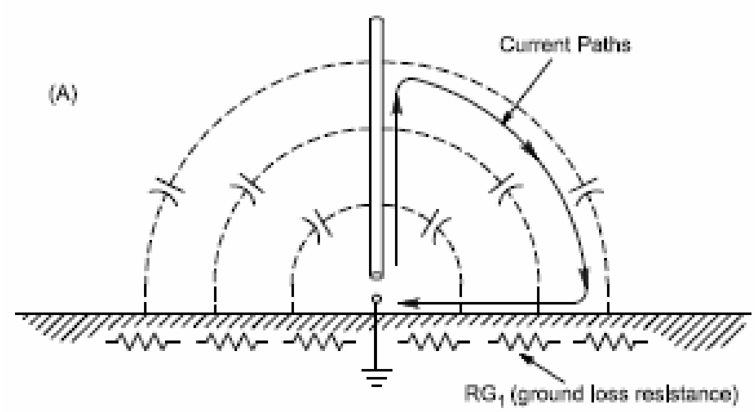
Vertical Antenna Ground Loss, Displacement Currents and Return Currents

We all know the story of displacement currents, forced on J C Maxwell by data when time dependent fields were investigated. An extra term was added to the early equations giving some symmetry to electric and magnetic fields (so changes in each can produce the other) and providing (fanfare here) freely propagating RF fields for hams - and the rest is history. As a side feature, Kirchoff's law can be salvaged for dynamic fields when it is recognized that charges can accumulate and all will be consistent if the old standard charge current density J has the Displacement current density dD/dt (call it Jd) added to it. (JCM would say div(J+Jd) =0) Here D, named the "displacement" is εE, the permittivity, ε, times electric field E. On these assertions, virtually all agreed ("established science" you could say) and there was much rejoicing.

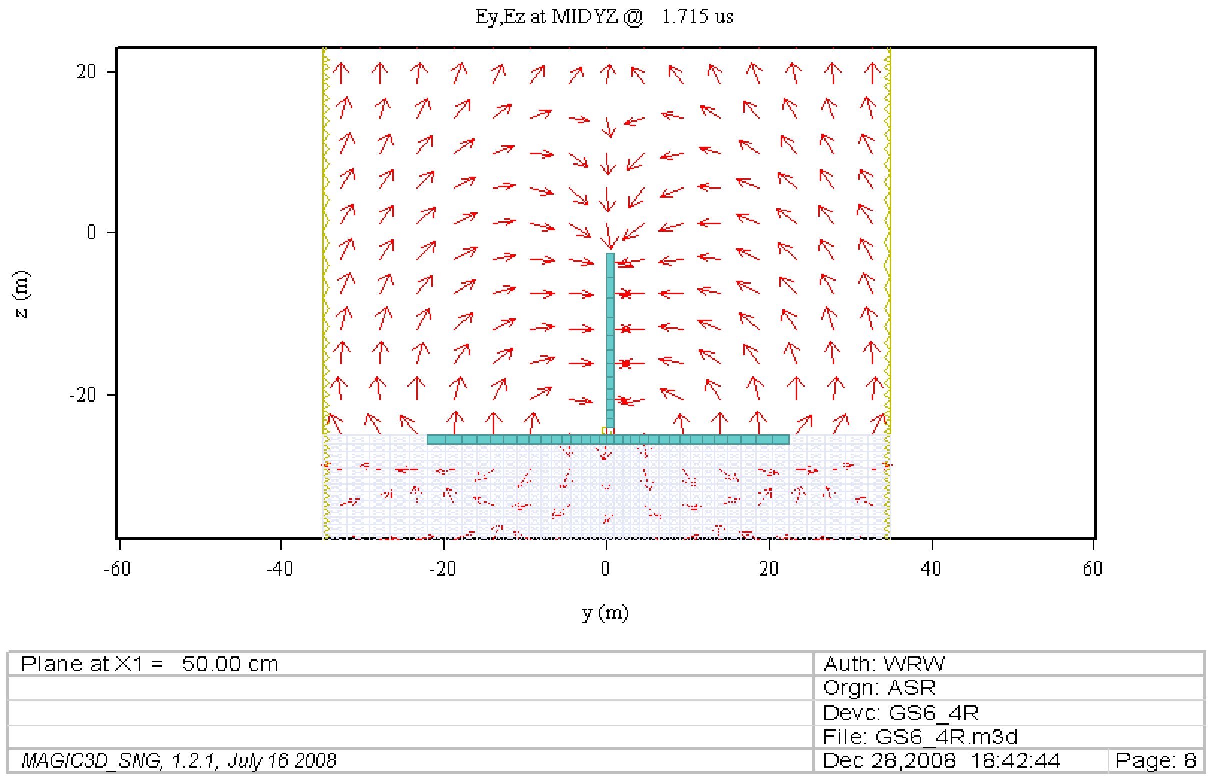
In spite of this, and sadly, looking on the WWW (or even in antenna books) for antenna displacement current and return current enlightenment is a very painful and often fruitless task.

The deceptive charm of looking at the "total" (now area integrated J to get I) current, or I + Id is that we can now trace out "Current Paths" such as pictured (Fig 9-41A, Low Band DXing, 4th), that have something called currents going up a vertical and bending back, "flowing" along a hemisphere in the air and then joining with a radial (or the ground) and flowing back to the feed point (the return current), completing the loop.



Note that in the air portion of the path, there is no charge flow and the "current" is all displacement. It being essentially a vacuum, Id is then proportional to dE/dt, the rate of change of the electric field AND for a single frequency, our standard case, dE/dt has the some direction as E, but with a 90 degree phase shift. This (purely illustrative) picture shows no radials or conductors near the ground, which is of course not an actual way to have an antenna unless you are trying to lose (even salt water is marginal).

So finally getting to the point, the following plot is of a snapshot of the simulated E field from an expensive commercial full-up Maxwell equation solver (limited in accuracy only by grid size) showing a cross section through a quarter wave vertical with four quarter wave radials (2 are visible in cross section) at 3.5 MHz, sitting on a representative soil base that has both a real dielectric constant (ε=10) and conductivity (σ=.002 S/m). Yes, the wires are rather large. Note that the E field in the air between the antenna and radials curves pretty much the same was as the figure current path in the prior figure, as expected. All is well so far.



Now for a revelation that may cause some to avert their eyes. For no wire resistance, the losses in EM calculations of this the actual JC Maxwell no kidding sort of solution, come from only two sources. First energy can flow out of the boundaries. The authors of this and other similar codes have worked long and hard to provide boundary conditions that minimize the distortions from the edges. They are very good but not perfect. But after that, the energy loss is only due to ohmic losses, and here it comes folks, this is proportional to the integrated value of the dot product of J and E. Note that the displacement current does not appear in J·E. To put more strongly, there are no losses due any particular character of any displacement currents (you can look it up). The only losses are from the "real" charge flow current in regions of non-zero conductivity. (Some may say: How about a lossy dielectric (perhaps described by a complex ε), such as in a capacitor, where the displacement current is a big deal. In such a capacitor, there is a small leakage charge current that contributes all the loss, in spite of the fact that its amplitude is much less than the displacement current. This is also true in the soil.)

Finally look at the E fields from the simulation that are in the soil under the radials. These are fields of strengths not much less than those in the air. However, in contrast to the air, the soil, although a really poor conductor by metal standards, has a bit of conductivity, σ, and so these E fields will drive charge currents (not displacement currents) that are generally proportional to σE (ohms law) producing the dreaded ground losses. There are also displacement currents in the soil, since dE/dt is not zero, but they play no role in losses. (Have I said it enough?)

And finally, unsupported by any pictures, but coming from other simulations:

First not surprising: If the conductivity of the soil ("good ground") is high, the layer with currents below the radials is less deep, the E fields are reduced in amplitude and the losses from the field driven currents are reduced. (It is not a priori obvious that this leads to lower losses since σ is higher, but it does.)

Second and maybe surprising: If the conductivity of the soil ("bad ground") becomes very small, the fields near the top of the soil are a bit larger, they extend to greater depths AND, if σ=0, worst case, there is <u>no</u> ohmic loss, or current J, at all. It turns out that this is not a good thing because the energy loss then is all due to RF flow out the bottom of the grid and that loss is even greater than for small conductivity. (Note that the displacement current is relatively large and goes to substantial depths in the soil, yet no losses.)

The bottom line is the usual wisdom that if you want to reduce the near-antenna losses from pushing currents in the ground, you need to get better soil (not an option for many) or a means of better screening the E fields from the ground by dense radials or ground screens or counterpoises. One could describe part of this issue using the language of displacement and return currents but it is not clear that is enlightening.

As a point of interest, Kirchoff's law is based on conservation of charge. For steady state conditions (no charges accumulating) the interpretation of the law in terms of currents summing to zero is standard. As indicated above, for non-steady state conditions such as antennas, a generalized definition of current (I+Id) recovers the steady state-like form of interpretation – BUT this does not mean that charges are not accumulating. They are and this is, of course, the reason that the voltage at the floating end of an antenna is high.