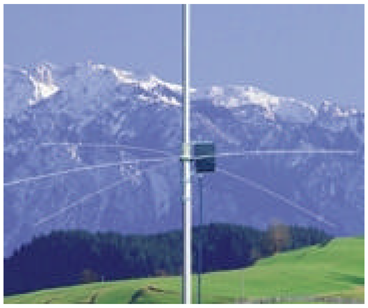
The Mystery of Radials

Many publications have examined the mystery of what effect radials have on the efficiency of antennas.

According to exhaustive tests conducted by RCA in New Jersey in 1937, the FCC specifies that to get a low-loss ground system using a 1/2λ vertical, 120 radials equally spaced and each at least an half-wave long extending radially from the base of the antenna are needed on the lowest working frequency. They must be grounded to prevent shock and other damage. Using many short radials evenly distributed around the antenna is preferable to a few but longer radials. On the other side, it is also reported that a ground connection for the HF spectrum may be useless and somewhere else that in the end a ground screen is still the best solution to get a perfectly conductive ground.



Close-up on Cushcraft R6000 radials that act like a capacitance all along this vertical antenna.

At last in restricted places the FCC notes that more than 12 short radials will have little effect on such antennas but that 15 radials are the minimum required to not loose too much power. In the last edition of its book ARRL suggests to install 16 radials 0.1λ long or 36 radials 0.2λ long or still 120 radials 0.4λ long.

Definitions

Before going further it is time to define the word "radial", often associated to another one, "counterpoise". Both terms are equivalent but you will find below their accurate definition by the ARRL.

Ground plane: A system of conductors placed beneath an elevated antenna to serve as an earth ground. Also see counterpoise.

Counterpoise: A wire or group of wires mounted close to the ground, but insulated from ground, to form a low-impedance, high capacitance path to ground. Used at MF and HF to provide an RF ground for an antenna. Also see ground plane.

This is maybe not clearer In fact both definitions are correct. But most of the time, we speak of radials when the wires are laid evenly on the ground, and of counterpoise when the antenna is erected a few meter above the ground and surrounded by an artificial ground plane made of thin tubing. Of course it will be never be false to say that a ground plane antenna is surrounded with a system of radials.

Radials

Do not confuse radials with the long vertical or tilted stubs, sometimes-over 1m long, used by some manufacturers to shorten the wingspan of their beams (e.g. Cushcraft or Butternut HF5B Butterfly). Other antenna arrays do no need to be grounded either as they already use elements 1/2λ long, straight or folded.

Radials are only used with some models of vertical antennas. The antenna must be a quarter-wave vertical, and only this design. They not apply to other models. In theory, all antennas should work against a ground, but using a balanced half-wave antenna can mitigate the need for that requirement. The same theory applies to a dipole.

These 1/4λ verticals need to be grounded first of all to create their "second half" in order to be resonant at 1/2λ as explained on the next page dealing with the different types of aerials. 1/4λ vertical antennas need also radials due to their vertical polarization and their general proximity with the ground. They are thus much more affected by the ground effects that antennas polarized horizontally (dipole, beam, etc).

The first confirmation of the use of radials comes from the FCC again who recommends to AM broadcasters to install as much as 113 radials each a quarter-wave long to reduce earth losses. To prove its efficiency Valcom in Canada suggests to install at ground level such a network constituted of 120 radials 34.2 m long (114 ft). To work on the 40 Meter band for example, you need a free space of 10 Meters of radius, of course in all directions. Thus first question, are 120 radials of 1/2λ long mandatory to operate with a 1/4λ vertical? We can easily prove the contrary. In the field if you remove all radials attached to your vertical your correspondent will immediately note that your modulation has changed. Your voice will have a metallic sound, more aggressive. Then your radiation pattern will be deeply affected, displaying probably a torus-shaped angle of radiation, suited for local QSOs but surely much less effective for DXing.

In fact in removing your radials, you reduced the size of your antenna by 50% because these radials are fully integrated in the antenna design. On the 20 Meter band for example, a vertical of 6 Meters high like the Fritzel GPA 404 displayed below (that uses 2 trap coils too) must be completed with a 5.2 Meter long radial, to give a vertical cut at 1/2λ; this is mandatory to create its mirror-image and be able to work on its harmonics and thus on several HF bands.

Attachment of radials on a quart-wave Fritzel GPA 404 multi-band vertical. As many ground plane antennas, these flexible radials work at ground level, but are of course very efficient a few meters above ground too, tight at 90 or 45°. They are made of stranded steel wires protected with PVC. Each radial is cut for a specific band (their length varying from 2.6 m for the 10 m band to 10.3 m long for the 80 m band) knowing that this vertical is 6m high. Radials must be tight, one end insulated, the other one fixed at the antenna base (in fact to the mast, the gray tube) to be efficient as they are fully integrated in the antenna design. i.e. on the 20 m band this antenna 6m high must be completed with a 5.2 m radial, giving a vertical cut at λ/2. In other words these radials fully participate in the correct waves propagation in a much better way than using traps. Like the braid of the coax, all radials are screwed and grounded to the mast, not to the antenna. The picture at right shows that radials are placed in an area of about 160° wide around the antenna, each 30° apart, the longest well separated from the others to prevent coupling. They are thus not symmetrically tight around the antenna like we would do in building a ground plane. This configuration uses what we call "counterpoises". It is unbalanced and does not provide shielding that requests a real ground (many more radials all around the mast). This configuration is however more directive compared to other kinds of designs. This vertical offers a gain of 3 dBi not really better than a dipole (2.14 dBi) with the advantages to provide some directivity by the position of its radials and to be easy to setup (in 15 minutes in the field). Documents T.Lombry.

Amateurs also observed that two 1/8λ radials reduced the efficiency of an antenna system up to 75%. In other words you loose 6 dB, 1 S-Unit or more, simply in modifying your radials!

But how many radials are really useful? The FCC states that the earth resistance decreases rapidly passing from 15 to 120 radials, advising broadcasters to use as much as 113 radials. Experiments also confirmed that placing the antenna at a height of 1/4λ over ground, the use of 15 radials does not increase the efficiency of the antenna higher than 50%. Different tests also demonstrated that using 15 radials of 1/8λ give the same result at if they were cut at 1/2λ. At last it appears that using many radials, even if some of them are short, give better results than using few but longer radials.

At last, RF technicians tell us that in average half the ground loss observed in a vertical antenna occurs within a circle which radius equals to the antenna height, thus practically 1/4λ, and the remaining loss resistance occurs in the next 1/4λ out from the antenna due to decreasing of the capacitance between the vertical radiator and the earth. So the radius covered by radials should reach 1/2λ.

Mixing all this data and checking what manufacturers designed in this category of antennas, we can consider that 15 radials cut at 1/4λ in #12 to #18 AWG are a prerequisite to operate a 1/4λ vertical placed at ground level in good conditions. But as we are going to explain below and in the next page, this is probably not the best installation that you can do.

The ground effect

There are several kinds of radials: those that design a ground plane, counterpoise or acting like capacitance. Generally speaking we consider ground plane radials are the ones acting like capacitance.

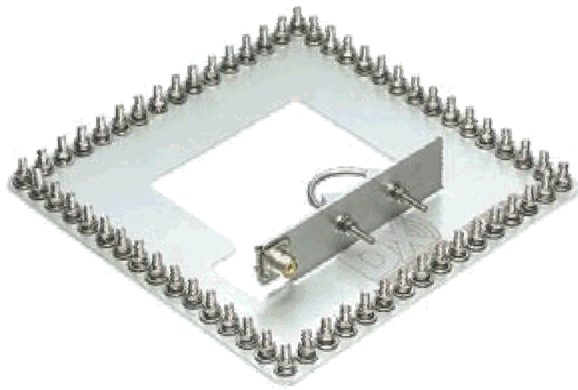
Indeed, when a vertical antenna is erected at ground level and powered, there are much ground currents generated by the earth capacitance and resistance that increase the effect of the earth on the antenna losses (associated to losses in the transmission lines, etc) that see its radials running at ground level be completely detuned. Radials being part of a 1/4λ antenna system, this detuning affect also increases the horizontal radiation lobes to the detriment of the inclined lobes. This problem affects also the listening in the same proportions (pick-up radiation lobe horizontal). To get an efficient harmonic antenna with an unaltered radiation pattern, we need an earth resistance as low as possible.

Type of ground	Dielectric constant	Conductivity (S/m)	Quality
Salt water	81	5.0	Excellent
Fresh water	80	0.001	Poor
Pastoral, low hills	12-14	0.0075-0.03	Very good
Pastoral, medium hills	13	0.005-0.006	Average
Rocky soil/mountainous	12-14	0.002	Poor
Sandy/dry flat/coastal	10	0.002	Poor
Cities/industrial areas	5	0.001	Very poor
Heavy industry/high rise	3	0.001	Extremely poor

First of all, losses in an antenna depend much on the soil conductivity, below and in front of the antenna: a stony or sandy area is a poor conductor compared to a meadow or seawater. Then placing radials at ground level, on the grass or just below the surface, is a lost battle as your radio signal will have to fight against a subsurface constituted of high resistance material (e.g. sand, sandstone, marble). Fresh water, on the other side, is not a better RF conductor. So in order that your antenna works efficiency avoid installing your shack in front of a lake, a swimming pool, a creek, a river, etc, so many spots that we usually see near antennas.

A ground system showing no loss at all is ideal but far harder to find and to build in the field. Such a system means that all power applied to the antenna radiator (excepting the few percent lost in loading) is radiated in space instead of being lost as heat.

Practically a fraction of the output power radiated by an antenna is lost in the coax, traps, coils and other accessories and contribute to warming the Earth. But another significant fraction falls down from the antenna radiator to the lossy ground. This loss can reach 80% of your output power on the lower frequencies. This part of radiations should be "re-injected" in the system, to the antenna feed point, with as little loss as possible, to be radiated by the antenna in a new cycle.



The DXE-RADP-1P radial plate ($50) from DX engineering. The saddle clamp and stainless U-bolt are an option as well as the SO-239 connector and radial wire sets.

They are perfectly right! If you lay evenly on your garden, at the base of your antenna, a mesh of copper or steel wires (a wire-netting) on a radius as long as possible, you will create a perfectly conductive ground in which radiations transmitted by your vertical will reflect like in a mirror. Thanks to this dense wire netting, the power losses will be also reduced because the antenna resistance will be much lower than the one of the ground. This change will also affect the radiation pattern of horizontal dipoles in splitting the main vertical.

Note that to attach all radials to the antenna ground, DX engineering had the clever idea to provide a very convenient stainless steel plate of 30 cm^2 ref. DXE-RADP-1P like the one displayed at left. The antenna base comes inside the clamp.

Using an electric screwdriver, and attaching one radial per bolt, you can bolt all radials in less than an hour.

The FCC states that the mesh constituting all radials has to be cut at 1/2λ (so displaying a radius of 20 Meters work on 7 MHz) to effectively establish the height of the antenna instead of the actual earth beneath the antenna. But contrarily to what the FCC wrote, this mesh buried in the ground has does not have to be resonant to work properly as our objective is to make the ground as conductive as possible for RF signals.

So far, when you work with a vertical cut at 1/4λ standing directly over a metallic plate (your car hardtop or even using a base like the MFJ-1904 RF ground-coupled base you do not worry about knowing whether this surface is in resonant or not. As states Bencher, the manufacturer of Butternut antennas, "*for mobile operations, according to the counterpoise principle, the metal body of the vehicle provides the capacitive coupling to the earth itself*". MFJ Enterprises confirms also that his "*ground-coupled portable antenna base, a 2x2 foot stainless steel square, provides an effective RF ground*". The same principle applies operating from a boat at sea where you do not expect that the "length" of the underneath open-sea surface is at resonant with your antenna, but rather that it constitutes a perfect conductive "ground", without losses. This "ground screen" plays in fact the role of an electrical mirror, not the one of the node of a string at which standing waves reflect back and radiate!

In fact many people confuse the ground with the antenna itself. To be resonant (what is not mandatory but necessary to match impedances), a vertical is usually cut at 1/4λ, and uses its mirror image to reconstitute its electrical "missing-half". It displays an omnidirectional pattern in the horizontal plane (the current or the radiation pattern increasing from the top to the ground connection, the RF voltage being the highest on top, at the open end of the vertical). This pattern in sine curve has to reflect in the ground, whatever its horizontal extent, to display the same radiation pattern as a 1/2λ vertical in free space. But in shortened vertical system for example, the electric equivalent circuit presents much ground losses. It must thus be balanced by a system offering to the antenna a low capacitance to the earth while keeping the capacitance to the radials. This RF ground coupling is got either in installing at ground level more radials around the antenna base or raising the antenna and its radials above ground, transforming them in radiative elements. On the lower bands on the contrary this is achieved in using loading coils for matching impedances. Therefore, in the first case, don't be surprised if some amateurs tell you that they buried hundreds of cans in their backyard just to give to their antenna an earth more conductive, Hi!

On the other hand, the extent of this artificial ground is, on the contrary, very important when you will emit as the distance up to 10λ around your vertical influences much the efficiency of its angles of takeoff. This both aspects are two things completely different.

Installation of radials

The soil surrounding an antenna or its radials has a very low resistance which entails more loss in transmission lines and buried radials. At the same time due to the soil permittivity and moisture content (water), the capacitance of any buried wire is also much higher than its value in the free space. Both factors contribute to slow down the velocity of propagation along a buried radial to a value as small as 1/12 of the free space value! For all these reasons it is nonsense to cut radial wires to particular resonant lengths if they are buried. At last the attenuation of the current along a buried radial wire is also very high. In average, calculations show that at the lower HF frequencies the optimum length of a buried radial is of the order of $1/10^{th}$ of the free-space wavelength. Using more radials can however counterbalance these losses, increasing the efficiency of the antenna system.

Theoretically radials must be constituted of copper wires or thin tubing, cut on particular resonant length, and be located as well as grounded at the base of the antenna, not a few meters way. However, when placed too close to the earth, due to their significant capacitance, any length of HF wire will couple tightly to the earth and will be thus detuned as we just said. Worse, if the vertical is elevated more than 30 cm (1 ft) or so above ground, the wire leading to the ground connection will become part of the vertical radiator and will no longer be resonant on one or several bands. This is one of the reason for which any radial system has to be placed right at the antenna feed point to give good results. Installing it at ground level if your antenna is fixed on top of a tower for example is in this case nonsense.

The role of the radials is thus to provide paths of low resistance back to the feed point. Practically if your antenna is placed at ground level, to protect radials from a lawnmower and human activity, they can be buried just below the grass (over 5 cm or 2" deep to not cut the roots) but do not expect a great efficiency working this way. Take also into consideration that due to the length of waves below the 20 Meter band, in the lower frequencies it is usually out of question to bury or attach dozen radials measuring at least 10 Meters long and most amateurs prefer to select other antenna designs like dipoles. However, a dipole doesn't display the same radiation pattern as a vertical.

A network of 60 radials 10m long (1/4λ) is installed over 360° at the base of the four verticals used by Dana Roode, K6NR. Working from the desert of California, this network improves and replaces the poor conductivity of the soil. It has a good size to work from 7 MHz and above and constitutes thus a perfect ground plane. A dedicated vertical is used to work on the 75/80 bands where radials are only 1/8λ long, but thanks to their large number, this kind of network work very well on this low band too.

From the 20 Meter band and frequencies above that, you want to build a true ground plane with your radials and get good shielding you have to equally space them on the ground over 360° around the antenna. On the contrary, if you are using a Ground plane antenna with only 1 radial per band, it will act like a counterpoise rather than a ground plane. I suggest you tighten all radials in the same quadrant, each 10° apart to prevent coupling, in order to get a common directivity on all bands.

As we have just said above, to build a ground plane the number of radials depends on how long they are, the longer being the best. The magic trick is to know that as such wires becoming longer, they intercept the current on the surface out to a greater distance than shorter wires. But in parallel - the word is appropriated - there is a side effect: for a given number of radials, the separation between adjacent wires increases as the wires become longer to avoid low-loss path. Take an example.

Four 1/2λ radials are preferable to six 1/4λ radials but the difference is weak as the intensity of currents flowing out near the end of wires will be much less than that of currents closer to the antenna.

According to various specialists, it seems that over 24 Meters long (80 ft) the gain is no more significant and it is preferable to use shorter radials but more numerous.

To confirm this last sentence, using software simulating the ground losses, it appears that by increasing the number of radials from 10 to 20 for example the improvement in signal strength is only 1/10th of an S-Unit.

It is proved for a long time that it is useless to add too many radials at ground level to increase the efficiency of an antenna, because there is a much better solution, which is to raise the antenna above ground for the benefit of better performance!

Raising the antenna above ground

The first effect of placing a 1/4λ vertical at ground level is that the mirror-image of the "missing half" has consequences on the feed point impedance that displays about half the impedance of a dipole, or about 35 ohms plus ground loss resistance. At the risk of being repetitious, its lower end displays a low voltage / high current, conform to its large lobe firing all the output power at 0° and not higher above the horizon.

But other effects look more amazing. Some manufacturers state for example in their advertisings that they sold high performing antennas that do not require any radial or counterpoise (ground plane). Does it mean that if we raise our vertical a couple of meters above the ground, we can remove all our radials and keep its efficiency? No, you can't. This is not really so simple, except if you are willing to loose all its efficiency and your money.

Do you remember the 120 radials 1/2λ long each laying on the ground? According Bencher one more time, "*at heights between 2 and 8m about ground, four 1/4-waves radials for 40 meters will suffice to provide enough capacitive coupling to earth to work on 40, 75, 80 and even 160 Meter bands*". And indeed, to avoid the detuning of wires running at ground level and reduce the ground currents you must raise the radials as little as 1 meter off the earth. Of course you will raise the antenna by the same occasion, and probably much higher as we will see in one moment.

In fact here also some amateurs confuse the height of radials above ground and the height of the antenna above ground. As both constitute the radiative part of a vertical antenna and that one without the other is ineffective, the melting is understandable.

For example, if one states like Bencher did that for the 40 Meter band radials can be placed between 2 and 8 Meters high (1/20λ to 1/5λ high) to remove all ground effects, the antenna itself displays its best radiation pattern when placed at least 3/4λ above ground (see table below), so about 30 Meters high! Find the mistake? Both values seem incompatible, but they are not. In fact your radials will rise with your antenna and will be thus be placed high enough above ground to be "out of reach" from the soil effects.

Height of antenna center (l)	Takeoff angle
1.5	0°, 20°, 43°, 90°
1	0°, 30°, 90°
3/4	0°, 43°
1/2	0°, 90° (large amplitude)
1/3	0°, 90° (small amplitude)
1/4	0° or almost on the horizon

Ground plane antennas

We have not said yet, but although our vertical is now raised in height, it needs always its mirror image to work properly. In this case, the earth is too far and our connection running to the ground will be detuned as we said before. So, instead of being grounded the vertical works against a simulated ground made of some 1/4λ radials or stubs attached to the base of the antenna to create an artificial ground plane at a few meters high, hence its name. These radials are either open at 45° like a tripod or attached perpendicular to the antenna axis. For mobile operations the radials are removed at the benefit of loading coils in order to reduce their profile.

If we raise the antenna base at a height of 1/2λ or so, as Bencher states, usually four or six 1/4λ radials only provide about the same efficiency as dozen or even an hundred 1/2λ radials running underground. However, whatever the advertisings state, when the height above ground decreases say below 1Meter, the number of radials required to get the same efficiency increases. This is purely technical point not a marketing one.

From 14 MHz and above (because it is impracticable on lower bands) the best radiation pattern for a vertical appears from 3/4l high above ground where an additional lobe appears at 43° of elevation. At 1.5λ high the vertical antenna sees its main radiation lobes split in 4 parts, the main horizontal one splitting in 3 parts at 0°, 20° and 43° of elevation and a fourth one appearing at 90° (vertical).

The "Bencher" configuration using some 1/4λ radials placed in height is called a counterpoise. Used in HF and VHF / UHF bands, these Ground plane antennas are installed on small masts from 2 to 5 Meters high usually erected above the common obstacles using as few as three radials or stubs. Rather efficient, these vertical antennas are largely used, not only by the ham community but also by other services using shortwaves, hence the presence of a large amount of VHF / UHF Ground plane antennas here and there at the HQ of many companies.

Height

As we saw in the table displayed above, for a vertical cut for the 20 Meter band, at 5 Meters high to use its mirror image in the ground, the best efficiency is reached by erecting the antenna center up to 30 Meters high (100 ft)! Some Amateur installations can exceed this height, but for most of us this is neither feasible, nor economical. So for the lower bands of 40 to 160 Meters, amateurs have found some hybrid solutions, like using together a vertical from 9 to 15 Meters high associated to a radial system made of 4 wires buried in the ground. The antenna being less than 1/4λ high, the input reactance without loading is capacitive. In this case a simple series-loading coil placed at the base of the antenna will ensure the matching to the feed line and the transceiver. QST magazine and the other publications edited by ARRL about antennas have provided several models of such designs (including several models using wire antennas in inverted-V or loop configurations).

Radiation and SWR

Another question arises when speaking of efficiency: what happens to the power put in the antenna and how losses affect the SWR?

The radiation resistance or RF energy radiated by your antenna has to be consider as a "good loss" compared to the loss induced by the ground and conductor resistance that are consider as a total loss. Thus, knowing that some "conductors" (including traps, loading coil, etc) loose more energy than others, we can use the concept of form factor, the famous Q-factor.

But due to ground losses, that can easily exceed the losses in conductors, traps and coils, a well tuned vertical cut at 1/4λ can display a high SWR in the middle of a band (over 2.0:1) which means dozens of ohms vanished in pure ground loss resistance. Here are some tests made *in situ*. The first shows the efficiency before (first row) and after (second row) installing 6 radials of 2 Meters long at ground level around the base of a 1/4λ vertical:

Antenna	SWR	Line Impedance (W)	Radiation Resistance (W)	Total Losses (W)	Efficiency
1/4λ vertical	2.0:1	50	35	65	35%
1/4λ vertical	1.0:1	50	35	15	70%

SWR is measured at the antenna feed point in place of the transceiver end to avoid transmission losses and increase the accuracy. Total losses are due to radiation lost in coax, traps, loading coils, and ground loss resistances. The efficiency is expressed as the ratio of power radiated to the total power fed to it (or the ratio between the radiation resistance to total losses).

Below is the efficiency before and after installing 6 radials at the base of the previous vertical but resonating at half-frequency (e.g. on 80 Meters in place of 40 Meters), the third case is using 120 radials to reach a zero ground resistance:

Antenna	SWR	Line Impedance (W)	Radiation Resistance (W)	Total Losses (W)	Efficiency
1/8λ vertical	3.0:1	50	12	138	8%
1/8λ vertical	1.5:1	50	12	63	16%
1/8λ vertical	1.5:1	50	12	5	16%

For comparison purposes, here is the efficiency of a dipole:

Antenna	SWR	Line Impedance (W)	Radiation Resistance (W)	Total Losses (W)	Efficiency
1/2λ dipole	1.0:1	75	12	1	90%

From these figures we can conclude that several parameters are very important to get the highest efficiency of a vertical:

1. The radiation resistance must be kept as high as possible, but it depends on total losses.
2. The radiation resistance depends on the height of the vertical, but as heights over 1λ are not always practicable, we can reduce the ground loss resistance using as many radials as possible and using high-Q loading inductors of large diameter. Therefore the slim loading coils and traps made of thin wire encased in metal usually found in ham stores are NOT at all adapted to this usage.

3. A low value of SWR does not mean that your antenna system is operating efficiently. Even the fence installed in your backyard or an electric heater could be fine-tuned with an antenna tuner to display a SWR 1.0:1 but it will not radiate any power.

Conclusion

A ground plane radial system is recommended as it provides low-loss "return" paths to currents that can be "recycled" in the antenna that might otherwise flow on the lossy earth. If these returns of current come back to the shack they can be stopped using a current choke, a variant of a 1:1 balun.

Even if a "no-radial" system displays a low SWR, by itself it tell us nothing about the antenna efficiency, and mainly how the ground interacts with the system. For short, a simple vertical 8 Meters long using radials and a commercial "no-radial" vertical will display the same performances, but the SWR of the second antenna at the feed point can reach 20.0:1 or more without losing any energy but without emitting any power!

When an antenna is placed near ground level, the earth losses are the major factor limiting the antenna performances, and no antenna tuner or matching device can do anything about that physical law.

Thus if you have to remember only one thing that will be the next one: radials reduce the ground losses and increase the antenna efficiency. A side effect, too few or too short a radial length affects the SWR.

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