Real ground and its effect on low horizontal HF antennas

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It is well known that all antennas interact to a greater or lesser extent with the ground beneath them. In the case of a vertical antenna driven against ground, that interaction affects the characteristics and the performance of the antenna very significantly. In most situations much effort will then go into ensuring that the so-called ground plane, usually extending at least a quarter of a wavelength in all directions around the antenna, is as good a conductor as can possibly be achieved. At HF, and particularly within the confines of most gardens, there are numerous constraints that apply over and above the purely technical. Not least of these is that the antenna enthusiast usually has to consult higher authority (his XYL) before desecrating the lawn and garden in the interests of amateur radio, science or other noble purposes. In the end, a network of radial wires around the base of the antenna (usually buried beneath the lawn) has to suffice. By contrast, far less attention is paid to horizontal antennas and so it is the purpose of this article to address the effects of the real ground that lies beneath such an antenna, particularly when the antenna is only a fraction of a wavelength above the ground as is often the case on the lower HF amateur bands..

What is real ground?

In our day-to-day world we talk loosely of the ground (or earth) beneath our feet as being some, usually, sandy substance within which things grow. And the more we water it the better they grow. In the electromagnetic world occupied by antennas, it is the electrical characteristics of the ground rather than its pastoral features that are far more important; though, as is well-known, watering the ground certainly helps antennas too. There are two measurable electrical quantities which define the important characteristics of the ground and its underlying strata whether they be as solid as rock, or some other geological material such as clay or a whole host of minerals that go to make up the Earth's crust. The two important properties are the electrical conductivity, usually indicated by the Greek letter sigma (σ) and the permittivity, or dielectric constant (but see below), indicated by epsilon (ε). Geophysicists tend to talk about the resistivity of rocks, indicated by the letter rho (ρ), which is simply the reciprocal of conductivity. I shall follow the usual approach adopted by practitioners of the antenna art and use conductivity. There is one other electrical characteristic of geological materials, the magnetic permeability, called mu (μ), which is only significant when the material is magnetic. In general, most geological media are non-magnetic.

Perhaps unsurprisingly, the intriguing concept of what is called free space also comes into play because the antenna 'sees' free space all around it except beneath it where it sees the ground or the earth, as it's known on opposite sides of the Atlantic. At this point it is useful to give some numerical values to those free-space quantities that go to defining what is known as the characteristic or intrinsic impedance of free space usually written as Z_o. Intriguingly, it has a value of approximately 377 Ω. How this comes about is bound up in the free space values of permittivity $\varepsilon_o = 8.854 \times 10^{-12}$ F/m and permeability $\mu_o = 4\pi \times 10^{-7}$ H/m where F and H are farads and henries respectively. From Maxwell's equations. it turns out that the ratio of the electric field intensity E to the magnetic field intensity H yields the impedance of the medium in which those fields exist and, in free space,

$$Z_o = \sqrt{\frac{\mu_0}{\varepsilon_o}} = 376.7\ \Omega.$$

This value of 377 Ω is one of the universal constants that applies everywhere; it is sometimes given as $120\pi\ \Omega$ because that can simplify the mathematics in some cases.

Whereas the impedance of free space is a constant, the impedance of the ground is anything but. It depends on the geology and, particularly, on the water content of the rock, sand, soil or whatever. The reason for this is that entrapped water usually contains various salts in solution which raise the conductivity of pure water. Another factor which affects the impedance of these geological materials (and which is often overlooked) is the frequency of the electromagnetic waves that strike and often pass through them. Of particular importance in the context of radio communications is that both conductivity and permittivity are frequency-dependent and so it is most misleading to call the latter the dielectric constant as one often sees in some places. In general, the relative permittivity ε_r of any non-conducting material is expressed relative to that of free space. Hence, we have that

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_o}$$

which is simply a number without any units. Conductivity, by contrast, is measured in siemens per metre, expressed as S/m

Figures 1 and **2** show the variations in the conductivity and relative permittivity of a range of grounds that could well be found beneath an antenna, though one has to concede that some of them are rather less likely than others. What is very important to note are the ranges over which both conductivity and relatively permittivity can vary. both in terms of the basic geology involved but, and most importantly in our antenna context, in terms of the frequency as well. The conductivity can change by as much as three orders of magnitude from as low as 10^{-4} S/m in a city, for example, to as much as 10^{-1} S/m if there is a rice paddy beneath the antenna. In between, we encounter the rather more typical ground types above which most amateur radio antennas are located. Of interest too is the case of sea water. As is well-known, salt water is a far better conductor than any non-metallic geological substance. In addition, its relative permittivity is much higher too. By contrast, fresh water is not a good conductor ($\sigma = 10^{-2}$ S/m), so erecting an antenna near a lake or pond is unlikely to yield any benefits other than perhaps of a scenic sort. It is particularly important to notice that whereas all geological media exhibit distinct variations in both their conductivity and the relative permittivity as frequency changes, those of sea water are quite independent of frequency which makes it a particularly interesting material. However, unless one is operating maritime mobile, most amateurs will never encounter those useful electrical features because the ‘ground plane’ beneath an antenna has to be large in extent in order to be effective.

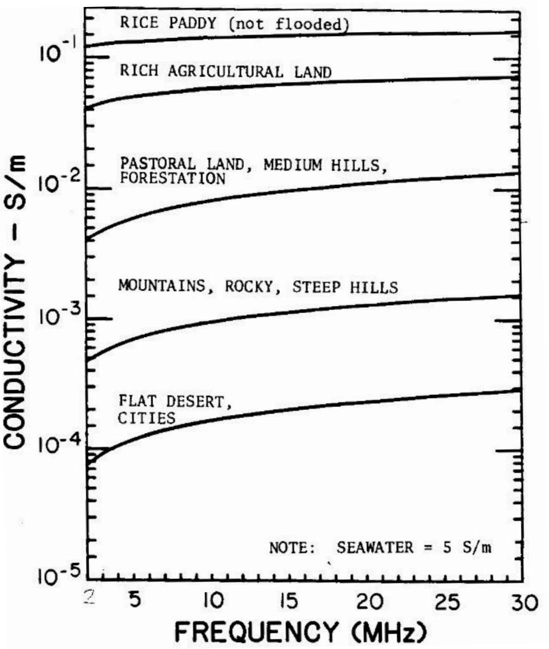

Figure 1. Variation of the conductivity of various ground types across the HF spectrum.

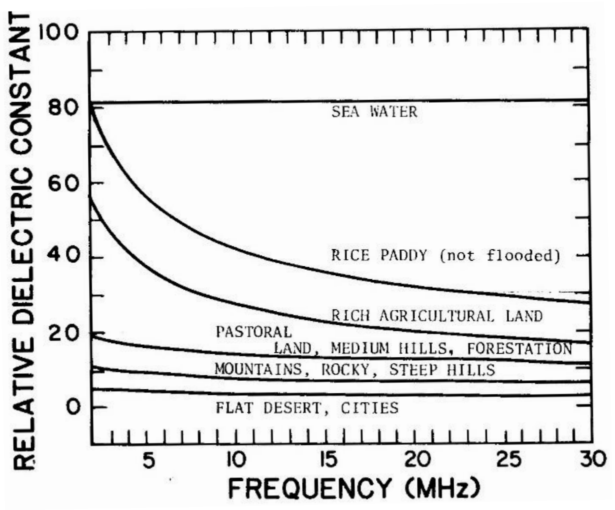

Figure 2. Variation of the relative permittivity of those same materials as in Figure 1 across the HF spectrum

The relationship between σ and ε

Since both the conductivity and relative permittivity of the ground affect the performance of the antenna, it is useful to be able to combine them in some meaningful way while also including the effect of frequency. This can be done very usefully by means of what is called the loss tangent. Again, Maxwell comes to our assistance (though most people probably don’t quite see it that way). In his famous equations. one of them indicates that the current density within any medium contains two parts: one called the conduction current density and the other, the brilliant piece of Maxwellian foresight, is called the displacement current density. Using the symbols shown above the total current density is proportional to

$$\sigma + j\omega\varepsilon$$

where $j = \sqrt{-1}$ indicates the rotation by 90 degrees and $\omega = 2\pi f$ is the angular frequency. This can be represented by the analogy of the currents I_c and I_d flowing through the resistor and capacitor of a parallel RC circuit as shown in **Figure 3**. Bearing in mind that those two currents differ in phase by 90 degrees, one arrives at the diagram shown there from which we see that

$$p = \tan\delta = \frac{I_c}{I_d} = \frac{\sigma}{\omega\varepsilon}$$

The loss tangent p is a very useful indicator of whether the ground behaves like a conductor or an insulator, a dielectric in other words, or falls somewhere in between. It should be clear from the equation above that when the conduction current is larger than the displacement current (*i.e.* $p > 1$), the material is predominately a conductor so values of the loss tangent greater than unity imply a conducting material and the larger that value of p the better the conductor it is. By contrast, materials with loss tangents less than unity appear more like dielectrics while those where $p = 1$ are classed as quasi-conductors. Beware of calling them semi-conductors: they are very different beasts.

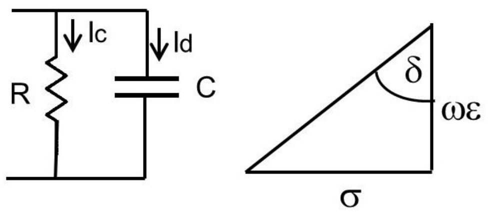

Figure 3. The currents through a parallel RC circuit and their phase relationship showing $\boldsymbol{p = \tan\delta = \frac{\sigma}{\omega\epsilon}}$

It will be noted that, in addition to the frequency dependence of σ and ε, the displacement current is frequency-dependent too because of the presence of the ω term. This is extremely important and it illustrates a most important fact. As a general rule, at ‘low’ frequencies a particular material could well be a far better conductor than it would be at a much higher frequency – all else being unchanged, of course. However, the applicable values of both conductivity and relative permittivity of the material (ground in this case) must be used at the appropriate frequency. **Table** 1 below shows the loss tangent for each of the ground types given in **Figures 1** and **2** at a frequency in the 40 m band.

GROUND TYPE	σ S/m	ϵ_r	$p = \sigma/\omega\varepsilon$
1. Desert, city	2×10^{-4}	5	0.1
2. Mountains	8×10^{-4}	9	0.2
3. Pastoral forest	8×10^{-3}	15	1.4
4. Rich agricultural	6×10^{-2}	32	4.7
5. Rice paddy	2×10^{-1}	50	10.1
6. Sea water	5	80	158

Table 1: Loss tangents of various types of ground at 7.1 MHz

Clearly, the desert and city types of grounds are poor conductors, exhibiting definite dielectric characteristics because of the small loss tangent, whereas a rice paddy is a reasonable conductor but not nearly as good as sea water. Pastoral and forested regions are very much in the quasi-conductor category at 7 MHz. Using the expression above for loss tangent, and after inserting the appropriate values for conductivity and relative permittivity from the two graphs, will produce the relevant values of p at any other frequency in the HF band. For example, at 21 MHz the loss tangent of the pastoral or forested region is now about 0.6 which makes it a far poorer conductor. Even the rice paddy, though still a good conductor, has seen its loss tangent drop to below 6 at 21 MHz. These results indicate how important it is to have some knowledge of the electrical characteristics of the ground beneath an antenna in order to be able to assess, by one means or another, how effective it might be. And this, naturally, brings us to methods of determining the radiation efficiency of an antenna but, before doing that, we need to consider how the antenna's height above ground affects its impedance and, most particularly, its input resistance.

Effect of antenna height on its impedance

As is generally well known, the input or driving-point impedance of an antenna changes as its height above ground changes. This happens because any antenna erected above a reflecting surface such as the ground behaves in a similar way to an object placed in front of a mirror. As the distance between the object and the mirror is changed so the apparent distance of the image of that object appears to change in step. In other words, the image always appears to be as far behind the mirror and the object is in front of it. This is a very important and useful analogy which can explain many of the characteristics of an antenna when erected (as most are) above the ground. Effectively, we have not one but two antennas – one being the antenna itself, the other being its image – and together they interact to determine the overall characteristics of the antenna in its operating environment. In this article I am only considering the effect that changes in height have on the antenna's impedance. The radiation pattern is directly affected by the presence of the image antenna as well because, effectively, an antenna and its image behave like a two-element array with some appropriate phase difference between the currents in the antenna and its image. But that is a subject for another time.

This fundamental phenomenon of the image antenna produces what is called the mutual impedance, written as Z_m or Z_{12} between the antenna and its image. Such mutual impedances exist between the elements of all antenna arrays such as the Yagi-Uda (to give full credit to its co-creator) and, as would be expected, the effect increases the closer the array elements are to one another. Mutual impedance effects always exist when an antenna is close to other conducting objects of significant size and so the impedance seen at its input terminals Z_{in} always consists of the impedance of the antenna, had it been in free space, plus the mutual impedance caused by the coupling of the fields to some other nearby conductor. This can be expressed as follows.

$$Z_{in} = Z_1 \pm Z_m \left(\frac{I_2}{I_1}\right)$$

Here Z_1 is the so-called self-impedance of the antenna alone and Z_m is the mutual impedance between the antenna and its image while I_1 and I_2 are the currents in the antenna and the image respectively.

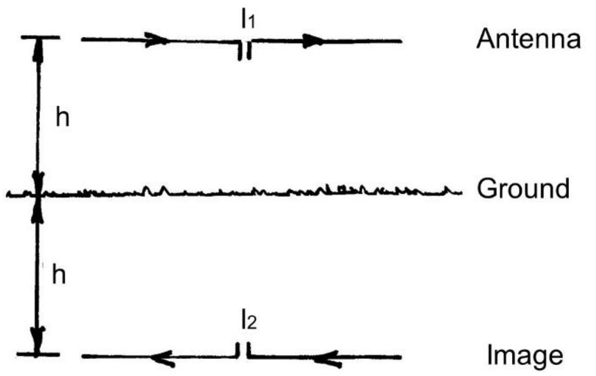

Figure 4. The horizontal antenna and its image in the ground showing the phase of the currents

Clearly, both the amplitudes and the phases of the currents in those coupled elements are all-important. It so happens that the currents in a horizontal antenna and in its image are 180 degrees apart as shown in **Figure 4**. By contrast, they are in-phase for a vertical antenna and its image. Not surprisingly, the magnitudes of those currents are equal when the ground beneath the antenna is a perfect conductor but this does not necessarily follow when the ground is a poor conductor (*i.e.* $p \ll 1$). And, just to complicate things even further, because of the 180-degree phase shift between those currents in the horizontally polarised case, the current ratio becomes negative. It's for this reason that the plus and minus signs occur in the general equation above. Clearly the existence of this mutual impedance complicates things rather more than somewhat and calculations can be far from straight-forward.

This added complexity makes the determination of an antenna's impedance at various heights above different types of ground a complicated and extremely tedious task. Fortunately, we now have very effective computer programs to do it for us. By far the most sophisticated of these is the Numerical Electromagnetic Code, or NEC, which was developed by a team at the Lawrence Livermore Laboratories in California, beginning in the late 1970s and continuing right up to the present day. NEC used to require mainframe computer support and, in order to make it accessible to a far wider group of users, both professional and amateur, various scaled-down versions have appeared over the years. In the author's opinion the best of these is EZNEC (as in Easy NEC), now in its 6th version, which resulted from a considerable amount of work by Roy Lewallen W7EL.

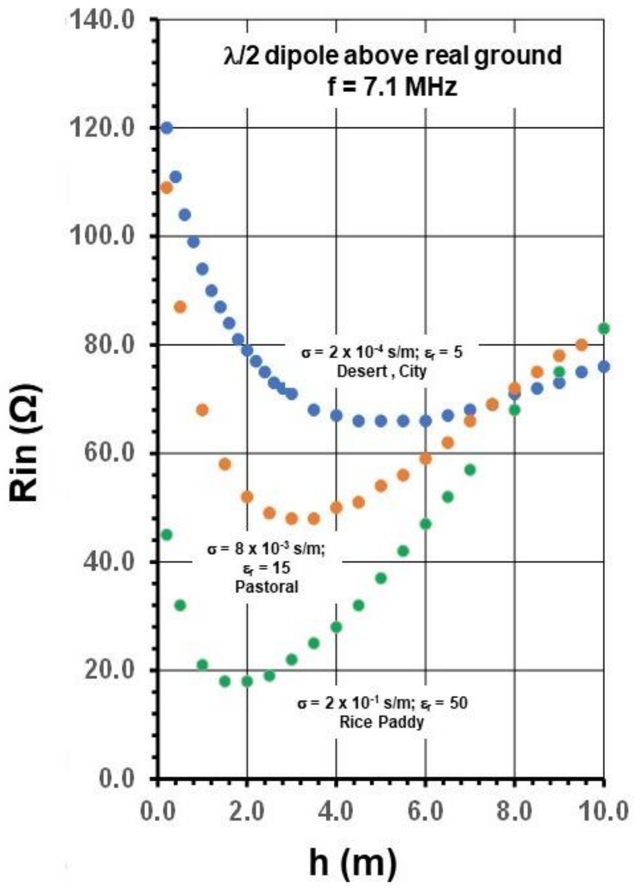

Figure 5. The computed variation of the input resistance of a half wave dipole with height above three different types of ground

Figure 5 shows the computed input resistance given by EZNEC of a half-wave dipole when very close to the ground. In the case shown there the antenna height varies from just 1 m up to 5 m above ground level. Such low heights were chosen in order to illustrate a most important fact about the effect of ground loss on an antenna's input resistance. Three different types of ground, selected from the details provided previously, have been used. The results are markedly different. In all cases, as the antenna approaches the air-ground interface the input resistance begins to rise sharply. If the ground was a perfect conductor (or possibly sea water) the resistance would actually approach zero as the antenna reached the ground. The reason, of course, is obvious: perfect ground would short out the antenna and so its radiation resistance would fall to zero. The 180-degree phase difference between the currents in the antenna and in its image imply exactly the same thing. But that doesn't happen here because the lossy ground couples with the antenna, *via* the mutual impedance between them, and induces resistance into the antenna thereby increasing its input resistance. Hence, we can write an expression for the total resistance as

$$R_{in} = R_{rad} + R_{loss}$$

where R_{rad} is the radiation resistance and R_{loss} is the total loss resistance within the antenna made up of its intrinsic conductor loss (caused by the skin effect) and the induced ground loss as revealed in **Figure 5**. In all the cases shown here the ground loss is dominant. What effect does this have on the antenna's performance?

Radiation efficiency

The presence of loss resistance within an antenna causes a loss of power in the form of heat when the antenna current flows through it. Therefore, the radiation efficiency of the antenna suffers. For most antennas, except those that are electrically small (*i.e*. very short dipoles and small loops), the radiation resistance is usually the dominant term and so the efficiency is good. However, if for any reason, the antenna can only be erected very close to the ground, then not only does the radiation resistance fall rapidly for the reason given above, but the loss resistance can be significant and, in fact, it can be the dominant part of the input resistance. We can express this by the simple equation below where η is the radiation efficiency usually expressed as a percentage.

$$\eta = \frac{P_{rad}}{P_{in}} = \frac{R_{rad}}{R_{rad} + R_{loss}} = \frac{R_{rad}}{R_{in}}$$

Clearly, when there is no loss, the efficiency is 100%.

Again, we can call on EZNEC to compute the efficiency of an antenna when it is erected above typical lossy ground and the results of such a computation are shown in **Figure 6**. I have made use of the loss tangent because it combines both the conductivity and the relative permittivity of the ground, as well as the frequency, in that useful form designated by

$$p = \frac{\sigma}{\omega\epsilon}$$

as described above. The results that follow are particularly revealing.

At the very low height of just 1 m above ground level the efficiency, as expected, is extremely poor and is almost independent of the type of ground beneath the antenna. However, as the antenna is raised to a height of 5 m the efficiency increases rapidly as the loss tangent of the ground increases. Why should this be so? Above the sea ($p = 158$) the loss in the 'ground' is lower than in any other natural geological medium because the conduction current $I_c$within the sea is much greater than the displacement current I_d and so instead of penetrating into the sea the electromagnetic radiation from the antenna is almost totally reflected back into what is called the 'upper half space', the air or what we generally refer to as free space. The antenna therefore radiates most effectively. This is further emphasised when the antenna is raised still further to a height of 10 m, or a quarter wavelength at the test frequency of 7.1 MHz, where the radiation efficiency is almost 100%. In all other cases where the ground is lossy, as it is termed, the efficiency drops and is worst of all when the antenna is above very poorly conducting ground within which the skin depth is large thereby allowing considerable current penetration into the ground.

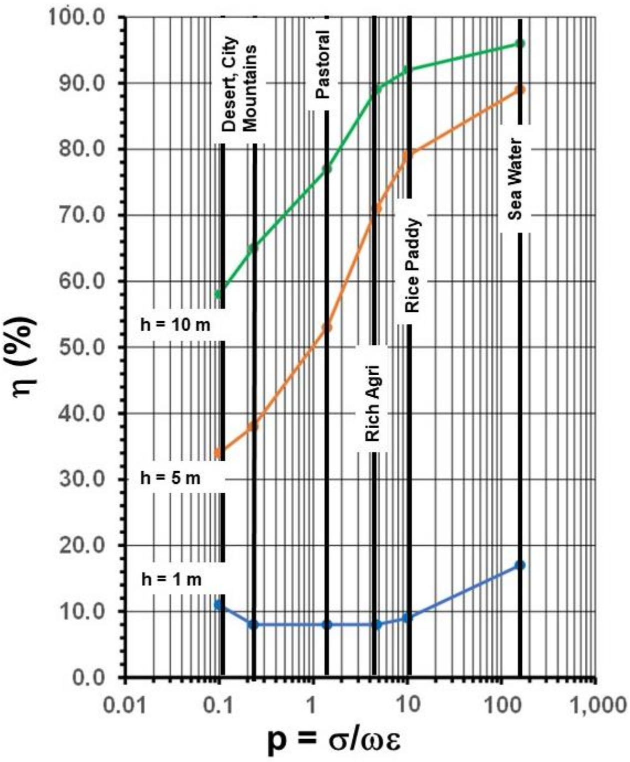

Figure 6. The computed radiation efficiency of the dipole

The effect on the VSWR

As will be appreciated, the changes in the antenna's input impedance caused both by the type of ground beneath it and by it its height above the ground will affect the VSWR on the transmission line feeding the antenna. Again, computing these with EZNEC is easy. One thing of some interest emerges from doing this. Even at low heights above 'typical' urban ground, the VSWR on 50- or 75-ohm transmission line is very low so the antenna will match easily to modern transceivers. However, this is not the case if the ground conductivity is a lot higher. The input resistance of an antenna at just a metre above those rice paddies, and particularly when it's above sea water, decreases significantly because of the mutual impedance and this causes the resulting increase in VSWR. Values well into double figures are not unusual.

Conclusion

This article has addressed a little-explored phenomenon, so often just taken for granted, when HF antennas are erected, as is often the case, in close proximity to the ground. The electrical characteristics of the ground are important as is their frequency-dependence. Examples of a wide variety of ground-types have been presented here and characterised in terms of their loss tangent, a term perhaps not too familiar to most people. From these the effects of antenna height and ground-type on the antenna's input resistance were computed from which the radiation efficiency followed directly. Perhaps surprisingly, it is shown that even at heights of just one-eighth of a wavelength, a half wavelength dipole will match well to coax cable and will lose only about 2 dB of its input power in heating up the ground and perhaps the odd earthworm or two. This is a useful result whether the antenna is to be deployed in some tactical military situation or in a SOTA expedition in the Cairngorms.

Acknowledgements

I acknowledge the very significant work done by a remarkable engineer, George Hagn, of the Stanford Research Institute in measuring the conductivity and relative permittivity of a variety of ground-types across the HF band. In addition, I must pay tribute to an equally remarkable theoretician, Professor J.R. (Jim) Wait, who possibly did more than anyone to demystify (though some of the mathematics is formidable) the mechanisms that affect antennas when erected above lossy earth. For those of a hardy disposition, I recommend Wait's chapter 'Characteristics of Antennas over Lossy Earth' in the book edited by RE Collin and FJ Zucker, "Antenna Theory, part 2", published by McGraw Hill in 1969.

Appendix: A note on the calculation of antenna radiation efficiency

EZNEC (and NEC) determine the radiation efficiency of an antenna by computing what is called an antenna's average gain which is given by the ratio of the total power in the far field (*i.e*. at a distance of many wavelengths from the antenna) to the power delivered to the antenna. Clearly, if there were no losses then these two quantities would be equal and so their ratio is equal to one and the efficiency is 100%. Any loss in the antenna will cause the radiated power to decrease and so that ratio is a direct measure of the radiation efficiency. This is a very useful tool. It also serves another useful purpose. If, for any reason, the EZNEC calculating engine, as W7EL describes it, is having trouble caused by some error in setting up the model, then the average gain feature may provide the necessary warning by displaying a value of average gain less than 100% even when no losses are involved at all. This cannot be, so something must clearly be amiss.

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