

# How Earth-Current Antennas Really Work

*With cave radio equipment, there has been a trend away from the use of induction loop antennas to the use of so-called earth-current antennas, i.e. long wires grounded at both ends. Both the HeyPhone and Nicola system use this type of antenna. However, the popular explanation for how this antenna works is fallacious. The antenna does not operate by allowing the current to flow in a 'big loop' in the ground, nor is it a 'conduction mode' of operation. In fact, it does not depend, fundamentally, on current flow in the ground at all. The fact that the popular explanation is wrong is important because, if we do not understand how the antenna works, it is difficult to know the best way to use it, nor how to design a better one. In this short note, David Gibson outlines a more useful model – that of the Grounded Horizontal Electric Dipole – but without the mathematical justification, which will be given in a future article.*

To some cavers who have speculated on the subject, it seems that the current injected into the earth from an 'earth-current' antenna must form a 'big loop' and thereby generate a magnetic field, which is detected by the receiver. We could call this the **Big Loop (BL) hypothesis**. To another group of people it seems that the mode of operation must be conduction through the ground – the **Conduction Mode (CM) hypothesis**.

The fault with the Big Loop hypothesis is that nobody has produced any evidence to support it, nor has it been shown to provide any useful testable predictions. It is, in any case, rather odd that cavers dreamed it up when the usual mode of operation of a Hey-Phone makes it closer in operation to a conduction mode device.

The Conduction Mode hypothesis is somewhat more sensible. It is straightforward (in the DC case, at least) to derive an equation that explains how the received signal strength depends on the lengths of the transmitting and receiving antennas, the transmitter current and the distance. It is also straightforward to derive the shape of the electric and magnetic field lines. These results are predictions that can be tested. The BL model gets nowhere near this and does not really deserve to be called a hypothesis – it is more of an 'uninformed guess'.

However, there are shortcomings with the CM model too. An earth-current transmitter is the source of electric and magnetic fields, and the magnetic field can be detected with a conventional induction loop receiver. However, the CM model does not predict this. The proponents of such a model claim that it is outside the scope of telecommunications regulations because it relies on 'conduction'. They are rather mistaken because the fields certainly do exist!

Another shortcoming of the CM model is that it cannot easily be applied to a non-zero frequency. Contrary to the general view, you

cannot simply add a skin depth term to a DC expression for a field to obtain the result at higher frequencies – the fields do not behave as simply as that. So, if these models have shortcomings, is there a better one to use?

## Different Models: Same Reality

The salient point is that there is more than one way to describe the situation. All descriptions – if they are usable – must eventually converge on reality (to some degree, at least) and the point is not really "which is correct?" but "which is the most practical?". That is, which allows us to make the best predictions?

Physics contains many examples of convergent explanations. For example, we can consider an electric circuit to be caused by a current flowing in the wires or caused by a transverse electric field travelling from the source to the destination. We would not expect to use the latter model when wiring up a battery and a torch bulb, but it becomes essential when analysing the decoupling of high-speed logic circuits. (Catt, Walton and Davidson, 1979).

Another example is HF terrestrial direction-finding. This is easily explained using the concept of a magnetic field and a loop antenna. If, perversely, we did not believe in magnetic fields, we could consider a loop antenna to be formed from two back-to-back electric monopoles, detecting the gradient of the electric field. This would be a strange way to proceed, but it would result in the same answer – it has to!

Thus, the question is "which is the most useful method of describing how the antenna works?". Clearly the BL model is of no use – it provides no insight into signal strength, orientation, power and so on. The CM model is a little better because it can be described analytically. However, it fails to describe the magnetic field.

A model that treats the antenna as a **grounded horizontal electric dipole (G-HED)** provides a better description of the fields, as I shall now explain.

## The Grounded Horizontal Electric Dipole

I mentioned G-HED antennas in my PhD thesis in 2003 (Gibson, 2010) where I referred to them as J-field antennas, writing...

...the J-flux in the ground is coincident with the D-flux from the electric dipole antenna, and thus we can expect that the field could, with suitable boundary conditions, be derived from an analysis of the electric dipole antenna alone. One conclusion we can draw from this is that the shape of the magnetic field lines is one of concentric rings around the antenna.

I avoided a detailed discussion because the problem seemed, at the time, to be too daunting. My recollection is that Graham Naylor pointed me in the right direction, noting the coincidence of the **J** and **D** fluxes, which is at the heart of the situation.

Having thought about the problem for some time since then, it seemed that the only way to tackle it was to take a deep breath and sit down with a large blank pad of paper. I was able to find time for this because, in 2010, I was asked, as part of my professional work, to produce such an analysis for a company involved with sub-sea communications. In September 2010, I gave a talk at Hidden Earth, which I repeated at (BCRA Cave Technology Symposium, 2011). So, to a large degree, I have considered the problem 'solved' since then, with the explanation – if not the detail – being in the public domain.

However, much of the analysis I did at work was not published and, unfortunately, the nature of the material I have means that it is going to be a lengthy task to combine it into a single coherent article (I have about 60 pages of material in total).

## The Solution is “Obvious”

One of the puzzles has been why authors such as Burrows and (Hill and Wait, 1973) in their analysis of a G-HED did not seem to address the issue of the current flowing in the ground. You may know the following story, related (e.g.) by (Blane, 2007) ...

The story is told of the eminent mathematician G H Hardy that he was once giving a lecture when he made a casual remark, and said, “Of course that’s obvious.” Then he stopped talking and looked very thoughtful. Time wore on and he continued staring dreamily into space. After a while the class was getting very restless, but finally the great man emerged from his deep thoughts and said to the students: “Yes I was right – it is obvious.”

I had something of the same feeling when sitting down with my pad of paper. By about the tenth page it was dawning on me that it was all obvious – the current flowing in the ground does *not* require any special consideration. Burrows and Hill & Wait do not discuss the problem simply because it *is* obvious to someone well-versed in electromagnetic theory. This is slightly embarrassing for me, as the salient point is precisely the one that I described in my PhD thesis ten years ago, although that statement alone is not a proof. A rigorous proof is lengthy.

## How the G-HED Works

*A practical earth-current antenna produces the same fields as would a theoretical isolated electric dipole with the same current flow.*

The salient point is that the current flow must be the same. This is not physically realisable in an isolated antenna, but that does not matter because we are saying that to model the *practical* antenna – with all its impossible complications of multiple tubes of earth currents – we simply need to model an equivalent *theoretical* antenna that is a lot simpler to work with.

With that in mind, we can see that the purpose of the grounding is similar to the provision of a ‘top hat’ for a vertical electric dipole – it is to allow the current to flow all the way to the ends of the antenna. We could not otherwise achieve such a high dipole moment from an isolated dipole at the low frequencies we are using.

The current in the antenna wire generates a magnetic field and it is this field that is detected by an induction loop receiver. The (unconstrained) current in the ground does not ‘materially’ contribute to the field, in the same way that the displacement current from a conventional electric dipole in air does not ‘materially’ contribute to the field. Of course, if you *constrain* the current in a layered

earth, then the operation is modified – but that is not the issue here.

The first prediction that arises from this model is that because the G-HED transmitter generates a magnetic field, it should really be used with an induction loop receiver. In practice, most cavers seem to believe that they need a wire antenna at the receiver too; but this can actually be detrimental to the operation. The reason it seems to work so well is because the antennas are generally quite long and quite close together. If these requirements are not met, we can now (armed with the new G-HED model) show that an induction loop would be better.

## Field Contribution From The Earth Currents

I have implied that the earth currents can be ignored, and the entire field can be described in terms of the electric dipole source, but this is a carefully chosen ‘brevity’. The phrase I used above – “does not ‘materially’ contribute to the field” – needs some explanation.

A formal proof uses the Ampère-Maxwell relationship, and continues via a derivation of Gauss’s law and the Biot-Savart law to show that, in an isolated antenna, the fields are due to the build-up of charge at the ends of the antenna as the current moves back and forth. It can then be shown that if the antenna is grounded – and there is therefore no charge build-up – the fields that arise *from the current flowing in the ground* are identical to the case of the isolated antenna. Thus,

- The effect of the line current (i.e. the current in the antenna wire) and all the current elements in the ground *combine* to generate the observed **H** field.
- But in the *absence* of grounding, and for the *same* line current (if that were possible), the charge that would build up at the ends of the antenna would have the *same* effect.
- So, to model the antenna, it is *only necessary* to consider it as an isolated current element, i.e. an electric dipole.

The salient point is that to model the entire system (including the ground currents), it is *only* necessary to consider an isolated (and theoretical) electric dipole with the same current. So, *in that sense*, the current in the ground is not ‘materially’ significant.

## Testing the Hypothesis

The hypothesis that a practical earth-current antenna can be *modelled* as a theoretical isolated dipole with the same uniform line current can be tested, although the problem of field distortion, which we know occurs in the real world (Drummond, 2002), will need to be addressed. We can test...

## 1) The Shape of the Field Lines

The analysis of a grounded wire was given by (Hill and Wait, 1973) and a Math-Cad simulation reported by (Lippold, 2000). The magnetic dipole was analysed by (Wait, 1951) and a MatLab simulation reported by (Gibson, 2000). In the latter case, a simple whole-space formula was found to be a good approximation to Wait’s complicated half-space model. Assuming this observation applies equally to the G-HED, we can write down fairly simple expressions, including a skin depth term, for its fields and test that prediction experimentally.

## 2) Performance Relative to a Loop

Limited space in this article prevents me from describing the details, but the salient point is that the G-HED model allows us to make – and test – comparisons between dipoles and loop antennas, which the previous hypotheses did not.

Interestingly, my analysis shows that the G-HED antenna may have a more restricted use than cavers are aware of. G-HEDs are useful where they are a replacement for a small loop or where it is difficult to deploy a large loop. They are also the preferred antenna in seawater. However, in general, a large loop will work better than a G-HED, especially if it is larger than a skin depth in size. On the surface, a vertical loop (provided it is of sufficient dimension) will be the most efficient for long-distance communication.

These results (which, admittedly I have not described in sufficient detail) arise out of a mathematical study of the G-HED antenna and are testable by experimentation.

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