GROUNDS FOR IMPROVED RECEPTION

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It's usually recommended that a receiver be attached to a "good ground", often without much detail as to what this consists of or why one should do it. This article will define a ground, discuss the difference between powerline and RF grounds and describe how each works, enlarge upon the reasons for using a ground, describe methods of grounding, and, after giving the results of some experiments using different ground systems, will provide some pointers to what sort of ground to use in specific situations. It will be assumed that the reader has an initial mental picture of a "ground" as a copper rod or water pipe in soil, although other approaches will be described later.

WHAT IS A GROUND?

A ground is a point of zero potential, a reference point. For example, the chassis of a receiver is regarded as a ground by the circuits of the receiver. However, the zero reference point for the "live" side of the AC powerline is the earth itself. An external ground is an attempt to place a body of metal (the pipe or rod), and the receiver chassis to which it is connected, at the same potential as the earth itself. This approach will be described first, then it will be decided if that is what is really required for improved medium wave and tropical band reception.

The electrical resistance between the system and the earth itself is known as ground resistance and can be easily measured (see Appendix I). Ideally it should be zero; practically it may be in the tens to hundreds of ohms. The bulk of this resistance occurs between the surface of the ground rod or pipe and the soil itself and is dependent upon soil conductivity.

Conductivity is the ability of a material to pass electric current. The more conductive the soil is, the greater the chance of getting that chunk of metal to nearly the same potential as the earth. Conductivity increases with soil moisture, soil temperature and soluble mineral content. Unfortunately, surface soil moisture and temperature vary throughout the year, causing varying conductivity. The traditional ground system uses rods of six feet or more to take advantage of the more stable soil moisture and temperature at those depths.

Local ground conductivity can be improved by keeping the soil moist around a rod but a more radical difference can be made by the periodic addition of a handful of rock salt or Epsom salts to the area. Only the immediate area (within a foot of a rod) need be treated with salt, as the concentric layers of soil immediately around the rod are the most important so far as total ground resistance is concerned. Salts can sterilize soil so keep them away from valuable plants. Also, watch out for corrosion of the rod at the surface. Finally, salt will be leached away over time and will need to be renewed periodically.

Incidentally, surface ground conductivity can be measured with simple equipment. See Jerry Sevick's "Measuring Ground Conductivity" in March 1981 QST, p. 38; also see the ARRL Antenna Book but note that an AC isolation transformer was found necessary. A way of deducing ground conductivity from ground rod resistance is found in Appendix I of this paper.

POWERLINE GROUNDS AND RF GROUNDS

A ground which is designed only for minimum DC resistance from ground rod to earth will be described here as a powerline ground, as it is the type of ground used at a building's main breaker panel to keep one side of the 110 volt AC line at earth potential. A powerline ground should provide a low impedance path from the equipment to earth at DC and low AC frequencies. Therefore ground rods should have a low resistance to earth and though length of the connecting cable from equipment to the rods isn't that important, it should have low DC resistance.

The household electrical ground could act as a receiver RF ground but noise problems are likely. Also an RF ground lead must be electrically short, i.e. much less than a quarter wavelength. At 5 MHz, "short" should be under 10 feet, and though longer runs might be tolerable at lower frequencies, most house wiring will not provide a short enough connection to provide a good ground. For a receiver RF ground, the connection could be made of large diameter stranded copper wire (#10 or better). Copper braid is supposed to have lower impedance and the braid from junked coaxial cable (the bigger the better) is an inexpensive substitute. Also, copper strip (copper flashing) or 1/4" copper tubing works well if the ground clamp will accept them. Ground clamps should be clean, placed over shiny metal, and be weatherproofed once attached. Low ground resistance continues to be important, though for higher frequencies and greater soil conductivity, resistance to the surface soil is more important. Also, the capacitance of the rod to earth becomes significant at higher frequencies as capacitive reactance decreases.

An RF ground is used with an unbalanced antenna such as a vertical, a random wire (inverted "L" or "T") or a Beverage, and its purpose is to complete the circuit at a receiver's input. A radio wave can induce a current flow in the antenna towards the receiver, but an equal amount of current must flow away from the receiver. In a dipole for example, the current flows toward the other half of the dipole. A vertical antenna or random wire[1] is normally modelled as one half of a vertical dipole, while the RF ground acts as the other half of the dipole. In this case, the equal amount of current is induced in the soil (and from the ground rod) by the portion of the radio wave which is travelling under the earth's syrface. (Note that half a cycle of the radio wave later, current will flow out of the earth, through the receiver, and into the antenna).

Because radio waves cannot penetrate deeply in conductive soil, especially at higher frequencies, the bulk of the earth currents are generated within five feet of the surface, implying that a short ground rod may be all that is needed at shortwave frequencies, as long as it has low resistance to the surface soil. (See Figure 1)

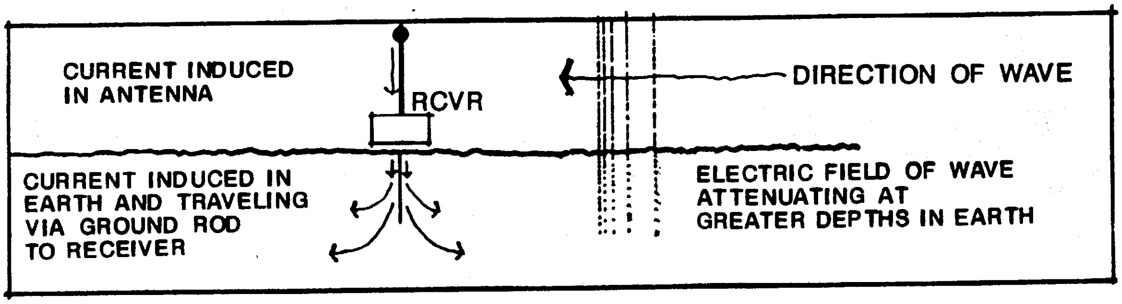

FIGURE 1. Illustration assumes a vertically polarized wavefront with no tilt and no slowing down of wavefront in the earth.

With a Beverage antenna, the RF ground also completes the antenna circuit, but in this case, the earth (as coupled to by the RF ground) is acting as the other side of a two-conductor transmission line.

One class of RF "grounds" has so far been left out of the discussion altogether: the radial system. Radials are lengths of wire laid on or under the ground to which the ground terminal of a receiver or transmitter is connected; they radiate outwards from the base of a vertical antenna. Notice that this type of "artificial ground" may have an infinite ground resistance if there is no DC connection with the earth, but they still complete the antenna circuit, the same way that the other half of a dipole does. Ground rods can be part of a radial system, and are often used at the base of an antenna.

WHY DO WE USE EXTERNAL GROUNDS?

The reasons for using an external ground are safety, reduction of received electrical noise, and for increased received signal strength. The last of these reasons is probably the most important for the diehard DXer, but the other two should also be considered.

GROUNDS FOR SAFETY

DXers' equipment is normally powered by household AC, and if a (rare) receiver fault occurs which puts household AC voltage on its chassis, it could subject the user to a shock. If the receiver chassis is placed at earth potential and the same receiver fault occurs, the resulting short circuit (remember that one side of the 110 volt line is at earth potential) will blow a fuse.

The third pin on AC power outlets is connected to the building's power line ground and if the receiver uses a 3-pin plug, it is likely grounded for safety. One needs to be cautious about connecting an external ground to the chassis of a receiver which uses a 2-pin AC plug. In vacuum tube receivers particularly, there may be a type of line filter which forms an AC voltage divider; as a result, current could flow between the chassis and an external ground. One can test for this potential danger by connecting a light bulb between the chassis and external ground; if it lights, there is a problem. Even if it doesn't light, check for current flow with an AC milliammeter. If there's no flow, you can connect the chassis to ground. However, if a recently-made unmodified receiver has an underwriters' approval sticker on it, then it is probably as safe as it needs to be, even if it uses a two pin AC plug.

Another concern is the safe discharge of static electricity, which can be built up on a wire antenna by precipitation or wind, thereby endangering sensitive receiver circuitry. On older receivers, such static charges were bled off to ground via inductive coupling to tuned RF amplifiers, but newer receivers rarely use that kind of circuit. It's therefore advisable to connect the antenna to ground outside the receiver via a 10k resistor and a neon bulb as suggested by Don Moman elsewhere in this book. Again, the third pin of the AC power plug should provide an acceptable ground for this sort of protection.

Although a ground can bleed off static electricity from an antenna, one should not trust a simple ground to protect your antenna or receiver against lightning. Elaborate low-resistance systems based on multiple ground rods and plenty of connective cabling have been used in commercial and amateur transmitting stations (cf Altman in the December 1987 CQ, pp. 76ff, or the treatment of the subject found in the ARRL Antenna Book), but the best and easiest protection for the listening post is to configure the antenna lead-in so that it can be easily disconnected where it enters the building. When lightning threatens, the antenna lead-in may be grounded externally to the building or it may be left hanging. It is also advisable at this time to pull out the AC power plugs to your equipment.

GROUNDS FOR NOISE REDUCTION

Man-made electrical noise is the only type which is affected by the type of external ground used with the receiver. Unfortunately, connecting an external ground to a receiver may make such noise problems worse than if one used no external ground at all.

To understand why such noise problems should develop, picture the live side of the AC powerline either as an antenna picking up electrical noise or as a conductor of electrical noise from elsewhere. The noise signal covers many frequencies, including the one being monitored, and can be capacitively coupled from the powerline to the receiver chassis. If an external ground is connected to the chassis, the noise signal will travel to earth through the ground resistance.

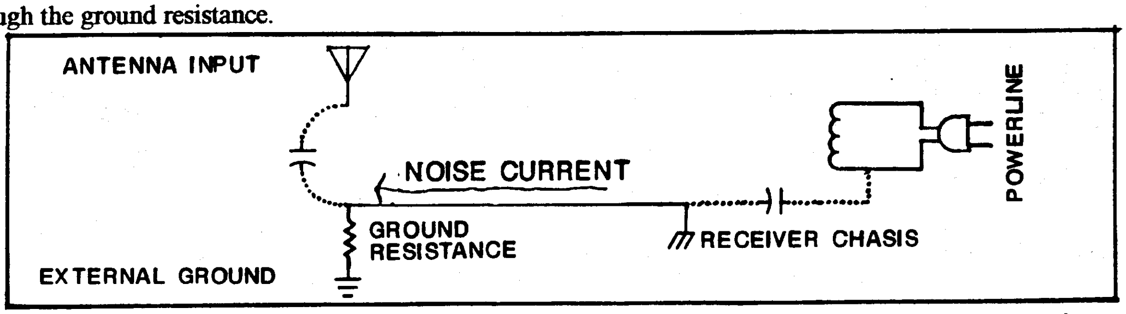

FIGURE 2. The ground resistance must be very low, otherwise the noise voltage developed across it may be capacitively coupled to the receiver antenna input. A "good" ground cuts down on the developed noise voltage which weakens the strength of received noise.

In some cases, local noise problems may mean that it is not practical to connect an external ground, particularly a mediocre one, to the receiver chassis. One possibility not tried here is to wrap the powerline around a ferrite rod just before it enters the receiver, providing an RF choking effect. Another possible solution is to use an input isolation transformer using a separate ground from receiver or powerline ground. The beverage matching transformer found in *Proceedings 1988* will work well; see diagram below.

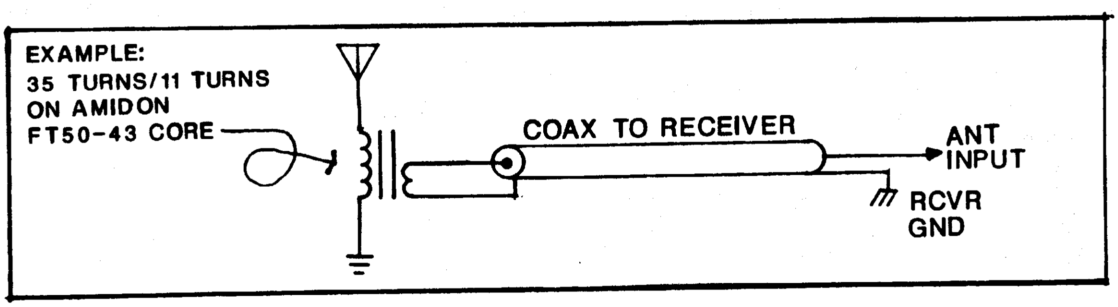

FIGURE 3. Note that this set-up also provides a path to ground for static discharge from the antenna.

GROUNDS FOR IMPROVED SIGNAL STRENGTH

Many DXers have found that connecting an external ground to a receiver has not improved receiver signal strength, yet Patrick Martin in Seaside, Oregon found that MW signal strength on his SP-600 improved as he added more ground rods to his system. For most of us however, the household power line ground seems to be as good an RF ground as anything that we are able to put into the earth ourselves.

Patrick's success with additional ground rods was probably due to his very conductive Pacific coast soil, but for the rest of us it is perhaps time to look at practical RF grounding systems to discover which are likely to deliver improved signal strength.

PRACTICAL GROUNDS

The use of a cold water pipe or copper rod as a ground have often been described before here and in other literature, but a brief recap is in order. If a copper water line enters a building near the receiver, it can be used as a ground connection, simply by attaching a short length of suitable cable (see "RF Grounds" above) from the receiver to a grounding clamp fitted onto the pipe.

Water pipe grounds may not work well if a joint underground is threaded, or mates with plastic pipe. The rest of the building's water system may also act as an antenna which could contribute to increased electrical noise or spurious signals.

Copper coated steel rods made for powerline grounding are available and are commonly 1/2" in diameter by six or eight feet long. Such a rod can be pounded into the ground near the receiver location, and again be attached to the receiver via a grounding clamp and suitable cable. Length of a ground rod is more important than diameter; doubling the diameter reduced ground resistance to earth by less than 10%, while doubling length reduced resistance by 40%.

If the local soil is dry or rocky, or if only short rods are available, or one simply wants the lowest ground resistance possible, then a multiple rod system might be the way to go. Such a system inexactly parallels the resistance to ground from each rod with the ground resistance of all the other rods. The classic arrangement has the rods spaced at 6' or more from each other, usually in series. These are connected together with braid, cable or copper tubing via ground clamps, and one end of the system is connected to the receiver with as short a conductor as possible.

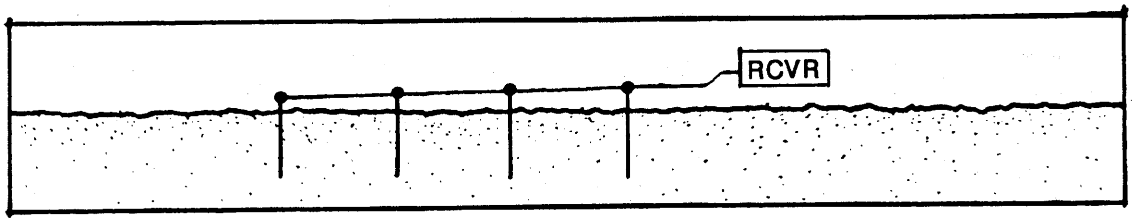

FIGURE 4. The SWG ground.

A variant of the multiple rod ground is the surface-wire ground (SWG) developed by the U.S. Army Signal Corps. It is 70 feet of 1/8" diameter wire configured in a loop on the ground around the radio equipment and held in place by 15 to 18 specially formed ground rods only 10 inches long. The loop is connected to the equipment by three equidistantly spaced cables.

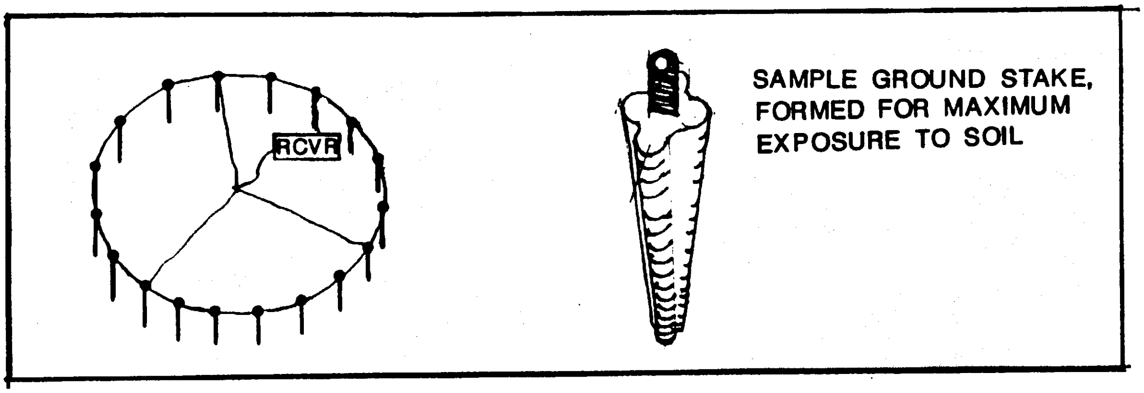

FIGURE 5.

One might contemplate using radials as a receiver ground, but the FCC requirements of a "minimum of 120 buried radials each 1/4 wavelength long" for AM broadcast stations would certainly be discouraging. However, those figures are for use with a 1/4 wavelength vertical; most low-band DXers use antennas with vertical segments much smaller than that. Fortunately, radio amateur researchers[2] have found that an antenna only a fraction of a wavelength long needs many fewer radials (no more than 40; even 4 or 6 gave reasonable results), that they need be no longer than 0.2 wavelength, and can be different lengths to fit the available space. A yet more efficient system was created when the ends of the radials were joined together. It was recommended that radials should be insulated and not be buried more than a couple of inches due to poorer penetration of radio waves through conductive soil as frequency increased. In fact, a counterpoise system (radials raised to six feet above ground) was the system of choice. It seems likely that a simple radial or counterpoise system could make a reasonable RF ground for receiving. In fact, a simple system may not look that much different from the SWG described above.

SOME OBSERVATIONS

I got the idea for this article when I realized that, although I was using very poor grounds on Beverage DXpeditions, I was getting quite reasonable signal strengths at the receiver. The soil at the expedition sites was damp but not particularly conductive; its rocky texture also meant that I was very lucky to get a rod into the ground more than 18 inches or so.

Indeed, experiments during July 1991 showed that a really minimal ground rod (8") in gravel and treated with salt water, delivered MW signals only one or two dB down from those heard using a 3 foot rod in salt treated mud. A Beverage matching transformer was used between antenna and receiver, as in Figure 3 above. Later, Don Moman told me that his Beverages with matching transformers delivered as much signal using a 6" ground rod in swampy soil as when using a 3 foot rod. Further experiments are needed to compare these "poor" grounds with a really low resistance ground once I can design one. But it did encourage me to find out whether "poor" grounds could also be successful with the more common random wire.

Similar experiments were attempted at home using a random wire made of a horizontal loop about 130' circumference at 15' high (using a 15' downlead). For frequencies up to a few MHz, this corresponds to a short vertical with a sizeable capacity hat. The reference ground system was four series-connected 6 foot long ground rods each separated by about 6 feet and directly connected to receiver ground as in Figure 4.

The following results were observed while using a Beverage matching transformer to couple the antenna/grounds to the receiver, as in Figure 3 above.

"Ground system" was the same as the multiple rod system used for reference, but was used with a matching transformer as indicated above. --local ground is clay loam; this was late summer 1991, and the soil surface was generally dry; 8" rod was in an area that had been watered. --"rod with salt" observations took place after the area had been treated with salt water.

f (kHz)	**Ground System**	**8" Rod**	**8" Rod with salt**
530	+ 9 dB	+ 7 dB	+ 8 dB
830	+ 8 dB	+ 4 dB	+ 6 dB
1560	0 dB	- 4 dB	- 1 dB
2500	0 dB	0 dB	0 dB
5000	+ 4 dB	+ 2 dB	+ 6 dB
10000	0 dB	+ 3 dB	---
15160	0 dB	+ 3 dB	---

NOTES:
"Ground system" was the same as the multiple rod system used for reference, but was used with a matching transformer as in Figure 3 rather than directly connected as in Figure 4.

Local ground is clay loam; this was late summer 1991, and the soil surface was generally dry; 8" rod was in an area that had been watered.

"Rod with salt" observations took place after the area had been treated with salt water.

No local electrical noise problems were noted when small rod was used.

For MW, a homebrew receiver was used, described in IRCA Reprint M56. It has a 50 ohm input, and due to inductive coupling to its first tuned circuit, provides a DC path from antenna to ground. Powerline ground is coupled -to chassis ground via stray capacitance.

For SW the Drake SPR-4 was used. It has a 50 ohm antenna input, also with a DC path from antenna to ground. Powerline ground is directly connected to chassis ground.

Early in 1992, similar experiments were performed, only this time, antenna and ground were connected directly to the receiver rather than via a matching transformer. The same reference ground was used as in the above set of tests and additional types of grounds were also evaluated.

f (kHz)	Receiver	Powerline Ground	Small Rod	6 Random Radials	SWG
530	Homebrew	-3 dB (noisy)	-3 dB (noisy)	-3 dB (noisy)	-3 dB
530	2010	-5 dB	-3 dB	0 dB	-5 dB
830	Homebrew	-1 dB	---	-9 dB	-5 dB
830	2010	-8 dB	-4 dB	-4 dB	0 dB
1560	Homebrew	-12 dB	-9 dB	-4 dB	+2 dB
1560	2010	-22 dB	-8 dB	+3 dB	-10 dB
2500	2010	-20 dB	0 dB	-6 dB	-8 dB
2500	SPR-4	-8 dB (noisy)	-7 dB	-4 dB	-8 dB
3360	SPR-4	0 dB (noisy)	0 dB	0 dB	0 dB
5000	2010	0 dB	0 dB	+3 dB	0 dB
5000	SPR-4	0 dB	0 dB	0 dB	0 dB
10000	2010	0 dB	-2 dB	+3 dB	---
15160	2010	0 dB	0 dB	0 dB	---

NOTES:

"Powerline ground" is whatever path to the AC powerline ground offered by the receiver in question.

Random radials varied in length from 14 to 35 feet arranged every 20 degrees over 100 degrees lying on the ground underneath the horizontal loop. An optimum system would have longer radials for the lower frequencies, cover the full 360 degrees, and be joined at the far ends.

SWG is surface wire ground as described above, (Figure 5) but ground rods were lengths of 3/4 inch copper pipe rather than the ground stakes.

When the 8" rod was used, little change in the results occurred when the area around the rod was treated with a salt solution.

Local soil is clay loam, damp at the time of the tests, likely with good conductivity. Ground resistance of various systems as derived by the set-up in Appendix I:

Multiple rod ground system	3.5 ohms
Small rod (8")	575 ohms
SWG	24 ohms
6 radials	infinity

2010 is the SONY ICF-2010, which does not have a DC path from antenna to ground; input impedance varies from 75 to over 200 ohms. Powerline ground is likely coupled to radio's DC ground via stray capacitance in its wall transformer.

Where "noisy" is parenthetically noted, local electrical noise was heard that was not observed using the reference ground system.

The above observations verify conventional wisdom, as long as the antenna and ground are connected directly to the receiver. The ground with the lowest resistance to earth (the collection of 6' ground rods), delivered the best signal strength with the lowest electrical noise, at least through 2500 kHz. Above 2500 kHz, that ground quickly lost its advantage.

The results were quite different when a matching transformer was used. A short ground rod delivered nearly as much signal as the larger system, with no worse response to local electrical noise. This is a particularly striking observation when the amount of work put into making the respective systems is compared. Note also that these observations took place when the surface ground conductivity was likely poorest, and therefore worst case for this area. In addition, the matching transformer with a "poor" ground almost always delivered a stronger signal than the best ground system did when it was connected directly to the receiver using the same antenna. Finally, the matching transformer provides a static bleed-off path and minimizes noise response if it is connected to a ground isolated from receiver and powerline ground. These experiments point out that the matching/isolating transformer is a powerful tool for those who cannot build the best possible ground system.

EXPLANATIONS

These are somewhat tentative, but are included for those who might investigate this subject further.

Why should the input transformer make such a radical difference? As far as rejection of electrical noise is concerned, it is important to isolate RF ground from chassis ground to prevent noise currents circulating through the chassis and being coupled to the antenna. The matching transformer does this very well.

Why does the Beverage work well with a poor ground and a matching transformer? The Beverage antenna can be modelled as a generator with a 500 ohm internal impedance; the load for this generator is provided by the input winding of the matching transformer and the resistance to earth of the ground rod. All these impedances can be modelled as resistances at medium and low frequencies; capacitive and inductive reactance exist but can be ignored. At higher frequencies, the capacitive reactance of the rod to earth in parallel with the ground resistance becomes significantly small, reducing ground resistance further.

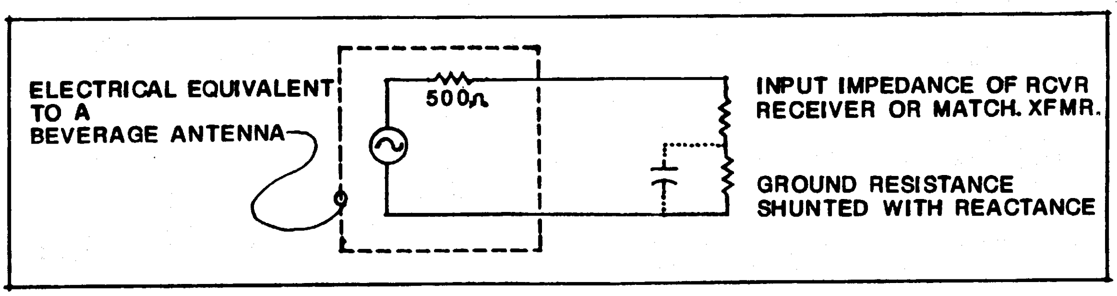

FIGURE 6.

Using voltage divider theory we will find that with a ground resistance of zero, half the voltage generated on the antenna will appear across the input winding of the matching transformer. But with a "poor" ground's resistance of 500 ohms, fully one-third of the voltage generated at the antenna will appear across the matching transformer winding. This is 3 dB down from the voltage developed with a ground resistance of zero....one half an S-unit. Such a difference might be significant in logging weak signals at dawn, but for temporary installations, the relative ease of setting up a "poor" ground may be more important than the loss in signal strength.

The explanation for why a poor ground and matching transformer should work well with a random wire is essentially the same, but the model of a random wire and ground is somewhat more complicated.

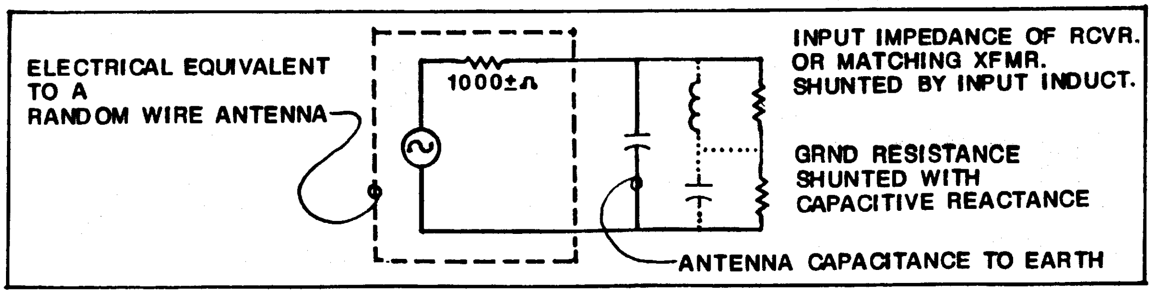

FIGURE 7

In this case, the random wire may look like a generator with an effective resistive impedance of well over 1000 ohms. The load is the inherent capacitance of the random wire to earth in parallel with the voltage divider formed by the input impedance of the receiver in series with ground resistance. Once again, capacitive reactance of receiver ground to earth can be ignored except at higher frequencies, where its low value is beneficial. Although the impedances involved are more complex in the case of a random wire, the basic voltage divider between the input of the receiver and ground resistance still exists. When a high impedance receiver input is used (such as is found when using a matching transformer), the voltage drop across a higher ground resistance becomes less significant, and relatively greater signal is delivered to the receiver.

In both the situations above, a receiver input of 50 ohms will have a correspondingly lower voltage dropped across it compared with the voltage dropped across the ground resistance. When using a low impedance receiver input, it is therefore important that ground resistance be low.

It is important to note that the Beverage matching transformer is not optimized for use with a high impedance (at medium frequencies) random wire. Further observations should be made using a 1000 or 2000 to 50 ohm transformer to see if yet greater signal strength results when using a poor ground.

CONCLUSIONS

A) The traditional emphasis in ground system design has been to get as low a resistance to earth as possible, implying deeply driven multiple ground rods. Although AC powerline grounds, transmitting grounds and lightning protection systems require a low resistance to earth, it is not essential for improved radio reception, unless one is listening at lower frequencies with a low impedance input receiver and with the ground system connected directly to the receiver chassis.

B) Safety considerations might seem to require a low resistance path to earth from a receiver chassis, but:

--Newer receivers need to have passed various underwriters' safety tests to be allowed on the market; if a safety ground is required, it will be provided via a 3-pin power plug.

--Older receivers should be assessed on a unit by unit basis before external grounds are connected; there may be a potential difference between chassis and earth, which would require that an external RF ground be connected via an isolating transformer.

--Direct Connection of an external ground may actually increase receiver response to local electrical noise.

--Bleeding off static charge from an antenna does not require a low resistance path to earth, simply a DC path. Other safety grounding requires a low resistance path to earth.

C) Using a matching transformer with an antenna and isolating the earth ground on the antenna side of the transformer from chassis ground on the receiver side will meet most DXers' requirements for improved reception with low response to electrical noise, especially below 2 or 3 MHz, even when using a "poor" ground.

D) A "poor" ground might be due to low soil conductivity, a short ground rod or both, but should still be connected to a matching transformer using as short a wire length as possible.

E) Soil conductivity can be improved by moistening the soil in the immediate vicinity of a rod, especially if salt is added. Improved surface conductivity seems to be improve signal strength, particularly below 2 or 3 MHz.

F) Unless the soil has very poor conductivity, ground rod depth becomes less important at higher frequencies, even if the rod is connected directly to the receiver. At these frequencies, the bulk of the ground currents generated by an incoming wave are close to the earth's surface. Above 5 MHz, an external ground doesn't seem to be of much use. Radials may help, but should not be buried more than a few inches. In fact they could be placed high enough to qualify as a counterpoise. For reception purposes, radials can be fewer and shorter than are the standards for AM broadcasting.

G) With a loop or dipole as a receiving antenna, an external ground does not appear to improve signal strength or response to electrical noise.

ENDNOTES:

[1]The sort of random wire which can fit on a city lot is modelled as a vertical for frequencies below 5 MHz, as the bulk of the signal pickup is on the vertical portion of the "L" or "T", with the horizontal portion acting as a "capacity hat", giving the antenna greater capacitance to earth.

It should also be pointed out that an RF ground is unlikely to improve the signal pickup of a balanced antenna such as a loop or a dipole. I haven't noticed any improvement in rejection of electrical noise using earth ground with these antennas either.

[2]Doty, Frey, and Mills, "Efficient Ground Systems for Vertical Antennas", QST, February 1983, pp.20-25
--Frey, "The Minipoise", CQ, August 1985 pp.30-39

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MEASURING RESISTANCE OF GROUND ROD TO EARTH AND EARTH RESISTIVITY

One requires (in addition to the rod being measured): two ground rods of two or three feet length; a voltage source, I've used 6 and 12 volt batteries; a milliammeter (an inexpensive digital multimeter may be preferable to a VOM, as measured current may be quite small); ten feet or more of insulated wire.

Pound the two rods into the ground at least ten feet from each other and from the ground rod to be measured, in a triangular arrangement:

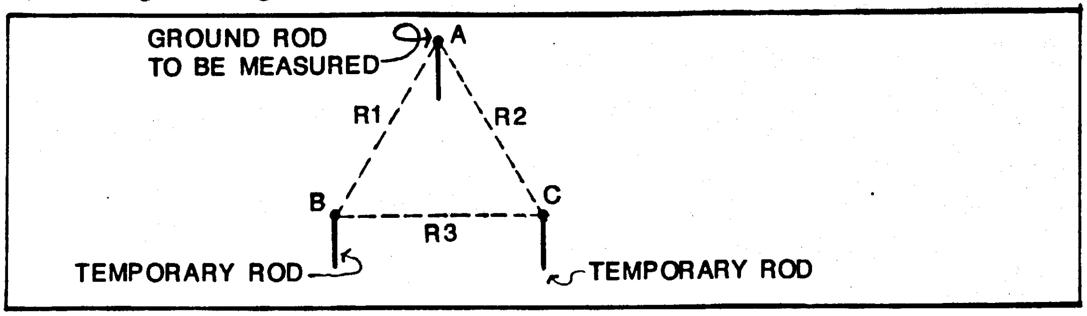

FIGURE 8. Connect one battery terminal to the ground rod to be measured (A), and connect the other (through the milliammeter and length of wire) to ground rod B. Using the voltage of the battery, the current through this circuit, and Ohm's law (R=V/I), calculate the resistance between the rods. This will be R1. Repeat the observation and calculation between rods A and C for R2, then for rods B and C for R3.

The ground rod resistance to earth (Rg) is found from the following formula:

$$Rg = \frac{(R1 + R2 - R3)}{2}$$

(I have not seen the following documented elsewhere, nor have I tried it, but the Sankosha Corporation in *San-Earth Technical Review* suggests finding ground resistivity using ground resistance (Rg) and the length of a ground rod (L) and its diameter (d):

$$\text{Resistivity} = \frac{2.75\ Rg\ L}{\log\ (4L / d)} \quad \text{in ohms-meters}$$

The inverse of the above is ground conductivity.

Acknowledgement: My thanks to John Bryant, David Clark and Don Moman for providing some of the background material for this article.