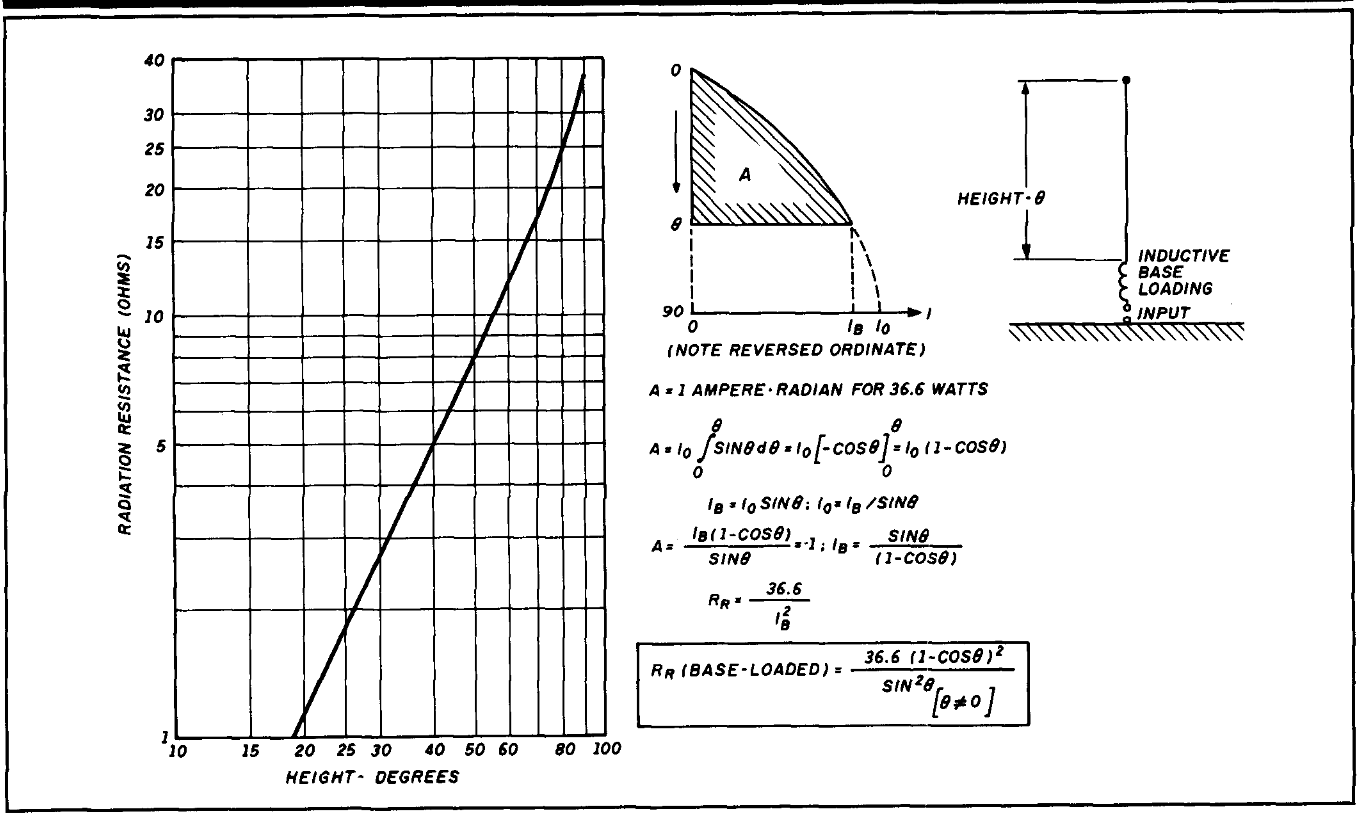
*This information can be found in several sources. We used one of Schelkunoff's antenna books.

FIGURE 3



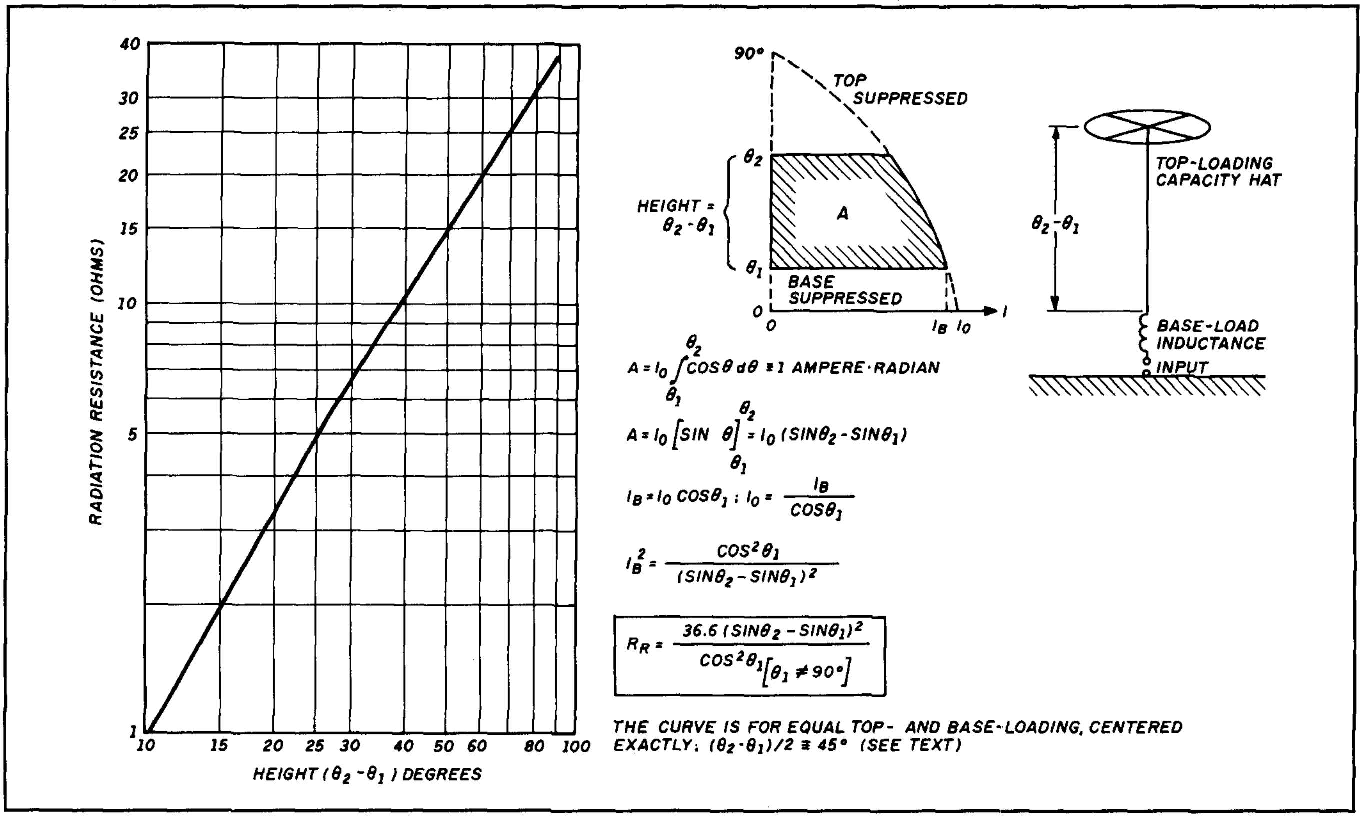
The curve and its derivation for the top-loaded Marconi vertical. The curve is computed from the expression in the rectangular box.

FIGURE 4



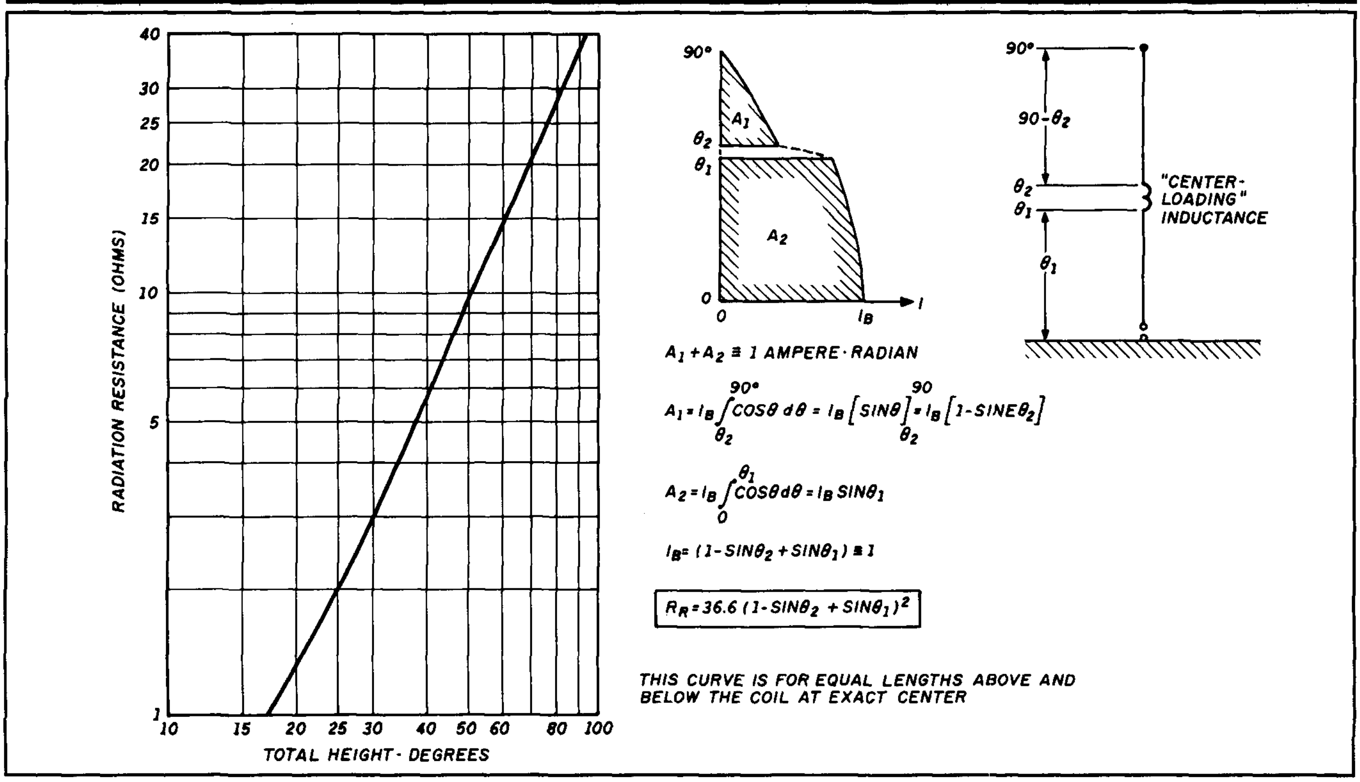
The curve and its derivation for the base-loaded Marconi vertical.

FIGURE 5



The curve and its derivation for a combination base and top-loaded Marconi vertical. This curve is for a combination of equal suppression at the top and bottom. This case and that of the "center-loaded" will produce a family of curves.

FIGURE 6



Curve and its derivation for the center-loaded case. The curve is for a coil in the exact electrical center. Technically this is a "segmented" antenna.

losses other than radiation, any configuration of loading will produce one or more profiles, the sum of which must total 1 ampere-radian for any single antenna. A trigonometric-algebraic expression evolves for the base current in each case. This expression is squared and divided into 36.6 watts, the assumed power input for 1 A in the reference antenna. The quotient is the radiation resistance as a function of the exposed element lengths expressed as angles. These derivations provide very good estimates of the radiation resistances, and can be calculated by anyone who has a handheld scientific calculator.

There are four derivations. The last one, shown in **Figure 6**, presents calculations for the "center-loaded" case. It's of limited use, for two reasons. First, few center-loaded verticals exist in which the top section is the same diameter as that of the bottom — a requirement for the derivation. It's usually a thin "whip." Second, the rules governing the way the derivations were perfomed may not fit the case as well as they do in the first three. It's difficult to determine the amount of "standing wave" that exists on the loading coil, if any at all.* We believe there is some standing wave on the loading coil, and intend to make some measurements to confirm it.

However, the existence of this wave may not be important, because the whip actually contributes almost nothing to the transmitted field. Almost all of the signal comes from the section below the coil. Thus you may estimate the radiation resistance of the antenna by using the expression for the top-loaded vertical with the length set equal to that of the bottom section plus the coil. Those who build a center-loaded vertical would be well advised to use a top hat and to place the coil — which would be considerably reduced in value because of the increased top capacitance — directly under the top hat, or to eliminate the coil entirely and resort to top loading alone. It's interesting to note that the coil under the top hat configuration isn't new; it was covered by a United States patent in 1909!

The combination top and base-loaded case (**Figure 5**) was solved for equal loading at the top and bottom; the radiating portion of the antenna is in the exact electrical center. A simple BASIC program for the computation appears as **Figure 7**. Both this concept and that of the center-loaded antenna will produce a family of curves. You can modify the program to generate the rest of the family.

Probably the most important characteristic of the top-loaded versus base-loaded vertical is that for heights up to about 30 or 40 degrees, the radiation resistance of the top-loaded vertical is nearly four times larger than that of the base-loaded system. This means that the top-loaded antenna would be four times as efficient as the base-loaded antenna erected over identical ground systems. We don't recommend using base loading in just any situation, except as a tuning network or part of a mostly top-loaded combination. These derivations also revealed that all other combinations of top and base loading result in radiation resistances between those two curves.

In 1977 Jerry Sevick, W2FMI, published what may be the best article in recent literature on short ground radials for short verticals.[4] Jerry tested many combinations of short (Marconi) verticals over several radial systems. One of his figures, shown here as **Figure 8**, plots measured values of input impedance (resistance in these cases) over a very good ground system of 100 quarter-wave terminated radials. The earth conductivity was higher than 30 millimhos per meter; it doesn't get much better than that! We're sure it was a result of Jerry's well-fertilized back lawn. The curve for the top-loaded antenna (the top curve) gives a value very close to its radiation resistance because there's virtually no parasitic ground loss and no coil resistance. The other curves

*Work by Robert Lewis, W2EBS, and the late Edmund Laport corroborates this finding.

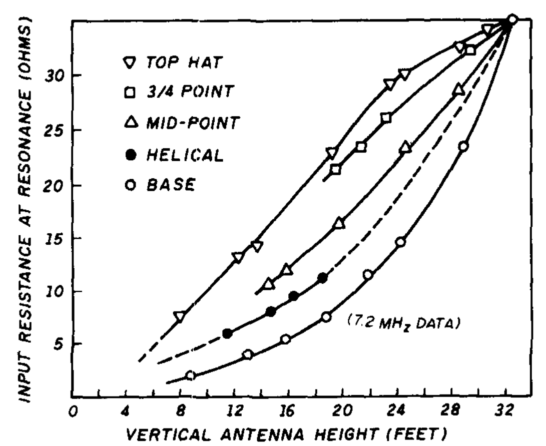
FIGURE 7

```
10 A = 45:B=45:
20 TH1 = 3.14159*A/180
30 TH2 = 3.14159*B/180
40 M = SIN(TH1):N = SIN(TH2)
50 RR = 36.6*(N-M)^2/(COS(TH1))^2
60 LPRINT USING "###.##     ###.##";B-A,RR
70 A = A-5:B = B+5
80 IF (B-A)=<90 THEN GOTO 20 ELSE END

  0.00     0.00
 10.00     0.95
 20.00     3.29
 30.00     6.54
 40.00    10.42
 50.00    14.81
 60.00    19.61
 70.00    24.83
 80.00    30.48
 90.00    36.60
```

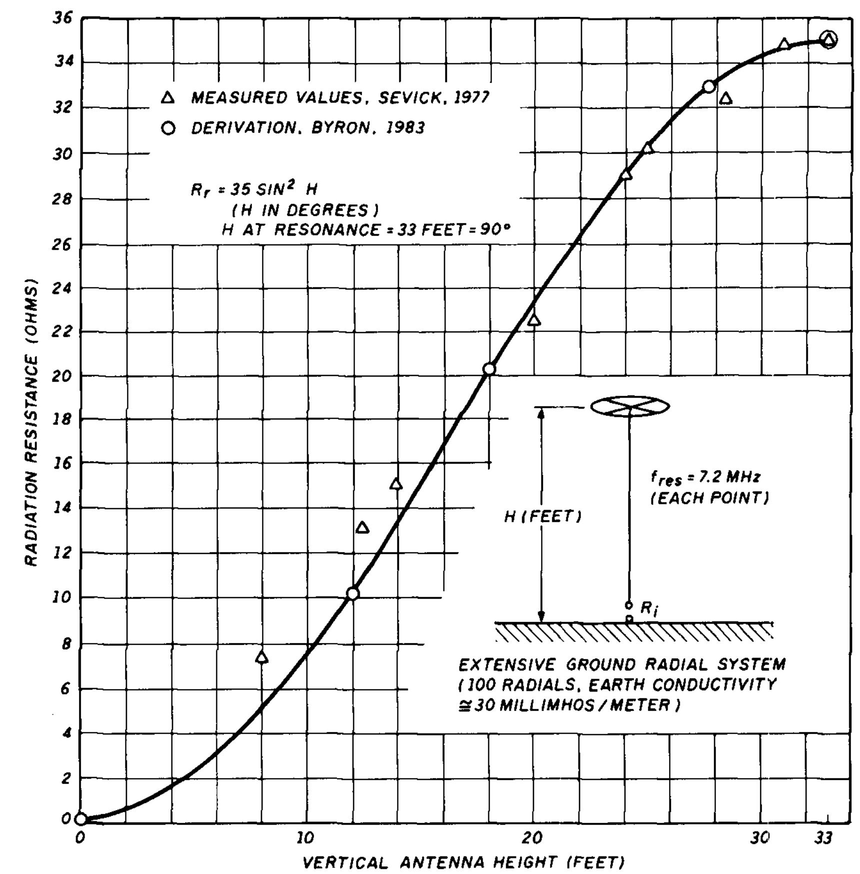
Short BASIC program to calculate the curve in *Figure 5*. The column lists first, the total length (B-A), and the second, its radiation resistance (R). Notice that at 90°, both the top and base loadings disappear, and the resultant is the resistance of a quarter-wave antenna.

FIGURE 8



Measured values from Jerry Sevick's (W2FMI) antennas erected over a nearly lossless ground system for several representative types from his 1973 article, "Short Radial Systems for Short Verticals," in *QST*. Used with permission of the author.

FIGURE 9



A plot of the measured values from *Figure 8* (the top curve) curve-fit by the derivation from *Figure 3*. As there was little ground-loss, and because there was no inductance, the points for the top-loaded system represent radiation resistances.

reflect the effects of the various loading coils. Even the construction of a coil of large wire (like no. 10) will contribute several ohms of parasitic resistance, depending on the frequency and inductance. This *cannot* be ignored. The RF resistance of a 13.8-μH coil constructed of no. 16 silver-plated copper wire measured 1.6 ohms at a frequency of 7.2 MHz.

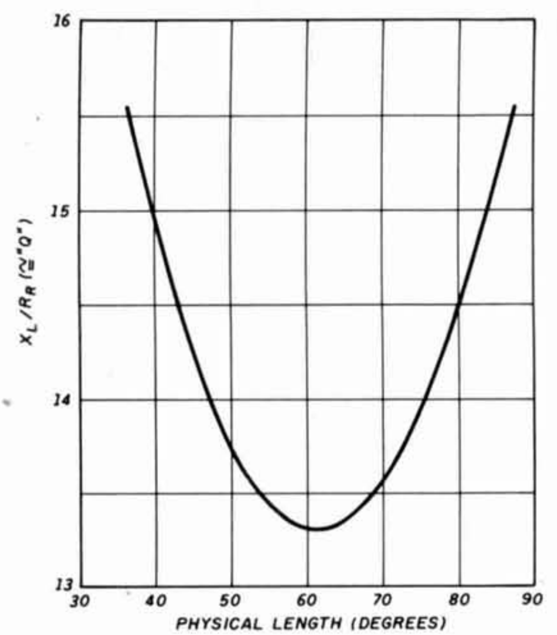
Proof of performance

Figure 9 shows the top-loaded antenna data from **Figure 8** as "curve fit" by the expression for top-loaded verticals from **Figure 3**. We did this to demonstrate that the coefficient (36.6) is just that — a coefficient set as a consequence of this particular derivation method. If the original dipole radiation resistance calculations had yielded, say, 32 ohms, then it would have appeared in the derivations. Jerry's full length vertical measured 35 ohms. This becomes the new coefficient and illustrates how you'd use these expressions. Notice how well the experimental data (from 1977-78) fit the curve (essentially from 1982) as published in 1990, even though a refinement to accommodate the decreasing L/D ratio for the points below about 14 feet in height wasn't performed. Given the absence of measured values for a full length vertical (the usual circumstance), a good starting coefficient for verticals of, say, 1-1/2 or 2 inches diameter would be 35. The arbitrary assignment of 35.0 wouldn't produce an error of more than 3 or 4 percent in almost any case, and probably less. Simply substitute 35 for 36.6 in all the derivations.

A surprise

We've all been told over the years that a shortened antenna results in a narrower bandpass than that of a full-sized vertical. This is quite obviously true for a base-loaded vertical, but might not be true for the top-loaded system. In 1989, Frank Chess made some calculations for top-loaded systems and calculated the inductance of the vertical section. He computed both the inductive reactance (X_L) and the radiation resistance (R_R) as the element was shortened. He assumed it to be over zero-loss ground. Consequently, as the element is shortened, resonance is restored by increasing the size (capacitance) of the top hat. The results are very interesting. As a matter of fact, they're startling. The Q of the vertical *decreases* as it's shortened down to a physical length of a little over 60 degrees, and then it increases (see **Figure 10**). We leave this as conjecture; we haven't performed any experiments for confirmation. However, if this is true, a totally top-loaded vertical over a good ground system resonant at a 62-degree electrical height may have a wider intrinsic bandpass than that of a full-sized quarter-wave vertical for a reasonable length-to-diameter ratio of, for instance, 200 or so.

FIGURE 10



The curve for the "Q" of a top-loaded antenna as calculated by one of the authors (Chess, K3BN) in 1989. As a full-length vertical is shortened, it is assumed to be brought to resonance by a top-hat. The inductive reactance (X_L) of the vertical section is calculated along with its radiation resistance (R_r) in each case.

With few exceptions, the behavior of most antenna systems is influenced by the ground beneath it.

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3. W.J. Byron, W7DHD, "Short Verticals for the Low Bands," *Ham Radio*, May 1983. See Figures 5 and 6.
4. Jerry Sevick, W2FMI, "Short Ground Radial Systems for Short Verticals," *QST*, April 1978.

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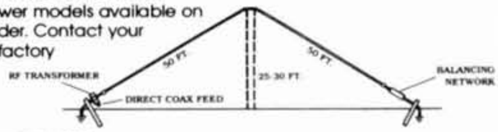

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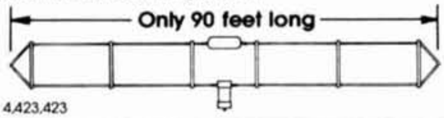

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