short vertical antennas for the low bands: part 1

Relative performance of 5 different shortened verticals is compared to full quarter-wave radiator

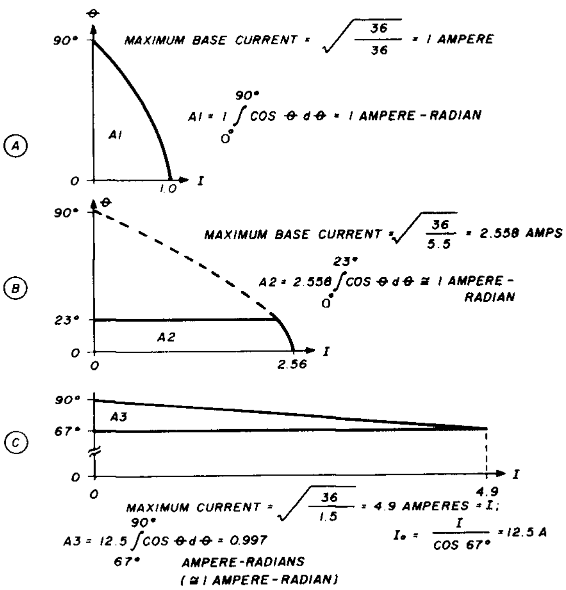

fig. 1. Current distributions for three referenced antennas, each over perfect ground, and 36 watts input to antenna terminals. All to scale, so areas are directly comparable. *(A)* Current distribution of λ/4 vertical (reference antenna) against a perfect ground, *(B)* Current distribution of λ/16 (23 degree) top-loaded vertical against perfect ground, *(C)* Current distribution of λ/16 (23 degree) base-loaded vertical against perfect ground.

The increasing popularity of the 160-meter band and recent FCC regulatory actions opening the lower 100 kHz to normal Amateur operations have attracted Radio Amateurs to the top band. Many are discovering that wire antennas normally used on the higher frequencies require difficult to achieve heights and lengths for effective operation, especially 160 meters.

The decision to investigate verticals rather than doublets or other horizontal antennas resulted from space limitations and performance requirements. (A maximum height of 35 feet, one of the constraints, equates to 1/8 wavelength on 75 meters and 1/16 wavelength on 160 meters. Most horizontal antennas at this height above *ground* provide only high-angle radiation.) A two-band trapped vertical is described that uses the same radiating element for both bands

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and isolates the top-loading capacity hats with a trap. A short vertical can be nearly as efficient as a full-size quarter-wave vertical if it is top-loaded, and has an extensive ground system.

design considerations

A quarter-wave vertical has a radiation resistance of approximately thirty-six ohms.[1] In quarter-wave (or shorter) systems, over non-ideal ground, a total resistance (R_T) would be:

$$R_T = R_r + R_\Omega + R_g$$

where R_r = radiation resistance
R_Ω = circuit resistance
R_g = ground resistance

Fig. 1 illustrates the calculated current distribution for three verticals. **Fig. 1(A)** is a plot of the current in the perfect quarter-wave, **fig. 1(B)** for a 23-degree high, top-loaded vertical, and **fig. 1(C)** for a 23-degree high, base-loaded system. **Figs. 2** and **3** show the values for helical, center-loaded, and 50/50 top- and base-loaded verticals, all 23 degrees in electrical height. The calculations show that short verticals can be nearly as efficient as full-size antennas. (The 23 degree electrical length is related to my height restriction.)

Short antennas have current distributions that can be approximated by triangular or trapezoidal shapes. The set of curves illustrated in **fig. 4**, extrapolated from a standard reference volume on antenna design[2] are used to determine the radiation resistance of short verticals for defined current distributions.

The curves worked very well for the 160-meter version of my antenna. I departed from the specific domain of the curves in the evaluation of the radiation resistance of the 75-meter system. The 19-ohm resistance for a top-loaded 48.9-degree-high vertical (determined from **fig. 4**) is very close to the measured value and to the value derived by original methods. **Figs. 5** and **6** resulted from my not knowing how far (or whether) to extrapolate the curves in **fig. 4**. **Fig. 5** has been modified to fit two well-measured resistances, but it is within three to five percent on the curve as derived. As modified, it is probably within one percent anywhere for θ between 3 and 90 degrees. **Fig. 6** presents the radiation resistances of base-loaded verticals ranging from 6 degrees to 90 degrees in height. Other combinations of base-loading and top-loading result in radiation resistances somewhere between these curves.

Free-space wavelengths were used to calculate antenna heights. No attention was given to the element length-to-diameter ratio, or to end-effects. For most systems the length-to-diameter ratio is high, and the differences between, say 20 degrees and 21 degrees in terms of radiation resistance is negligible.

Once the calculations were made for the radiation resistances, the feedpoint resistances were defined, and the final evaluation proceeded.

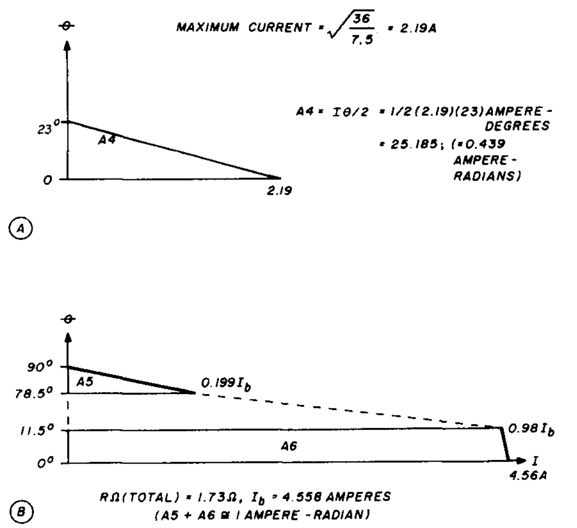

fig. 2. Current distributions for λ/16 (23 degree) helical and λ/16 center-loaded vertical antennas over perfect ground. No coil loss is assumed in center-loaded case, but 6-ohm helical ohmic resistance was included in *fig. 2A*. Figure is drawn to same scale as *fig. 1*. *(A)* Current distribution of λ/16 (23 degree) helical vertical over perfect ground, but with 6 ohm helical resistance, *(B)* Current distribution of λ/16 (23 degree) center-loaded vertical over perfect ground, no coil loss.

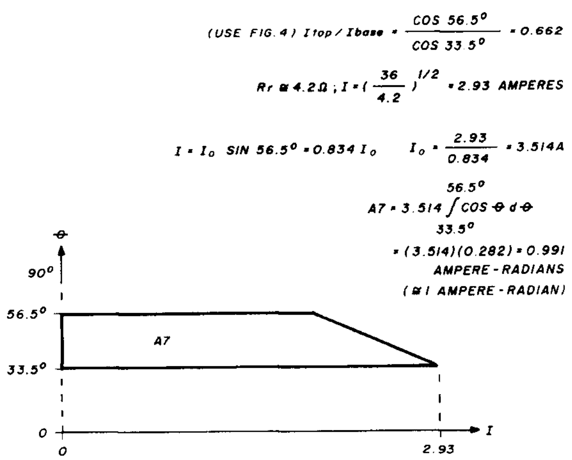

fig. 3. Current distribution on λ/16 (23 degree) vertical antenna with equal top- and base-loading, over perfect ground, no coil loss. (Same scale as *figs. 1* and *2*.)

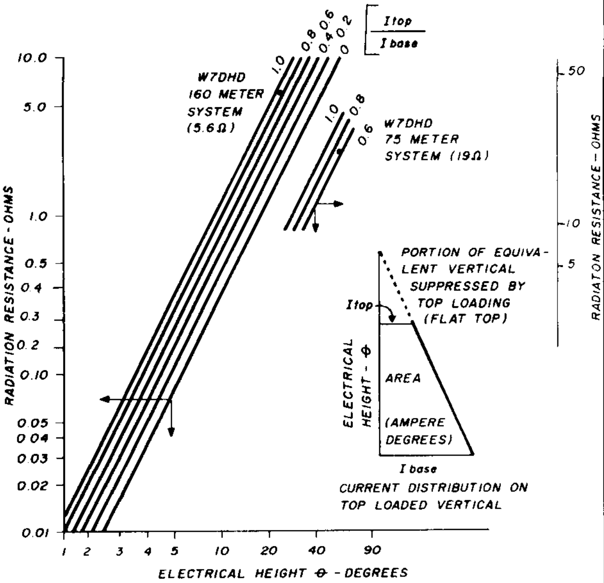

fig. 4. Radiation resistance versus angular aperture (electrical height), θ, for top-loaded vertical antennas.[2]

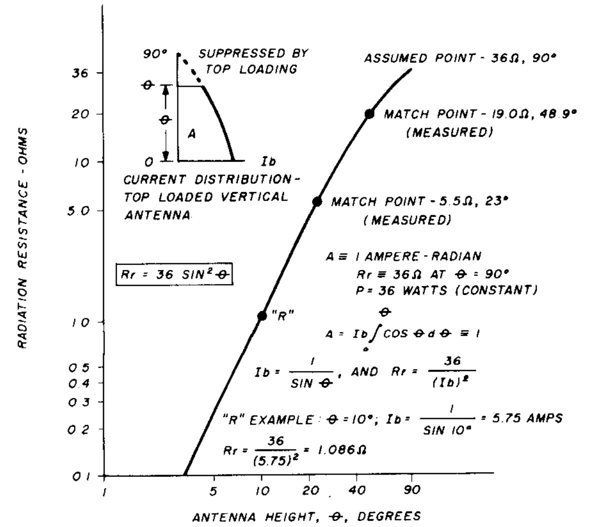

fig. 5. Radiation resistance of top-loaded vertical antennas from 3 to 90 degrees. Theoretically derived and modified to fit measured resistances (Δr less than 1 ohm at $\theta = 50$ *degrees*).

In all calculations a lossless quarter-wave vertical was used as reference. Field strength is directly proportional to the product of the length of radiating element, and the current in that element in ampere-degrees or ampere-radians. The areas under the profiles of currents in **figs. 1** through **3** are equal to one ampere-radian for 36-watts of input power. The one exception, the helical antenna, was calculated at six ohms rf-resistance in the helicoid, and the integration was done graphically, since current varies linearly along its length.

evaluation

In order to compare the vertical antennas, a ground system consisting of 40 1/8-wave radials was used.

A quarter-wave vertical working against this ground system (12 ohms at 1.8 MHz) exhibits a 75-percent efficiency.[3] This ground system is now used with the shortened verticals.

Since the calculated radiation resistance for a $\lambda/16$ base-loaded vertical is 1.5 ohms (see **fig. 6** with $\theta = 23$ *degrees*), the efficiency is

$$\eta = \frac{1.5}{1.5 + 12 + 2} = 9.7 \text{ percent}$$

where the 2 in the denominator is the rf resistance of the wire in the base-loading coil. Consequently a base-loaded antenna over the same ground system is one-tenth as efficient as a lossless quarter-wave antenna.

Since efficiencies are indicative of radiated field strengths, signal levels, referred to the quarter-wave standard, would be:

$$20 \log_{10} (\text{relative efficiency}) = dB$$

In the case of the base-loaded vertical, this becomes:

$$20 \log_{10} (0.097) = -20.26 \; dB$$

Table 1 lists the expected performance of seven vertical antennas:

All the calculations are the same, with the exception of the helical vertical. It was evaluated by making some assumptions: it requires $\lambda/2$ of wire to achieve $\lambda/4$ resonance; wire size is No. 12, 250 feet, $R_\Omega = 6$ ohms; overall height is 35 feet, or 23 degrees; very small (< 1 degree) top-hat (the pie tin); the current decreases linearly over the helix.

The current distribution is triangular with an area equal to 1/2 $I\theta$ ampere-degrees. It ranks seventh out of seven verticals, and was not further considered. It is a poor choice, especially when the amount of material and the difficulty of construction are considered.

actual design

Two-band operation would be achieved with the same radiator if a method of switching top hats could be engineered. This was accomplished by use of two separate top hats and a parallel-resonant trap.

table 1. Relative ranking of several vertical systems by field strength, constant 23 degrees aperture and constant power input.

antenna system	description	conditions	relative field strength, dB
A	full-sized λ/4 vertical	zero losses	0
B	full-sized λ/4 vertical	12 ohm ground	−2.5
C	λ/16 top-loaded	12 ohm ground	−10.0
D	λ/16 top and base loaded	12 ohm ground, 1 ohm coil	−12.4
E	λ/16 center-loaded	12 ohm ground, 2 ohm coil	−19.25
F	λ/16 base-loaded	12 ohm ground, 2 ohm coil	−20.26
G	λ/16 helical	12 ohm ground, 6 ohm coil	−20.28

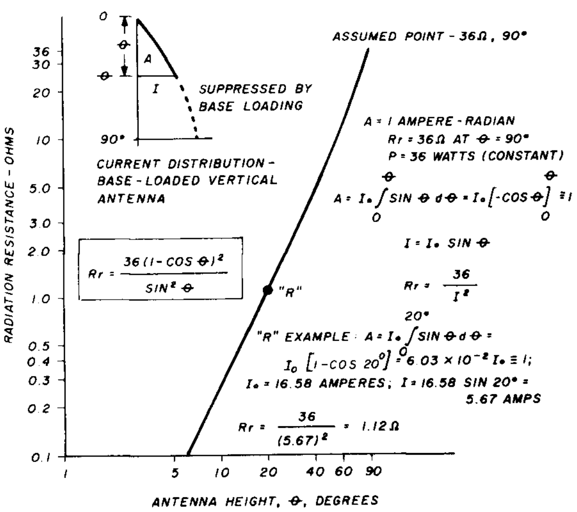

fig. 6. Radiation resistance of base-loaded vertical antennas from 6 to 90 degrees high, (theoretically derived).

The 75-meter top-hat seemed achievable while top-loading on 160 meters (accounting for 67 degrees or 105 feet of missing vertical) seemed more formidable. One source in 1915[4] describes short vertical antennas that use umbrella-loading for top hats.

trap affects performance

Antenna performance depends on the behavior of the trap, tapped onto the 75-meter section at the 49 degree point. The voltage is estimated at 1200 volts, peak, at a one-kilowatt power level. Since the large umbrella is connected to the other side of the trap, that end is assumed to be held constant at or near zero potential. The entire voltage appears across the trap.

The T-200-2 (red core) powdered-iron toroids were wound with No. 12 solid copper wire and resonated with 400 pF at 3.8 MHz. The fundamental wave shape was observed at the kilowatt level for signs of distortion and for ticks in the reflected power on the Bird wattmeter. This was done to determine whether the trap core saturates. No calculation was performed during design — an oversight.

The trap is subjected continuously to the same abuse as is a tank circuit of a kilowatt linear which is unloaded, dipped to resonance, and driven by an exciter. Any trap must be designed to withstand that treatment. Consequently, any trap in any system should be built from the same size and quality components used in the amplifier that drives them — preferably better quality.

power dissipated in the trap

With a trap-resonating capacitance of 400 pF, and a trap-inductance of 4.5 μH, both exhibit 108 ohms at 3.8 MHz, while the ten feet of No. 12 wire has an rf resistance of 0.25 ohms. This calculates to 31 watts of power, dissipated by the trap. This would prove very significant if the antenna were subjected to five or ten minutes of RTTY or a-m operation.

These considerations must be balanced by other factors. If the trap Q is increased, the loss is reduced; but so is the system bandpass. These are engineering trade-offs. The trap in this system effectively limits the 75-meter bandpass (between 2:1 VSWR points) to 86 kHz. Other methods are used to circumvent that limitation.

Another characteristic of short antennas is their very low feedpoint impedance — so low that it is sometimes hard to measure. In highly efficient systems the inclusion of even one ohm of non-radiating resistance will make a significant change in the feedpoint resistance. The equivalent series-input resistance (R_Ω) of the trap resistance, calculated above, may be estimated very closely if the as-built base current is known:

Given $P_D = 30.9$ *watts (dissipation in trap)*
and $I_B = 7.14$ *amperes*

then $$R_{eq} = \frac{30.9}{(7.14)^2} = \frac{30.9}{51} = 0.61 \text{ ohms}$$

So it is known already that the trap with its 0.25-ohm coil resistance will be reflected at the antenna base as 0.61 ohm in series with the other instrinsic resistances.

The calculated radiation resistance for the 75-meter system is 19 ohms. The measured feedpoint resistance is 19.6 ohms. It is highly probable that the 0.6-ohm discrepancy can be explained by the rf resistance of the trap, calculated in the preceding paragraphs.

The construction, measurements, and performance characteristics of verticals in general, and of a two-band trapped vertical antenna in particular, will be described in Part 2, the conclusion of this article.

references

1. F.E. Terman, *Electronic and Radio Engineering*, McGraw-Hill Book Company, 1955, page 892.
2. Edmund A. Laport, *Radio Antenna Engineering*, McGraw-Hill Book Company, 1952, or Mei Ya Publishing Company, Taipei, Taiwan, 1967.
3. Jerry Sevick, "Short Ground-Radial Systems for Short Verticals," *QST*, April, 1978.
4. Dr. J. Zenneck, translated by A.E. Seelig, *Wireless Telegraphy, McGraw-Hill Book Company, Inc., 1915.*

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design of short vertical antennas for the low bands: part 2

An efficient radiator for 160 and 75 that uses two top hats

a good radial ground system in a small back yard

You don't need a large back yard to have a good radial ground system. I helped a friend install a good system in a back yard that measured only 65 × 40 feet (20 × 12 meters). At that location there are chain-link fences around the entire yard, and about thirty fence posts. Other fences terminate near the corners, but they are not bonded to the back yard fence. We placed an aluminum plate on the grass, approximately in the center of the yard, and each fence post was connected to that plate by a No. 17 galvanized steel wire. The wires were buried in a slot dug by an ordinary edger. That made thirty radials, the longest of which was not more than about 40 feet (12 meters).

The fence posts and the plate were drilled, tapped, and provided with solder lugs, and the wires were soldered at each end. A temporary base-loaded whip was then resonated to 1.850 MHz, and the impedance was measured with a noise bridge. During these measurements, various fence corners were temporarily connected together with clip leads, and the effects were immediately noticeable. Within an hour, the ground system measured a fairly reliable 10 ohms. No measurement was performed at 3.8 MHz; however, it certainly would measure less than 10 ohms. Note that this minimal, small-lot radial system is *better* than the hypothetical ground used as the basis for calculations in this article.

The first half of this article reviewed the characteristics of several short verticals over ordinary ground radial systems. This information is now applied to the construction of a very short two-band trapped vertical.

the antenna system

The antenna consists of two top hats separated by a parallel resonant 75-meter trap and a 35-foot-long (10.67-meter-long) section of 2-inch aluminum irrigation pipe. It resonates on 1.836 MHz and 3.830 MHz. The 75-meter top hat comprises four 8-foot (2.44-meter) pieces of 3/4-inch aluminum tubing, mounted at right angles to themselves and to the mast.

Four 50-foot-long (15.24-meter-long) sections of No. 8 aluminum clothesline wire double as the top guys and the 160 meter top-hat. The trap is placed between these wires and the top of the mast. For design purposes the trap inductance is 4.5 μH with an equivalent inductance when paralleled with 400 pF of slightly over 5 μH at 1.8 MHz. With the trap shorted the antenna resonates at 3 MHz.

The general layout is as shown in **fig. 1**. Six rather small trees and the lower guys are not shown. **Fig. 2** shows the electrical connections.

Since 2-inch irrigation pipe is very limber, it needs to be guyed. The first installation had eight guys; four comprised the 160-meter top-hat, plus four more at the 60-percent level. On one windy day the mast section below the lower guys vibrated at 20 to 30 Hz, displacing at least half an inch. Wind velocity at the time was probably 30 to 40 mph (50-65 kph). Another set of guys was subsequently installed at the 12.5-foot (3.8-meter) level. The positions are now at 35 feet (10.7 meters), 21 feet (6.4 meters), and 12.5 feet (3.8 meters). This damped the motion.

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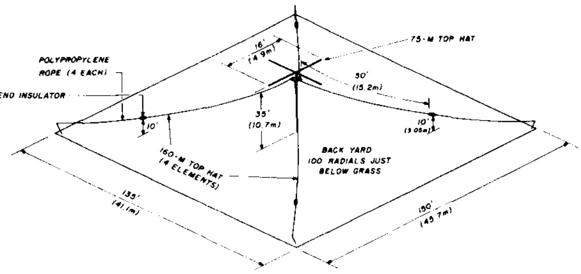

fig. 1. Configuration of trapped 75/160 meter vertical, approximately to scale.

The system is resilient enough so that continued vibration certainly would not have damaged the structure, but it does stranger things: it unscrews nuts, bolts, and machine screws, and it causes fatigue in electrical connections. The fastening points for the guys on the mast are steel devices designed for connecting 2-inch fence posts together. All guys are broken up into sections approximately 10 feet (3 meters) long, insulated by TV-mast-type "egg" strain insulators.

A 30-kV ceramic stand-off insulator is used, supporting the weight of the antenna system. In this application the potential across it is under 100 volts. For this (and even more stringent requirements) an empty (but corked) champagne bottle will do just as well: they have heavier walls than soft-drink or beer bottles. An alternative base insulator for this antenna could be a 500-ohm "glo-bar" resistor, since the higher antenna input resistance (achieved on 75 meters) is only 19.6 ohms.

It is a much different story, however, if a *base loading* coil is either wound around the insulator or connected across it. Assuming total base-loading, the rf potential on a $\lambda/16$ vertical could reach 5000 volts, and that puts insulator requirements in an entirely different light.

the ground system

Short verticals must have good rf grounds. At my location the longest radial wires are the four diagonals that run across the back yard, each about 90 feet (28 meters) long. The shortest are the two that span the short side, each 65 feet (20 meters) long. All other radials are of lengths between those limits. Since all are shorter than $\lambda/4$, it was decided to put as many radials down as would be practicable. One hundred radials were installed, utilizing 7,300 feet (2250 meters) of galvanized steel, 17-gauge electric fence wire.

Heeding the advice of Jerry Sevick, they were laid down, in October, 1978, on the surface of freshly close-cut lawn. At those places where the ground dipped a wooden stake was driven in flush with the average ground height, and the radial wire was stapled to the top of the stake. None of the radials were buried. By midsummer, 1979, grass had concealed all the wires. By that time a metal detector would have been necessary to find even one of them. A couple of wires did catch in the mower in the spring of 1979, but these two were replaced and there has been no trouble since.

The radials are attached to the base plate by solder lugs and No. 6-32 (M3.5) stainless steel screws. The base plate is an 18-inch (0.5-meter) square piece of 6061-T6 aluminum, 1/4 inch thick. One hundred holes were drilled with a 6-32 (M3.5) tap-drill (twenty-five on a side) and then tapped by hand.

Most radial wires are terminated by an 18-inch (0.5-meter) piece of reinforcing rod, supplied and cut by a local building supply company. Some are terminated by 4-foot (1.2-meter) ground rods. These were reserved for the shortest radials. All this paid off; the ground loss was very small.

lightning protection

Something should be said about grounds for lightning protection. At my location some of the larger trees and also some of the power-line poles are higher than the antenna, but none of them are in the immediate vicinity of the antenna. I drove four 4-foot (1.2-meter) rods below ground level several feet off the corners of the baseplate and connected them to the corners by a No. 8 solid copper wire. The rods are on about 6-foot (1.8-meter) centers.

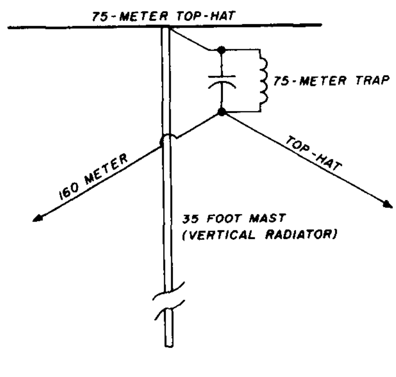

fig. 2. Top-hat electrical connections.

A little research into grounding revealed that if two rods are spaced close together, say less than a foot or two, their parallel resistance to ground is no less than that of one rod. In other words, rod surface area alone has very little to do with contact resistance. Ground rods should be spaced at a distance *at least* equal to their length for minimum resistance to ground. It has been shown also that athough there is little correlation between their surface areas (rod diameter) and resistance, there is a *direct* correlation with their length. So the proper lightning ground should have been composed of 8-foot (2.5-meter) rods spaced approximately 10 feet (3 meters) apart.

Even if the ground resistance could be reduced to 5 ohms (ohmic resistance, dc), a direct hit delivering a pulse current as low as 2,000 amps would still produce a voltage at the base of the antenna of 10 kilovolts with respect to nearby objects such as coaxial feedline and the shack. Lightning ground rods can help protect the shack or the house; *they will not protect the equipment.* Despite the rods, when I leave the shack for the day I uncouple the coaxial transmission line and leave it dangling on the wall.

matching

The system exhibits two distinct resistive feedpoint impedances, both less than 50 ohms. Several options exist for feeding the antenna, but the one I chose involves running a "flat" transmission line (that is, matched at both ends), the impedance transformation being accomplished by a transmission line transformer (TLT) at the base of the antenna. Construction details are given in **fig. 3**. There is a slight mismatch at the 75-meter tap. The load impedance (measured) is 19.6 ohms. At the 2/3 point of the TLT, the impedance is 22.22 ohms, providing a best-case match (VSWR) of 1.13. The 160-meter tap is exactly at the measured value of antenna resistance, 5.5 ohms, which occurred by lucky coincidence. Those two taps could be switched by a relay energized in the shack. At the time I didn't have a relay with sufficient contact force or size to do the job. At the kilowatt level, the base current in the 160-meter antenna is nearly 13.5 amperes. At this level each 0.1-ohm circuit resistance dissipates 18 watts, a loss which would hardly be missed in the resultant signal but which is serious if it happens to occur in a relay contact, which may have a total volume of less than one-tenth of a cubic centimeter.

Another option is to use a quarter-wave matching section, computed in the usual way:

$$Z_M = \sqrt{Z_i Z_o}$$

For $Z_i = 50$ *ohms*, and $Z_o = 5.5$ *ohms*, $Z_M = 16.6$ *ohms*, almost exactly one-third of 50 ohms. It would require a total of 350 feet (107 meters) of RG-58: three cables, each 117-feet (35.6-meters) long and operated in parallel. That is a lot of cable but it works. On 75 meters, the length would approximate $\lambda/2$, and the 19.6-ohm resistance would be repeated at the transmitter with an intermediate point SWR on the 16.6-ohm transmission line as low as 1.18. Its use would require a transmatch at the transmitter, however.

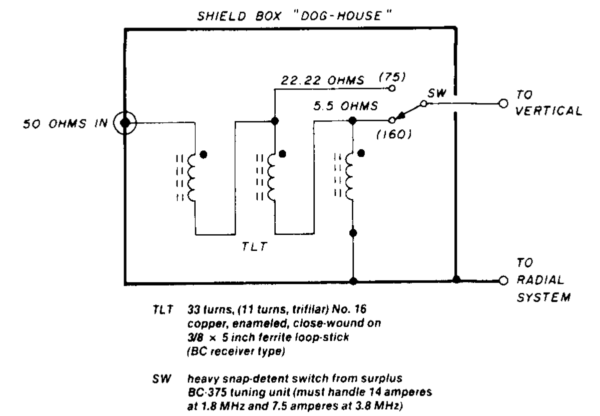

fig. 3. Transmission-line transformer (TLT) and switch.

When it's cold outside it's a chore to go out and switch the TLT. I soon discovered that with the TLT on the 5.5-ohm tap and the excitation on 3.8 MHz, the resultant 4:1 SWR could be compensated for by the transmatch at the transmitter with apparently no loss in efficiency. The loss due to that mismatch is about 1 dB. Whenever the weather is foul enough to discourage a "switching trek" I use the transmatch. Note that the loss is low only for frequencies of 4 MHz and lower. It would not be true at 30 MHz.

Figs. 4 and **5** are plots of the measured VSWR within the two bands. The measurements were taken from the shack at the end of the long RG-8/U transmission line. I used a Bird Model 43 wattmeter and the barefoot exciter with its digital frequency display. The readings reveal a couple of important facts:

1. The measured impedances at the antenna base were correct.

2. The transmission line transformer is adequately designed.

The antenna systems, although narrow in bandwidth, can be tuned by means of transmatches. I use two, one for 160 meters and the other for 80 through 10 meters, enabling me to operate over a range of 200 kHz on 75 meters and 100 kHz on 160 meters with little loss. Mine are both the McCoy "ultimate transmatch" type. In general, transmatches are recommended for use with trapped systems to reduce harmonic radiation.

performance

The 75/160 meter antenna has proven to be an effective radiator. Because of the low-angle radiation and the efficiency (high radiated field), I can make two-way contacts on 160 meters at high noon in mid summer over distances of up to 200 miles. At the equinoxes, I've made two-way SSB QSOs with New Zealand. At various other times in the winter the system has enabled me to work England, Brazil, Panama, Nova Scotia, Bermuda, and most of the United States. On 75 meters the performance is much the same; I've made contacts with all of the above places plus Germany, Alaska, and western Australia. All of these contacts were incidental, since I do not seek DX actively.

conclusion

In various contacts I've made with other users of verticals, it's become obvious to me that the Amateurs who have become disillusioned with, and consequently abandoned, short verticals did not fully understand just how important the ground system is. The shorter the antenna, the more sensitive it is to ground losses. The problem becomes worse when the antenna is both short and base loaded. Consequently, more attention should be paid to the ground system than to the "top-works," while not neglecting the reduction of ohmic losses in coils, relay contacts, electrical connections, and bonding strips.

I also often hear it said that the antenna should be erected over a high water table: "The water table is only five feet below the surface here, and I have

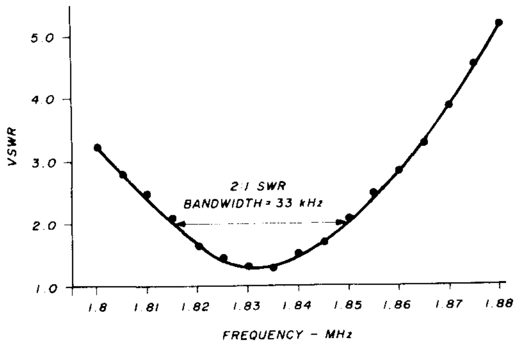

fig. 4. VSWR plot between 1.800 and 1.880 MHz of the 160-meter system.

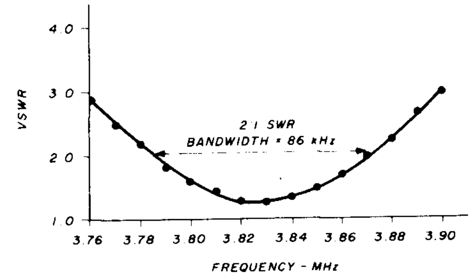

fig. 5. VSWR plot between 3.76 and 3.90 MHz of the 75-meter system.

grounding rods driven right down into it." That means absolutely nothing, unless that "ground water" is salt water. Fresh water, particularly if it is potable, has the conductivity of *poor earth*. The answer to all this, of course, is to know what the antenna should "look" like, and to measure the base-impedance over the ground system. If the system should present a 20-ohm load and has no ohmic loss but measures 50 ohms, you know immediately that the ground resistance is 30 ohms. Consequently, the signal from that antenna will be considerably reduced, *even though it will present a very good match to the transmission line*.

The use of a very short base-loaded whip (such as a mobile whip) reveals something interesting. It is such an inefficient radiator that it can be used to estimate ground loss. Resonate the whip over the ground system and measure the total resistance. Then remove the whip above the coil and replace it with a variable capacitor to ground. Reresonate the coil.

When all this is done, the radial system is effectively removed from the circuit. You can then make another noise-resistance measurement, determining the coil resistance. Absence of the whip ($R_r \cong 0$) has no measurable effect. The ground resistance is then the difference between the two measurements.

acknowledgements

I wish to acknowledge the encouragement I received from W1DB, the late Nick Lefor, who persuaded me to write this article. I also wish to thank Tony Sivo, W2FJ, Walter Schulz, K3OQF, and Nevell Greenough, N2GX, for reading drafts and for other assistance; also Jerry Sevick, W2FMI, from whom I learned to make my first transmission-line transformer; and Edmund Laport, my principal reviewer.

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