Coil Basics

by Carl Moreland

While most people have no idea what's inside the control box of a metal detector, many actually have a misperception of what's in the disc at the other end of the pole, and how it works. In this article we'll take a peak inside.

Electromagnetics

Many detectorists refer to the coil as an antenna. It is not, at least in the classical way that antennas are used. Like an antenna, it converts electrical current into electromagnetic (EM) energy, and vice versa. But the EM energy produced by an antenna behaves differently depending on how far away from the antenna it is. There are generally two regions, the near-field region and the far-field region. The transition between the two regions is gradual, but basically it occurs at about one wavelength away.

In either region the EM energy gets weaker as it travels farther away. That's because the energy is spreading out into a greater and greater expanse[1]. In the far-field region the EM energy falls off as a function of $1/d^2$ (where d is the distance away), just like you would expect from basic algebra, where the surface area of a sphere is proportional to r^2 (radius). Weird things happen in the near field, and the energy falls off as a function of $1/d^3$. That's much worse, and I'll give you two guesses as to which region the detector loop operates in[2].

Why? Well, look at the wavelengths we're working with. Let's take a typical VLF of 10kHz - the wavelength is the speed of light divided by the frequency, or

$$\lambda = \frac{c}{f} = \frac{300,000,000\,\text{m/s}}{10,000\,\text{Hz}}$$

The answer is 30,000 meters, or roughly 18-1/2 miles! From classical antenna theory, elements like dipoles and circular loops are most efficient at transferring energy when they have dimensions (length or circumference) equal to a quarter wavelength. In our case, we would need a loop with a diameter of about 1-1/2 miles. Not good for pinpointing. Alternately, consider a classic Yagi-Uda TV aerial, the kind stuck on many rooftops. The low channel VHF band is around 75MHz, so the wavelength is

$$\lambda = \frac{300,000,000\,\text{m/s}}{75,000,000\,\text{Hz}}$$

or 4 meters, and the quarter-wavelength is 1 meter. This makes for a reasonably sized antenna and, indeed, this is about the size of a basic TV aerial.

Obviously our coils are nowhere near the optimal size for classical EM wave propagation (at VLF) and, indeed, that is not what we are using them for. That is, we are not interested in propagating (or receiving) a wave at a distance of miles. We're using it more as an inductor, and looking at the close-in magnetic field distortions.

Most loop coils are wound as skinny donuts, using multiple turns of insulated wire. If you pass a current through such a coil it will generate a field as shown in Fig. 1. Direct current (DC) will generate a *static* magnetic field, and alternating current (AC) will generate an *alternating* magnetic field. We're interested the AC field, which we'll call an electromagnetic field for simplicity. When we bring a second coil close to the first one, the signal from the first coil will couple into the second coil via *induction*. Induction is incredibly useful, and is how transformers work. Inductive coupling efficiency depends on several things, like coil placement and the core material they're wound on. Transformers use iron or steel to improve coupling efficiency, while metal detector coils use air.

If you bring a piece of metal into the field, the EM energy will produce circular currents in the metal known as *eddy currents*, which in turn produce a reverse EM field. So now we have a

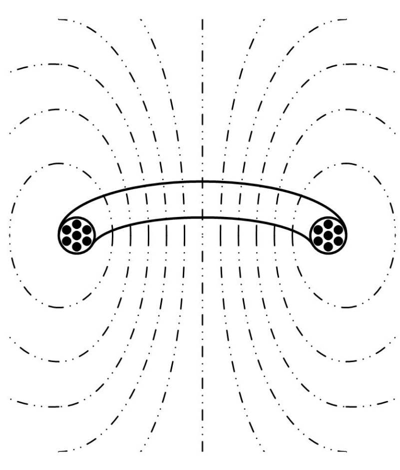

Figure 1: **Coil Field**

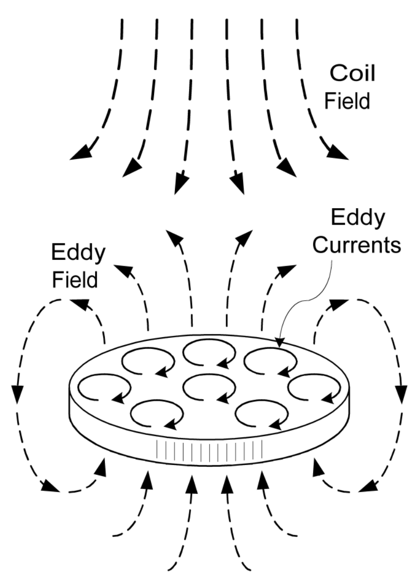

Figure 2: **Eddy currents**

1. The same way a light bulb looks dimmer the farther away you get. Less photons hitting the retina.
2. Yup, the near field.

transmit coil producing an EM field, and a metal target close enough to produce a reverse EM field (see Fig. 2). Remember, I'm using the term "EM" loosely; all we're really interested in is the alternating *magnetic* field.

Now we need a way to detect the target's induced field. Keep in mind that this is a *very* small field in the presence of a much larger transmit field, so for optimal detection we need to get rid of the transmit field. It's like trying to hear someone whisper at a rock concert. In a PI detector we do this by quickly turning off the transmitter and "listening" for a weak target response. VLF-type detectors continuously transmit so we need to do something different.

As I said before, a second coil can be placed such that it inductively couples with the transmit coil. By careful placement, we can also get the second coil in a "null" of the transmit field, such that there is no coupling. In such a case we say the coils are *inductively balanced*, and this is where the term "induction balance" (IB) comes from. Induction balance is the method used for what most people call VLF, TR, and even "RF" (two-box) detectors. However, IB can also be applied to PI and even BFO detectors.

Coil Types

So, the transmit coil produces a large electromagnetic field; the target produces a teeny-tiny reverse EM field via induction; and we want a receive coil that will ignore the gigantic transmit field while detecting the miniscule target field. No problem.

The solution is to somehow "balance" the receive coil so that the transmit field does not inductively couple with it. There are various ways to do this, including mechanical balance and electrical balance. Let's look at mechanical methods first since I think that's what everyone is currently using.

Fig. 3 shows what seems to be one of the earliest methods of induction balance. You should recognize it as the two-box locator, or what some people call the "RF" detector. In this case the receive coil is turned 90° to the transmit coil and placed so that it lies exactly along the isomagnetic lines of the transmit field. This way, the receive coil does

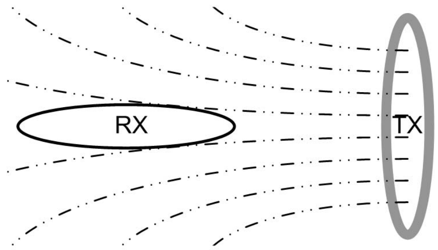

Figure 3: **Orthogonal coils**

not get any magnetic field cutting *across* it, and therefore no induced current. Inductive coupling is theoretically zero.

There are at least a couple of problems with this approach. You can shrink the coils down and put them on the end of a shaft, but the orthogonal coil orientation results in a bulky search head. A 1969 article in Popular Electronics describes such a design using 3 coils (Fig. 4). A second problem is that ground balancing is tough in mineralized soil. As soon as the coils are moved near the ground, any mineralization will start to compress the transmit field on one side only and throw the balance out of whack.

Fig. 5 shows another early method of attaining induction balance in a coil. The receive coil is slightly overlapped with the transmit coil, so that part of the inner field of the TX coil goes through the RX coil, and part of the outer field of the TX coil also goes through the RX coil. The inner and outer fields of the TX coil are of opposite "polarity," so if the RX coil is precisely positioned, it is possible to get the effects of the fields to cancel. This type of coil is often referred to as *coplanar*, because the TX and RX coils lie in the same plane.

For the TX coil, the greatest EM field strength is along the imaginary axis that goes through the center of the coil

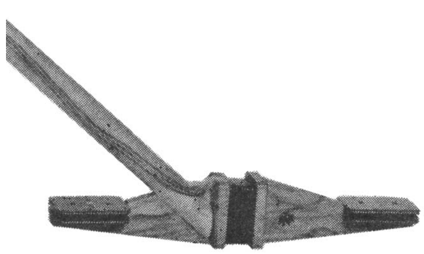

Figure 4: **Othogonal search head** (Popular Electronics, Feb. 1969)

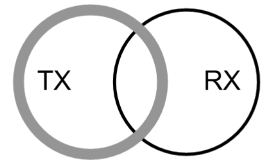

Figure 5: **"OO" coils**

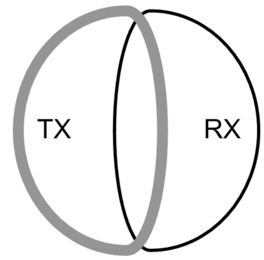

Figure 6: **"DD" coils**

(see Fig. 1). Similarly, the RX coil is most sensitive to target signals along the axis through its center. For this type of coil arrangement, these axes are not coincident. It turns out the area of greatest sensitivity is where the two coils overlap. Since this is not the point of greatest sensitivity for either coil, this method has somewhat lower overall sensitivity than other methods.

Fig. 6 shows a variation of the overlap design which has become very popular. The overlap portions of the coils are somewhat flattened which produces three improvements. One is that the overall shape of the search head is round. Secondly, the overlap area—still the area of greatest sensitivity—now runs from the front to the back of the coil, producing a long narrow detection zone. Thirdly, the axes of highest sensitivity for each coil are moved closer to the overlap area, which improves depth.

In this variation, each coil looks like a letter "D", so the overall type is commonly referred to as the "DD," or "double-D," coil[3]. Although overlap coils probably date back to the earliest experiments involving induction (1830's), and were definitely in use in the early 20th century, the DD coil appears to have been pioneered by Compass Electronics in the early 1970's. It is now the second most popular coil type, and is almost exclusively used on Minelab detectors.

Fig. 7 shows another method of

3. Also called the "widescan" coil.

attaining balance in a pancake coil. This is commonly called a *coaxial* coil because all the coils lie along the same center axis. The transmit coil is placed between two receive coils, and the receive coils are wired in opposition so that their induced currents cancel. Alternatively, you can sandwich a receive coil between two transmit coils wired in opposition, such that their fields cancel right in the middle, where the receive coil is placed (Fig. 8).

The coaxial coil was used in early Garrett VLF machines and the 'Cat detectors from C&G Technology, maybe others as well. I believe that the C&G units actually used a modified coaxial design, where the receive coils are smaller than the transmit coil. This still achieves induction balance, and also reduces the magnitude of the ground signal for a better target-to-ground ratio.

The coaxial coil arrangement usually carries a slight depth penalty, because of partial signal cancellation between the "+" coil and the "–" coil. However, it does have one distinct advantage. Because induction balance is achieved in the vertical direction, it makes the overall coil less sensitive to metal targets on the edge of the stack. This allows a coaxial coil to get closer to objects such as metal fence poles without detecting them. Today, the only coaxial coils made are from aftermarket vendors.

Fig. 9 shows a coplanar coil design that was very popular in the 1970's and early 80's. It is commonly called the "4B" loop and was widely used in TR and VLF detectors from White's and Bounty Hunter. A small part of the

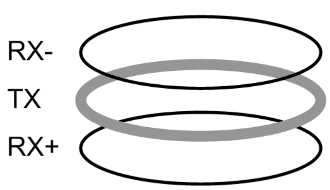

Figure 7: **Coaxial coil I**

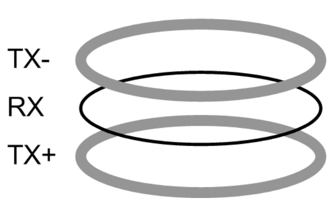

Figure 8: **Coaxial coil II**

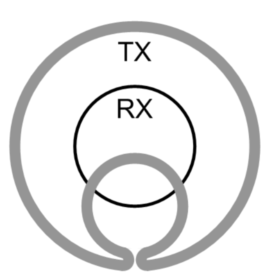

Figure 9: **"4B" coil**

Figure 10: **Red Baron coil**

transmit coil is folded inward, and the receive coil lies across this section. The folded portion generates a smaller reverse transmit field about the receive coil that cancels the larger transmit field. Fig 10 shows a photograph of a Red Baron coil. Note the small epoxied circuit board, used to trim the balance.

Many detectors today use the concentric coil, shown in Fig. 11. Normally, if you place a receive coil concentrically within the transmit coil you will get heaping gobs of inductive coupling. The trick here is to add a bucking coil, which is another transmit coil placed very close to the receive coil. The bucking coil gets an out-of-phase transmit signal and, in the vicinity of the receive coil, cancels the main transmit field.

The bucking coil can be placed just outside the receive coil, or just inside, or even right above it. Another way to configure the concentric is to use a counter-receive coil that is placed close to the transmit coil, but wired out-of-phase, as in Fig. 12. I believe that most concentrics use the transmit bucking coil, but I'm not sure exactly which placement is most common. Fig. 13 is a concentric coil from White's. The single strand of wire (taped down) is used to fine-tune the balance. The black object is conduc-

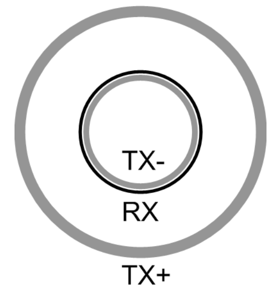

Figure 11: **Concentric coil I**

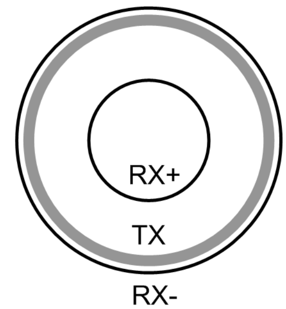

Figure 12: **Concentric coil II**

Figure 13: **White's coil**

tive rubber that presses against the shielding that is sprayed into the other half of the coil shell.

With the exception of Minelab, the concentric coil is standard for practically all detectors. Concentric coils have about the best overall sensitivity of all coil types, and is relatively easy to manufacture. In most cases, the receive coil is half the diameter of the transmit coil, though it does not have to be. In some Fisher coils, the receive coil is elliptical. In Garrett imaging coils, there are two receive coils; one about half the diameter of the TX coil, and the other at about ¾ the TX diameter.

One last interesting loop configuration is the "Figure-8" shown in Fig. 14. The TX loop is twisted in a figure-8 so it

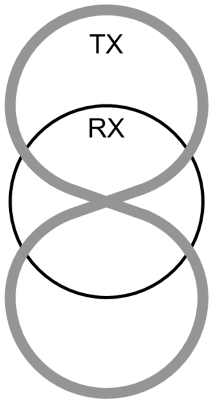

Figure 14: **Figure-8 coil I**

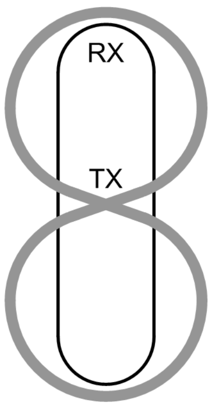

Figure 15: **Figure-8 coil II**

produces both a positive and a negative field. With the RX coil centered at the crossover, it sees the same amount of each field and is inductively balanced.

This coil configuration has two quirks. First, the transmit field has a null at the crossover, so theoretically it will have poor sensitivity at the center. Second, the transmit field at the front half of the coil will be 180° degrees out-of-phase with that of the rear half. This means that in a phase discriminating design, proper target ID will work only in one half.

Figure-8 loops can be made in a variety of ways. Figure 15 shows one with an elongated RX coil, which produces a detection area that is long and narrow, giving a faster ground coverage. Figure 16 shows a RX coil in figure-8 with a standard TX coil; this has the same drawbacks as having the TX coil as the figure-8. Finally, Fig. 17 is a double-figure-8, which produces accurate phase ID for the center part of the coil, and with two nulls away from the center.

There are many other interesting ways to make inductively balanced

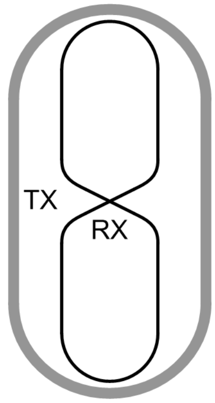

Figure 16: **Figure-8 coil III**

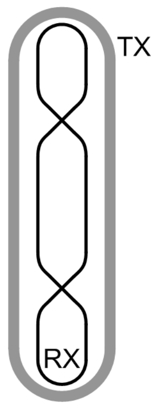

Figure 17: **Figure-8 coil IV**

loops, but these cover the vast majority you will see on the market. With any IB coil, good balance is very sensitive to an exact placement of the receive coil, and moving the receive coil even slightly will upset the balance. Normally, all the coils are placed in a form, adjusted for near-optimal balance, then rosin is poured over them. To fine-tune the balance after the epoxy sets, a single loop of wire can be left hanging and moved around, then glued in place.

Ground Effect

Good balance is fairly easy to achieve when the coil is in air, away from anything that might distort the field and upset the balance. When a metal target is brought near, it upsets the balance, which is what we want. But soil often contains minerals that also distort the TX field, and this can produce an unwanted RX signal.

As the coil is lowered to the ground, the soil distorts the TX field, effectively squashing the field on the bottom side of the coil only. See Fig. 18. It is not due to eddy currents as with a metal target, but rather due to a shift in permeability, much like a powdered iron core is used to increase the value of inductors. The top side of the coil still sees air, so the field projected upward is not squashed. For most coils, this will upset the induction balance and create a RX signal. We will call this the “ground signal” to differentiate from the target signal.

Metal detectors get around this problem by providing a “ground balance” control. It is beyond the scope of this article to fully explore this technique, but we’ll do a high-altitude flyover. Most detectors identify metal by looking at the phase response of the target signal. With the coil up in the air, there is no ground signal, therefore when a target is waved in front of the coil the resulting RX signal will consist only of the phase of the target signal.

But with the coil to the ground, there is now a constant ground signal that has its own phase, and any target signal phase will get added to the ground signal phase. Essentially, the ground balance adjusts the reference phase from which the phase response of a metal target is compared; i.e., it zeroes out the phase of the ground signal.

However, it does not eliminate, or even reduce, the ground signal seen by the RX coil, or the subsequent receive circuitry. What this means is that highly mineralized ground can produce a large amplitude ground signal that can overload the receive circuitry, or at least reduce sensitivity to metal targets.

By now you should be thinking that the amount of ground signal produced depends on the coil design. A good

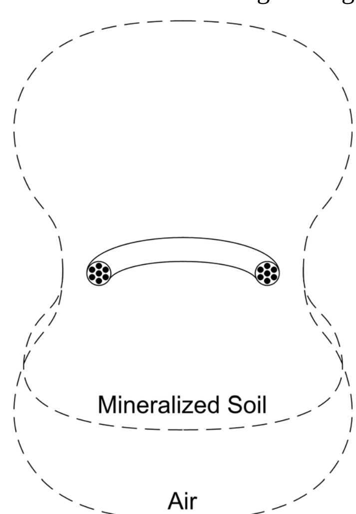

Figure 18: **Ground Effect**

design should maintain induction balance even when mineralized soil is compressing the TX field. Intuitively, a Figure-8 coil should be the hands-down winner, especially one such as in Fig. 16. Regardless of how the TX field is compressed, the RX coil will always have excellent cancellation.

DD coils are touted for their good performance in bad soil, which is why they are the standard coil type for Minelab coils. Australia has what is probably the most mineralized soil in the world. It also makes intuitive sense that the DD coil will work well, because part of the TX signal is outside the RX coil, and part is inside. As long as field compression doesn't alter the ratio of the inside and outside portions, balance is maintained. But the ratios are altered some because of the flattened sides along the overlap area. Most likely, the "OO" coil (Fig. 5) would be even less sensitive to field compression.

The most popular coil, the concentric, does not fare as well in bad ground. TX field compression affects the main TX coil far more than the bucking TX coil[4], and results in an imbalance. Orthogonal coils (Fig. 3) also do poorly, as do coaxial coils (Fig. 7 & 8).

Mono Coils

So far, all of the coils we've looked at are designed for induction balance. Some detectors do not require balanced coils. The old BFO detectors used a single loop coil, commonly called a *mono* coil. In a BFO, the oscillation frequency of the search coil is compared to that of a small coil in the control box, and a frequency shift caused by a metal target is detected. The BFO has passed into history, but today's PI detectors also use mono coils. A PI detector transmits a magnetic field, then quickly shuts it off to listen for a receive signal. It can receive using the same coil.

Although mono coils are generally round, they can really be any shape: oval, square[5], and even triangular[6]. PI

4. The same is true when an RX bucking coil is used.

Figure 19: **Tesoro printed coil**

coils typically have low inductance, and can be fabricated on a printed circuit board instead of winding wires. Fig. 19 shows a Tesoro printed spiral coil[7]. PI detectors can use separate TX and RX coil which, interestingly, do not have to be inductively balanced since the TX signal is off during RX processing.

Coil Performance

Except for Minelab which uses double-D coils, the vast majority of general purpose detectors today come with a concentric coil. Specialty detectors, such as high-frequency gold detectors and a few pulse induction units, sometimes have a double-D coil, and two-box detectors still use the orthogonal arrangement. Beyond that, there are some various aftermarket types, including coaxial and figure-8.

Why is the concentric coil so popular? First of all, it's fairly easy to make since all the coils used in it are round, and induction balance is easily achieved. But beyond that, they perform just about as good or better than any other coil type. Pinpointing is easy with concentric and depth is quite good (relatively speaking).

So why make anything else? As we've seen, double-D coils perform better in highly mineralized ground than concentric. In Australia, where Minelab detectors are made, soil mineralization is legendary, which is probably why Minelab had made the DD coil standard. However, a double-D coil doesn't get quite the depth of a concentric, and discrimination (target ID) with a DD is also supposedly not quite as good, for reasons that are not clear to me.

5. Many deep-seeking PI detectors have a 1-meter square coil.
6. I know of a home-brewer who uses triangular coils on his PI detector.
7. Roke Manor in the UK had an experimental PI detector with a square-shaped printed spiral coil.

The double-D coil is also known as a widescan coil because it has a sensitive detection area that pretty much runs front-to-back across the overlap area. The concentric coil is most sensitive under the receive coil area. The sensitive area of both coils (all coils, actually) shrinks somewhat as you get farther away. At the absolute maximum depth, coverage is limited to maybe 50% or less of the coil width, so to get those deepest coins you will need to overlap your sweeps.

Figure 8 loops, such as the aftermarket Bigfoot coil, also do better in highly mineralized soil because the receive coil is half inverted. However, this leads to a positive response area and a negative response area with a null right in the middle, so they take a little getting used to.The coaxial coil is not as sensitive as a concentric, but it has one advantage. Because the receive coils are vertically stacked and out-of-phase, metal targets at the coil's edge tend to cancel. This makes it useful for getting up close to metal posts where other coils would howl. Also, because both figure-8 and coaxial coils have receive coils that are half-inverted, they reject outside electrical interference exceptionally well, and will outperform concentric and DD coils under power lines.

Finally, keep in mind that one size does not fit all. Large coils get better depth on large targets with less sensitivity to small objects, while small coils have better sensitivity to small targets, albeit with less depth. Also, a small coil is good for working trashy areas because it gives better separation of close targets. So even if all you do is coinshoot, having 2 or 3 coil sizes, or having specialty coil types like a DD or coaxial, will expand the areas you can hunt.