

METAL DETECTOR BASICS AND THEORY

Introduction:

The following paper is both informative and helpful for metal detector users with an interest in technology. This article offers an insight into the basic theory and electronics of metal detectors.

Whilst a technical paper, this is not a formal “scientific paper” and the language used is deliberately more “reader friendly.” Additionally, some terms are used loosely. For example; the terms “magnetic soils” or “mineralised soils” indicates soil that contains materials with significant magnetic permeability (or susceptibility).

Minelab spends a higher percentage of annual revenue in research and development than any of our competitors. We, as the engineering team, appreciate that our company supports this approach allowing the freedom to dream of what might be and act upon that vision. The result of this effort is demonstrated in the break-through technologies that Minelab has incorporated its world-class detectors.

A basic approach to creating a superior metal detector includes:

1. Products that offer the most useful features and best possible performance
2. Products that are highly reliable
3. Products that exceed expectations every time they are used.

To achieve these goals we must know advanced detector theory intimately. A sound working knowledge of electronics, mathematics, and mechanical engineering are essential as is familiarity with government regulations. We also pride ourselves on our practical knowledge of hands-on detecting in the field.

This paper will give you a basic overview of the subject and some insight into the way we at Minelab approach the challenges of creating the world’s finest metal detectors.

Obviously, the majority of our IP is confidential and is thus absent from this paper.

1. Basic operation.

Written by Bruce Candy. ¹

Metal detectors work on the principle of transmitting a magnetic field and analyzing a return signal from the target and environment. The transmitted magnetic field varies in time, usually at rates of fairly high-pitched audio signals. The magnetic transmitter is in the form of a transmit coil with a varying electric current flowing through it produced by transmit electronics. The receiver is in the form of a receive coil connected to receive and signal processing electronics. The transmit coil and receive coil are sometimes the same coil. The coils are within a coil housing which is usually simply called “the coil,” and all the electronics are within the electronics housing attached to the coil via an electric cable and commonly called the “control box”.

This changing transmitted magnetic field causes electric currents to flow in metal targets. These electric currents are called eddy currents, which in turn generate a weak magnetic field, but their generated magnetic field is different from the transmitted magnetic field in shape and strength. It is the altered shape of this regenerated magnetic field that metal detectors use to detect metal targets. (The different “shape” may be in the form of a time delay.)

The regenerated magnetic field from the eddy currents causes an alternating voltage signal at the receive coil. This is amplified by the electronics because relatively deeply buried targets produce signals in the receive coil which can be millions of times weaker than the signal in the transmit coil, and thus need to be amplified to a reasonable level for the electronics to be able to process. In summary:

1. Transmit signal from the electronics causes transmit electrical current in transmit coil.
2. Electrical current in the transmit coil causes a transmitted magnetic field.
3. Transmitted magnetic field causes electrical currents to flow in metal targets (called eddy currents.)
4. Eddy currents generate a magnetic field. This field is altered compared to the transmitted field.
5. Receive coil detects the magnetic field generated by eddy currents as a very small voltage.
6. Signal from receive coil is amplified by receive electronics, then processed to extract signal from the target, rather than signals from other environment magnetic sources such as earth’s magnetic field.

As with most introductions, the above brief description is over-simplified. The signal induced in the receive coil, by the magnetic field of the eddy current, can be thought of as made up of two simultaneous components, not just an altered component:

- One component is the same shape as the transmit signal. This is called the **reactive signal (“X”)**. Because it is the same shape as the transmit field, the signal, by definition, responds immediately to what ever the transmit signal is doing.
- When this X component is subtracted from the eddy current induced signal in the receive coil, the shape of the remaining signal depends only upon the history of the transmitted field, and not the instantaneous value. This signal is called the **resistive or loss component (“R”)**.

Both the target X and R signals vary depending on the distance of the target from the coil; the further away, the weaker the transmitted magnetic field at the object, and the weaker the received signal from the eddy currents; thus the weaker the receive coil R and X signals which, as stated, may be very weak for deep targets.

¹ Bruce Candy:

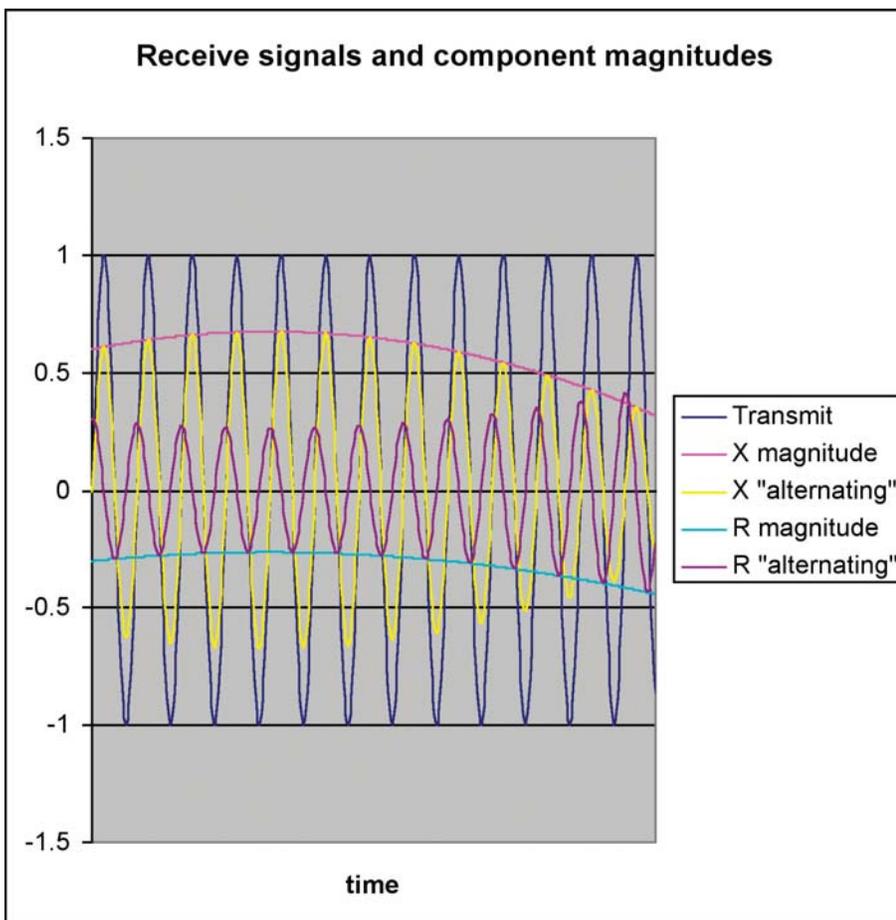
- Co-founder of Minelab.
- Pre-Minelab: designed advanced communication electronics (linear HF transmitters, VHF radar transmitters and receivers, ultra fast-frequency hopping etc), ultrasonic cleaners, fast photon counters, light detection.
- Designed concepts, analogue electronics and discriminator algorithms of Minelab detector (e.g. GS15000, GT/FT/XT. Eureka Gold series, Musketeer, Sovereign, PI units, Explorer series, Excalibur).
- Designed Halcro audio amplifiers.
- Holds patents in metal detecting and audio fields.

The received signal is usually processed by the electronics to produce at least 2 signals: the strength of one signal is proportional to the R signal strength or magnitude, but is no longer an alternating signal. Similarly, the other signal is also not an alternating signal, but rather a signal simply related to X signal strength or magnitude only. Unfortunately, both the terms “X signal” and “R signal” may refer to both these two different meanings: the one meaning referring to the alternating receive signal at the transmit frequency, and the other meaning to the strength of the received signals or magnitude (how big they are). So the term “X signal” may refer to the alternating X signal waveform at the transmit frequency, or just the X signal strength or magnitude, which of course changes as the coil is moved about over different areas of ground. The same applies to the R signal.

This dual meaning of the same term is common in electronics. For example, when referring to a received medium-wave signal, it is not always clear if an engineer is referring to the signal at the medium-wave frequency, or its varying magnitude; namely, the information transmitted regardless of the transmit frequency. In metal detectors, the terms “X” and “R” signal, usually refer to their magnitudes, not the alternating signals.

These X and R signals (magnitudes) are further processed to give an output signal which may be reported to an operator in a number of different ways, the two most common being:

1. a **ground balanced** audio signal, whose loudness is usually proportional to the received signal strength from the eddy currents in metal targets.
2. a **discriminated** signal which only makes an audio “beep” when a target with selected properties is detected. These properties may be varied by a metal detector operator varying the controls of the metal detector. Most discriminating metal detectors also have a visual display which indicates properties of a detected metal target.



In gold, de-mining or UXO (Unexploded Ordinance) detectors, the ground-balanced signal is the most important, and for coin and treasure detectors, the discriminated signal is the most important.

Figure 1. Transmit signal, receive X and receive R at the receive coil, X magnitude, R magnitude. (The rates of change of magnitudes are exaggerated for the sake of clarity.)

1.1 Coin metal detectors.

Almost all Coin and Treasure detectors have discriminator controls for selecting desired properties of a sought metal target. The properties that may be selected are

- **ferrous/non-ferrous (+/-X)** and
- **time constant** (sometimes called conductivity).

If a metal target is attracted to a magnet, this is called a **ferrous** target, if not, it is called a **non-ferrous** target. Ferrous targets are not normally sought and considered “trash” or “junk,” so when a ferrous target is detected, the discriminator controls of the metal detector are usually set so that these do not cause an audio response or “beep.”

As the vast majority of buried metal targets are ferrous, the most important capability of the discriminator is not to detect these targets, but only to detect sought targets; i.e. non-ferrous. This includes non-ferrous targets close to ferrous targets when the ferrous (+X) signal competes with the non-ferrous (-X) signal.

Metal detectors may differentiate between different non-ferrous targets by measuring how well eddy currents flow in them. This is determined by a target's “time constant,” but is often referred to as “conductivity”, which is not a suitable term as conductivity is not the only property of a target that determines its time constant.

Two properties of a metal target determine its time constant. One property is called the target inductance. This inductance may be thought of as the effective “mass” of the eddy currents, and which is basically the size of the eddy current path. Thus, for a given eddy current flow, the bigger the effective target inductance, the bigger the “momentum” of the eddy currents. Another property is called target “conductivity,” which is a measure of how easy it is for eddy currents to flow. This is the opposite of electrical resistance. High conductivity (low resistance) means the eddy currents flow easily (low current “friction”). Low conductivity (high resistance) means high eddy current “friction.” The better the target conducts electricity, and the bigger the inductance, the longer the time constant. That is, a high eddy current momentum with a small slowing resistance, like a heavy vehicle with low friction, takes a long time to stop. Conversely, the poorer the target conducts electricity, and the smaller the inductance, the shorter the time constant. That is, a low eddy current momentum with the resistive “brakes” hard on, like a light vehicle with high friction, takes only a short time to stop. Time constants vary very considerably between targets. Small bits of aluminium foil have very short time constants whereas, for example, gold ingots have a much longer time constant. Here is a table of targets of increasing time constants (from short to long):

small bits of aluminium foil,

fine jewellery chains,

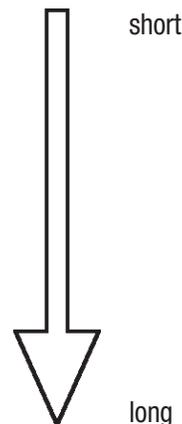
small old Roman coins,

US dime (small 10c coin),

solid US civil war bronze belt buckle,

solid Bronze Age axe head,

large gold ingot, or large thick copper or aluminium plate.



Gold nuggets cover a very large range of time constants, from very short to longish. However, it should be noted that even large gold nuggets mostly produce relatively short time constants compared to similar sized man-made metal targets of high conductivity, because of the way gold nuggets are formed; they have many voids and impurities which significantly reduce conductivity and inductance.

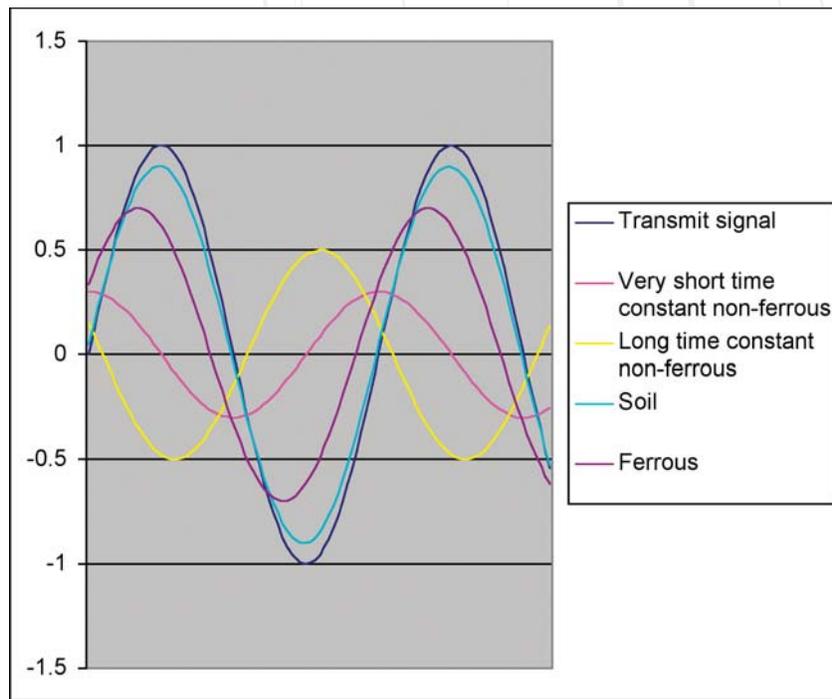


Figure 2. Different time constant non-ferrous targets, ferrous and soil signals at the receive coil relative to the transmit signal. Indicated signal strengths are arbitrary, and different for clarity.

The magnetic properties of ferrous targets cause them to have a high inductance. This is because the magnetic field created by the eddy currents is made stronger by the magnetic property of the ferrous targets. In effect, this “amplified” magnetic field makes the inductance of the target higher. So, even though most ferrous targets may have poor electrical conductivity, they usually have long time constants because of their high inductance. Only pieces of steel or iron that have almost completely rusted through, or extremely thin steel wire have short time constants ² (e.g. highly rusty steel/iron flakes or very thin staples.) However, some mildly ferrous targets may also have short time constants, e.g. some mildly ferrous coins or weakly magnetic stainless steel, and some plated steel targets too.

Most coin detectors may be set to select various ranges of non-ferrous time constants. For example, the old pull tabs of soft drink and beer metal cans have moderately short time constants in a fairly narrow range. This time constant range may be discriminated against, but targets with differing time constants will still be detected. This range may be selected by a “notch” discriminator control. However, other targets with time constants very similar to the pull-tab time constant range will also not be detected, so some care should be taken in setting the discriminator targets. The most common discriminator setting is to discriminate against ferrous targets and the shortest time constant non-ferrous targets.

1.1.1 Ground signals and mineralisation.

Unfortunately, soils are magnetisable and thus also detected by metal detectors and cause signals which interfere with metal target signals. The degree of the magnetic properties of soils varies considerably. This magnetic property of soil is usually called “**mineralisation.**” The mineralisation produces almost entirely X and only a small fraction of R signals. The R and the X signals of a deep metal target are typically much less than the soil X signal, so obviously it is better to use the R signal to locate metal targets, rather than X.

In geologically new soils, the degree of mineralisation is usually weak, except for some volcanic soils. These relatively new soils are commonly found in North America and Europe (from glacier scrapings during the last ice age and mountain erosion etc).³

² The time constant of targets, especially ferrous targets, is dependent on orientation of the target relative to the coil. The time constant may be relatively short in some directions at right angles to the “principle Eigen magnetisation vector.”

In contrast, surface soils which have remained surface soils for a long time often have high mineralisation, because the action of water, over a long period, causes iron compounds to migrate to the surface. For example, Australia has old soils, having had no glaciers recently or significant mountains to be eroded. Some volcanic rocks or sands, known as black sands, may be highly mineralised and are found, for example, in a few USA mainland and Hawaii areas. These black sands (or rocks) are made of mostly magnetite, an iron oxide called ferrite. These typically produce almost entirely X signals, and almost no R. They are heavy, that is they have a high density, and can be identified because they are strongly attracted to a magnet. Small roundish magnetite/maghemite pebbles (a few mm in diameter) are also attracted to a magnet. These, for example, may be found in many Australian goldfields, but do produce significant R signals.

Thus, USA goldfields are typically different from Australian goldfields:

- The USA soils are mostly mildly mineralised but in some areas may contain either nearly pure magnetite black sands or rocks, which are problematic for metal detectors as they have very high X components (strongly attracted to magnets).
- Australian gold fields have highly mineralised soils, but very few black sands or rocks that contain nearly pure X magnetite. The magnetic materials are in the forms of magnetite-rich small pebbles and rock coatings, clays and general “sandy” soils. These all contain magnetic materials that produce high levels of X signals as well as R. The ratio of X and R is random, and the R component arises from extremely small magnetic particles called superparamagnetic materials, which are discussed below.

1.1.2 Discrimination problems in mineralised soils.

In order to determine if a target is ferrous or non-ferrous, metal detectors measure the “X” signal. Ferrous targets produce positive (+X) signals and non-ferrous targets negative (-X) signals. Unfortunately, as stated, the signals from mineralised soils also produce large positive (+X) signals. This obviously causes a major problem, as the soil signal interferes with target ferrous/non-ferrous measurements, especially because the strength of signal from the soil is often much larger than the target signals. Also as stated previously, because most targets are ferrous trash, failure to discriminate these ferrous targets from non-ferrous will result in excessive digging up of this trash.

Basically, the target signal must be more distinctive than the mineralisation signal in order to determine accurately its properties, particularly the ferrous/non-ferrous nature of the target. The closer the target is to the detector coil, the stronger the target signal. Hence in mineralised soils, only targets not buried too deeply may be accurately discriminated. The sensitivity to discriminating targets (how deeply a target may be detected) is controlled by a “**sensitivity**” control. Hence, in mineralised soils, the sensitivity control must be made less sensitive in order to avoid false discrimination. However, in most Minelab detectors the sensitivity is set automatically with further operator sensitivity control relative to this automatic setting, to maximize depth and minimize false discrimination. This feature is very useful.

The mineralisation is random in concentration, but luckily does not vary very much over short distances (e.g. a foot or two or 30-50cm or so), whereas target signals are concentrated over short distances. Hence, as the coil is passed over mineralised soils, the soil signal changes relatively slowly, but over metal targets, the target signal changes quickly. Electronic “**filters**” in the metal detector take advantage of this difference. They reduce the strength of slowly changing signals and increase the strength of quickly changing signals, thus making the difference between target and soil signals bigger. This makes the discrimination far more accurate, but by no means does it completely suppress the slowly changing soil signals, so the depth at which discrimination is accurate is still affected by mineralisation despite the assistance of filters.

The above discussion explains why it is important to use the detector in the following manner: If a metal detector coil is passed parallel to the surface of the soil, with little variation in the distance of the coil from the soil, then variations in the soil mineralisation signal are relatively small and tend to be slowly changing, so will not pass through the filters well. In contrast, if the distance of the coil from the soil surface varies rapidly, then variations in the soil X signal are relatively large and vary quickly. This rapidly changing soil X signal will pass well through the filters, causing interference to the metal target X signal, and hence produce false discrimination readings. Thus, in order to improve accurate target identification and discrimination target depth, it is important to move the coil parallel to the surface of the soil, with little variation in distance between the coil and soil surface, and at a smooth constant sweep speed.

³ In some huge areas of Alaska, mid USA mainland, the “great plain” of central Europe through to the Ukraine, and China etc, relatively new soils are deposited by wind blown winnowed dust from former glacial and semiarid desert areas. These soils, known as “Loess,” consist of particles typically from about 1 to 100µm (quartz, feldspars, clay etc), with a mean size of typically about 30µm, and are sometimes yellow in colour; hence the colour of the “Yellow River” in China. The soils typically contain about 1% or less of magnetic materials.

1.1.3 Multi-frequency or multi-period coin detectors.

Multi-frequency transmitting and receiving metal detectors have a significant advantage in time constant discrimination, and to some extent ferrous discrimination capability, over the most common form of detector, the VLF detector. “VLF” stands for Very Low Frequency, and refers to the frequency of the single-frequency sine-waves that they transmit, usually at high pitched audio frequencies.

There are basically 2 types of “multi-frequency” detectors currently available for coin detection. Some transmit square waves, which is effectively a multi-frequency transmission. Minelab’s Sovereign, Excalibur and Explorer units use a more advanced transmit signal consisting of multi-period rectangular waves, which gives more useful information (more frequencies, in effect) than square waves. The major advantage results from having several different frequency R signals. These can be used to more accurately determine time constants of targets because these different frequency R signals are not contaminated by soil mineralisation X signals, unlike the more common VLF detectors which use R and the mineralisation contaminated X channel to determine the target time constant. In essence, targets with short time constants produce larger high frequency R signals than low frequency R signals, whereas with long time constant targets, the low frequency R signals are larger than the high frequency R signals. Thus, the ratio of the low frequency R component to the high frequency R component gives a measure of the target time constant without interference from the large soil X component. In addition, it is possible to extract a better assessment of the ferrous/non-ferrous nature of a target using multi-period rectangular waves by measuring X when this target component is maximized during a particular period of the multi-period rectangular signal. No equivalent such period occurs in a VLF system. See Chapter 2.9 for more information on Minelab’s BBS and FBS ferrous target processing. This results greater accuracy of discrimination at greater depths.

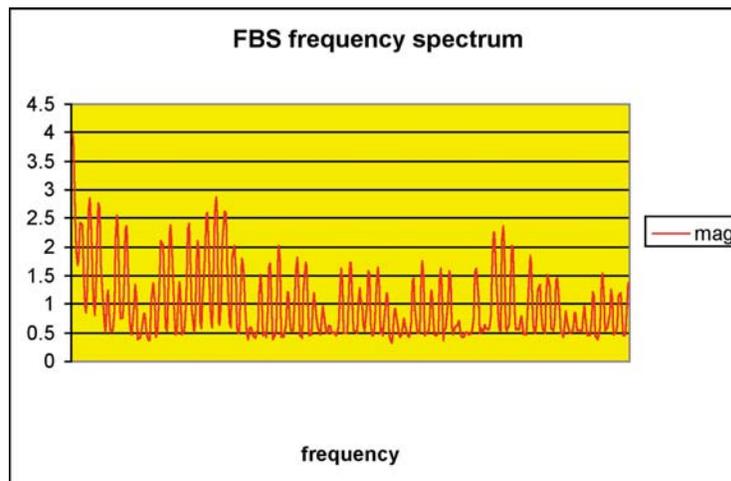


Figure 3. Minelab’s FBS transmitted frequency spectrum. Note the large number of frequencies.

1.2 Gold detectors.

The differences between a gold detector and coin/treasure unit are that:

- the emphasis of gold detectors is in the all-metal mode whereas the emphasis of coin detectors is in the discriminate mode.
- gold detector frequencies and transmission waveforms are optimized to detect very short time constant targets (e.g. most VLF units), and also short through to long time constant targets (e.g. PI units like Minelab’s SD and GP range of models), whereas coin units are optimized for detecting more mid-ranged time-constant targets.

There are substantial differences between gold detectors, which lie mainly in the differences in their ability to reduce the signals due to mineralisation of the soil. This is because, in the most productive goldfields, the concentration of interfering mineralisation signals are extremely intense and thus limit detection depth.

As stated earlier, mineralisation produces a large X component and a much smaller R component. Unfortunately X and R are unrelated and their relationship varies randomly from one location to the next. Salty soils produce R signals from the mineralisation, as well as from the salt conductivity. However, most goldfields do not have salty soils, and in these non-salty soils, the soil R/X ranges from about 0.5% to some extreme “hot rocks” with R/X about 5%. However, the nearly pure magnetite black sands and rocks exhibit very low values of R/X; <0.1%. In very highly mineralised soils, such as Australian goldfields, median soil R/X is between 0.5% and 1%, but this ratio varies from location to location. Some non-salty non-goldfield soils have R/X as high as about 10%. Because of the soil R component, it is not possible to simply detect a metal target by detecting R without a great deal of interfering ground signal, so a technique called ground balancing needs to be employed to reduce the R signal due to the soil.

Different types of ground balancing technologies.

The different categories of ground balance capability are:

1. Manual ground balance VLF.

These units have ground balance knob(s) which need to be manually adjusted and the adjustments vary the amount of X signal subtracted from the R. As stated above, R/X in soils is random, but luckily, the variation changes fairly slowly with distance across the surface of the ground, that is, soils tend to be fairly homogeneous over short distances, so fine adjustment of the amount of X subtracted from R is fairly effective.

For example, suppose the ratio of R to X at a particular location is 1%. If the detector adds no X signal to R and just detects R, then a signal = 1% of X will vary the audio. To reduce this to zero, 1% of X needs to be subtracted from R. Once this is done using the ground balance control, no soil signal will be present in the audio signal. However, say for example that 1 metre away, this ratio has changed to 0.95% instead of 1%. This will mean that $1\% - 0.95\% = 0.05\%$ of the soil X signal will now be reported by audio. Therefore, the ground balance control will have to be changed to 0.95% of X being subtracted from R to reduce the audio signal to zero again. Hence, in order to avoid X contaminating the audio, the ground balance control needs to be adjusted frequently so the faint deep target signals may be heard without louder fractions of the X signal obscuring them.

2. Automatic ground balance VLF.

Metal detectors with automatic ground balance measure the average amount of X contamination in the audio signal. Slowly, the amount of X signal subtracted from the R signal is varied so that the average amount of contamination in the audio signal is minimized on average. The rate of how quickly this adjustment is made must not be too fast as this will also cancel out the weak R signals from metal targets because the metal detector will “think” the small variation in the R signal from the target added to the larger soil R signal is simply due to the usual ground variation and thus will try to automatically track it out. This automatic ground balance (or ground tracking) is a useful feature as it:

- does not require the operator to waste time manually ground balancing,
- saves the tedium of manually ground balancing, a process which usually results in the operator tiring of this procedure, therefore becoming “sloppy” and not ground balancing properly and thus missing targets. This is particularly true for casual amateur operators.
- balances on the average soil mineralisation properties rather than specific locations as manual ground balance units do,
- produces less interfering soil signals as the ground balancing action is continuous and not intermittent as is the case with manual units.

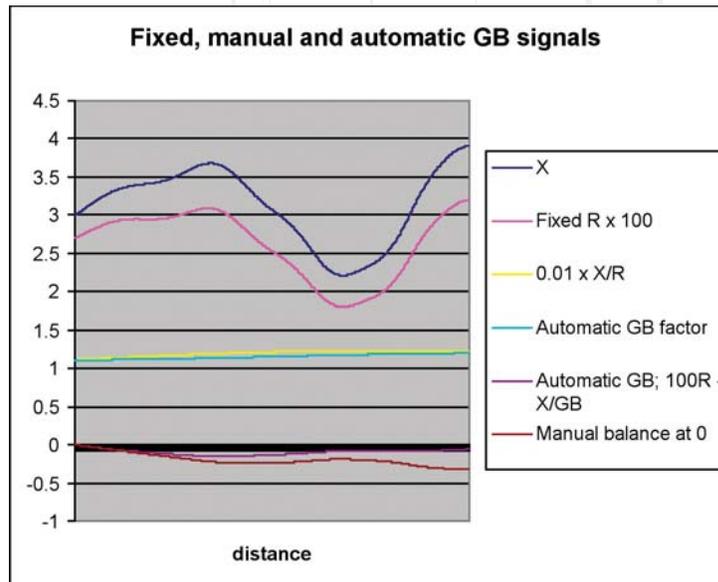


Figure 4. Graph of manual ground balance once at 0, versus auto ground balance. Fixed, manual and automatic GB signals are amplified by 100 times for visual clarity.

Historical note: Minelab was the first company to produce a genuine automatic ground tracking gold detector, the GT16000. Interestingly, at the time many prospectors initially rejected the product, because they suspected that it could not do the job as well as they could. It took some persuasion by demonstration and experience to change their minds. However, to some extent their suspicions were not wholly ill-founded; the automatic action could track out faint targets as mentioned previously, but only if the coil is passed back and fourth over the faint target signal, and then only with relatively short sweeps. For this reason it was, and still is, important that prospectors turn off the automatic ground balance when sweeping back and fourth over a suspected target. The correct procedure is for the operator to automatic ground balance a short distance away from the suspected target, turn the automatic ground balance off to use fixed ground balance, then detect over the suspected target (from many different directions). Only use the automatic ground balance when searching for “new” undetected targets.

3. Pulse Induction (PI) detectors.

In 1995 Minelab PI detectors set a new benchmark for finding gold and landmines deeper in highly mineralised soils. PI technology is very similar to the ignition system of an internal combustion engine. A transmit voltage (e.g. -6 volts) is applied to a transmit coil which produces a transmitted magnetic field. This magnetic field is suddenly turned off (this is when the spark occurs in the ignition system). After the magnetic field is stopped a period occurs when the metal detector measures a receive signal produced by a magnetic field from the environment. During this receiving period, there are no X components, only R, because X only responds to the transmitted field which has been stopped. These R signals come from 2 sources:

- The eddy currents in a metal target dying down and thus their generated magnetic field decaying in strength.
- The magnetisation of the mineralised soil, caused by the magnetising transmitted field, decaying in strength.

Fortunately, most mineralised soils demagnetize in a predictable way following the magnetizing transmitted field, so it is possible to subtract this predictable signal from the received signal, thus only detecting metal target signals, which as commented earlier, may have any decay rate from very fast to slow.

There being no soil X component during the receive signal period has two advantages:

- Soil X is unrelated to soil R as their relationship is random and, as soil R is predictable during the receive period, it can be cancelled without having to deal with a randomly related soil component such as X.
- Soil X is much bigger than soil R and, indeed, X is very large in highly mineralised soils, so it is much easier for the electronics to cope with the very much smaller soil R component in isolation than when it is produced simultaneously with very large X components.

Unlike PI technology, using multi-frequency sine-waves or rectangular waveforms for example, has to cope with both soil X and soil R simultaneously which, as stated, is difficult.

In summary, the order of improved target detection in mineralised soils is:

1. Detection of target X signal:- very poor because of extremely large soil X signal.
2. Detection of target R signal:- roughly 100 times better than point 1, but there is still the problem of large soil R signal.
3. Manually ground balanced R signal:- very roughly more than 10 times better than point 2, but R/X still changes from location to location.
4. Automatic ground balance:- roughly about 50% better than point 3, but ground signals are still significant because of random R/X.
5. Minelab gold and de-mining PI systems:- hundreds of times better than point 4 in highly mineralised goldfields, depending upon R/X variability and concentration of mineralisation.

1.3 More on discrimination and ground balancing.

Some coin detectors include a variable ground balance control, while others have a fixed ground balance set for average soils. Contrary to popular belief, this does not affect the discrimination capability, except to some extent in **multi-frequency** detectors for reasons given in 1.1.3. This is because the problem of the soil signal (almost all X) interfering with the ferrous/non-ferrous X target signal is unaffected by ground balance. To explain this, consider the following example:

Suppose

- the soil X signal after filtering has a signal strength of, say, 4,
- the metal target X ferrous/non-ferrous signal after filtering, has a strength of, say, 2,
- the changed metal target eddy current signal R after filtering, has a strength of, say, 1
- the soil R signal after filtering has a strength of, say, 1/10,
- then clearly there is no problem in very accurately measuring the target R signal after filtering because the target R signal is 10 times bigger than the soil R signal. There is, however, a major problem in determining whether the target is ferrous or not because the interfering X soil is bigger than the target X signal. By improving the R signals through ground balancing, to give a soil signal of say 1/100, obviously makes absolutely no difference, as it does not affect the problem of the interfering X soil being bigger than the target X signal. Hence, ground balancing accurately does not affect the capability of determining whether a target is ferrous or non-ferrous, as the limitation of the soil X signal versus target X signal remains unchanged.

As can be seen in the diagram below, the target R signal is much bigger than both the soil R signal and the ground balanced soil signal. The ground balanced soil signal is approximately zero, so it is irrelevant which one is selected. The target "R" signal is virtually unchanged using R or ground-balanced conditions. In contrast, it is difficult to distinguish target X within the soil X + target X signal, making discrimination impossible, despite a clear target R signal compared to soil in either the R or ground balanced modes of operation.

However, the advantage of ground balancing in the all-metal mode, especially for gold detection, is described above in 1.2.

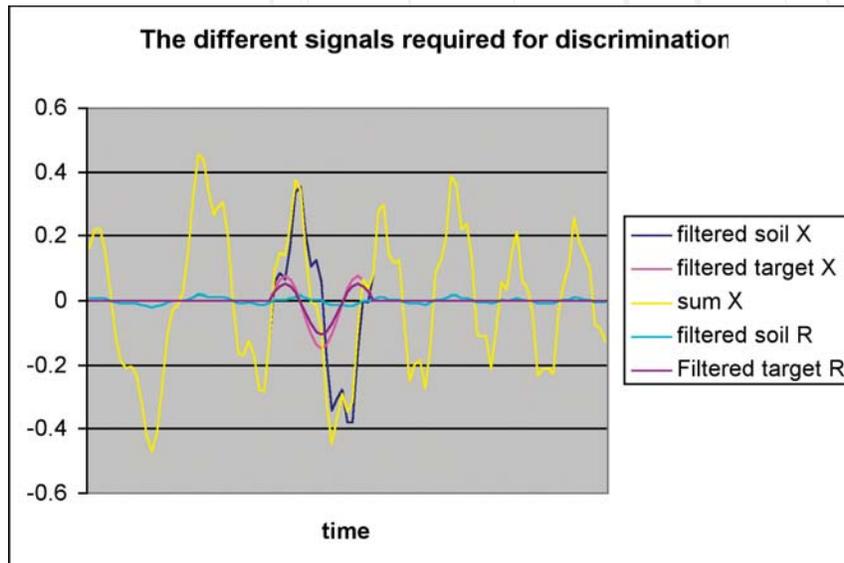


Figure 5; After filtering, note the much larger value of target R signal to either the small soil R or very small ground balanced R, and also the larger soil X signal compared to target X.

1.3.1 Discrimination in goldfields.

In goldfields, discrimination is required only against ferrous targets, without any time constant discrimination, as gold nugget time constants include all values from very long to short.

Unfortunately, X discrimination in goldfields has several major problems:

- Most productive goldfields are extremely mineralised, and thus the soil X signal is extremely large. As was stated earlier, it is only possible to assess the target X signal if this is comparable to, or greater than, the soil signal after filtering. In such extremely mineralised soil, this will only occur when the target signal is also very large which means the target must be close to the metal detector coil. Hence, discrimination in highly mineralised goldfields is only effective for targets buried at shallow depths.
- The discriminator action must be very conservative so that gold nuggets are not falsely discriminated as ferrous targets. Thus, the metal target signal must not only be comparable or merely greater than the soil X signal after filtering, but significantly greater so that there is no doubt whether the metal target is ferrous or not. This further reduces the depths at which targets may be discriminated.

2. More Advanced theory.

2.1 Environmental magnetic noise sources.

Metal detectors, on occasions, may be susceptible to environmental magnetic noise sources. The susceptibility of a metal detector to magnetic or electromagnetic (radio waves) interference is highly dependent upon its sensitivity and detection bandwidth, that is, how much (frequency) information the detector receives. The Minelab PI gold and de-mining units have very high sensitivities, and receive broadband magnetic signals, as do all PI units. The “broadband” receiver and processing electronics means that the detector is sensitive to detected magnetic signals at the fundamental operating frequency (e.g. 1260Hz), and integer multiples of this frequency (e.g. $2 \times 1260 = 2520\text{Hz}$, $3 \times 1260 = 3780\text{Hz}$, $4 \times 1260 = 5040\text{Hz}$, etc). The sensitivity generally decreases with increasing frequency, and the coil circuit further decreases sensitivity above several hundred kiloHertz. The two effects together mean the sensitivity is very low at and above medium-wave frequencies (broadcast band). However, the sensitivity at these discrete frequencies is high between 1220Hz and several tens of kiloHertz. Therefore, they are particularly susceptible to magnetic interference in this range.

There are two main sources of electromagnetic noise:

- Man-made sources.
- Atmospheric sources.

The principal man made sources are:

- **Electrical Mains.** This is most problematic near mains electricity, especially near houses, factories and mains power lines. The mains waveforms are by no means the pure sine-waves suggested in text books. Rather, appliances connected to the mains distort the mains waveform. This distortion is the main culprit for causing interference in metal detectors, because it produces many frequency signals much higher in frequency than the mains, called harmonics. For 50Hz mains; these are $1 \times 50\text{Hz} = 50\text{Hz}$, $2 \times 50 = 100\text{Hz}$, $3 \times 50 = 150\text{Hz}$, $4 \times 50 = 200\text{Hz}$... etc., and for 60Hz mains; $1 \times 60\text{Hz} = 60\text{Hz}$, $2 \times 60 = 120\text{Hz}$, $3 \times 60 = 180\text{Hz}$, $4 \times 60 = 240\text{Hz}$... etc., The strengths of harmonic signals decrease with increasing frequency, and the harmonics in electrical mains become fairly insignificant above several kHz. Most PI detectors, for example, operate at frequencies where the mains harmonics are still very significant in strength. Owing to their very high sensitivities, they are very susceptible to mains interference. To avoid this interference, Minelab PI units have a tuning control which enables the detection frequency to be varied to fall between mains harmonics (e.g. for a 50Hz system, say between say 1250 and 1300 Hz). However, a few appliances running from mains electricity cause broadband interference, and no frequency tuning will reduce interference from these sources.
- **TV and switch-mode power supplies.** Another major source is TV line frequencies at about 15-16kHz plus harmonics. Similarly, modern electronic power supplies (e.g. found in computers) may produce low-level interfering signals at many tens of kHz. Again, one needs to be near these sources for them to be a problem.
- **Electric fences and ignition systems.** These sources are well known to prospectors in goldfields far from mains. They produce broadband frequency interference and so cannot be tuned out.
- **Other metal detectors.** If one metal detector is transmitting a similar magnetic field to another, they are likely to interfere with each other if close.
- **Long and medium wave radio transmitters.** These are not as big a problem as people imagine, unless one is close to the transmitter.
- **Sometimes TV stations, microwave links, mobile phone tower signals and particularly radars etc.** are blamed for interference. These are mostly not significant sources and interference from these is very rare. The signal from a mobile phone is generally stronger when it is a few metres (yards) or so from the detector, than most distant transmitters. This is because the signal strength decreases as an inverse square law (e.g. at ten times the distance, the signal is $10^2 = 10 \times 10 = 100$ times less.) Some mobile phones (but not all) will cause interference if less than about 2 metres (6 feet) away from the sensitive PI units. Beyond 2 metres, there is no effect. Hence, because of the inverse square law, a transmitter at 2km rather than 2 metres away will have its signal attenuated, relative to

its strength at 2 metres, by $1,000^2 = 1,000,000$ times weaker. Of course the transmitters cited above are considerably more powerful than a mobile phone and hence still may cause problems; the very powerful radars up to about a mile away, and the less powerful transmitters, up to about 100 metres (or yards) away, if that. As radars have very intense peak powers with highly directional antennas, which direct all their energy in a narrow beam, they tend to be worse than other transmitters but, nevertheless, usually produce no effects in metal detectors when more than about a mile away. If one is this close to a powerful transmitter, it is very likely that one is also near mains electricity, so it is hard to tell which source is the dominant source of interference. Generally one can tell, because mains can be tuned out, but usually not the powerful transmitters. As these very powerful transmitters are few and far between, there are very few locations where they present a problem.

- Figure “8” receive coils or the “cancel” mode of some Minelab models will eliminate the effects of magnetic sources of interference (mains, TVs, other detectors, sferics described below etc), but not strong “electromagnetic” high frequency radio signals such as radars etc. So, check with a figure “8” receive coil or the “cancel” mode; if the interference is unaffected, then the source may well be from a powerful transmitter such as a radar, but if the interferences ceases with the figure “8” coil or cancel mode, it is not from a radar etc.

The principal atmospheric sources are:

- Lightning. This is the main source of problems for prospectors or de-mining operators with highly sensitive detectors far from mains sources (>100 metres or yards away). Lightning signals may travel thousands of km (miles) and are known as “sferics.” Because there are hundreds of strikes per second in the world, the interference, when significant, is effectively continuous, and as the sferic pulses are broadband (i.e. all frequencies), cannot be tuned out by a change in metal detector frequency. Sferics is manifest through an apparently random unstable threshold and, on some occasions, with loud transients. As there is much more lightning in tropical and subtropical regions, these areas suffer the most from this source, especially during “wet seasons.” Owing to the way the sferic electromagnetic waves propagate around the world, the magnetic field is horizontal, so when the coil is horizontal (as it mostly is), sferic signals are usually not a problem. However, when coils are tilted (as they are on a hill side), this source can be troublesome. Alternatively, some magnetite or maghemite rich mounds, banks, hills etc, may direct the sferic magnetic field away from the horizontal slightly, and so detecting near these may cause sferic interference even when the coil is horizontal. Note that the intensity of sferics varies very considerable from place-to-place, season-to-season, day-to-day, and even hour-to-hour. With the plane of the coil vertical, the detector may be used as a sferic “direction finder” for relatively close thunderstorms (e.g. < a thousand km away). The main direction of the sferic waves is perpendicular to the plane of the coil that gives least interference. However, the sferics is often from all directions, and so orientation (with the plain of the coil vertical) has little effect on signal strength. Generally speaking, the sferic signal has two components; isolated transients from closer lightning, e.g. several per minute, or once every few minutes, and a general continuous random weaker back ground from distant lightning (tens/hundreds of weak broadband pulses per second). Usually there is a mixture of both, but sometimes one type or the other dominates. The spectrum of sferics that usually affects metal detectors ranges from about 5kHz to a about 200kHz. There usually is a very broad spectral peak at several tens of kHz . As this frequency range is fundamental to the operation of PI detectors, and the gains of the Minelab units are very high with very low-noise amplifying electronics, it is unfortunately impossible to “filter out” this continuously random, very broadband, source. One has to use a far-field balanced coil to eliminate sferics e.g. a figure “8” receive coil, or the “cancel” option on the Minelab detectors.
- Long conductors (e.g. > a few hundred metres or yards) such as phone lines or wire fences, and even mains lines. These act as antennas which amplify sferic signals well and transform the magnetic field to a more vertical field, which a horizontal coil may detect well up to 10 metres/yards away, depending on the length of the cable, level of sferics etc. Note that, near the ends of these long conductors, the magnetic field is weak, but far from the ends (e.g. middle), is much stronger. These long cable antennas are most effective when they traverse hills, even if not steep, rather than reside entirely on a horizontal plain. Sometimes the main source of interference from long electrical cabling is from amplified sferics, rather than mains current harmonics!
- Another source may on occasions be static electricity charged prospectors discharging via their detector coils through conductive vegetation on low humidity days. The “conductive vegetation” is usually green moist plants. The voltages involved are considerable and of the order of 10kVolts, and these transient discharges are difficult to eliminate. Sometimes wind borne charged particles are blamed for continuous background interference, but this source is not significant. Almost always the real culprit for continuous

background interference is sferics, mains and very occasionally, radars etc. To determine the source of interference, change the orientation of the plane of the coil from horizontal to vertical. If the interference increases dramatically, the source may be sferics. Alternatively, check with a figure “8” receive coil or the “cancel” mode; if the interference is unaffected, then the source may well be from static (or radars etc), but if the interference ceases with the figure “8” coil or cancel mode, its source is not from static, but magnetic fields.

In summary,

1. Mains electricity, including TVs, is a major source of interference to very sensitive PI detectors and, to a much lesser extent, coin detectors. This interference may extend up to 100 metres (yards) or so, but this is very variable depending on the particular interference.
2. Nearby operating metal detectors may cause interference.
3. Ignition systems and electric fences.
4. Far from mains (>100 metres or so), the major source is sferics.
5. Sferics are amplified by fence lines or any long conductor (e.g. phone lines).
6. Interference from static electricity, or radio transmitters, especially radars, is rare.
7. To determine whether any source is magnetic or not, check with a figure “8” receive coil or “cancel” mode. If the problem is absent with this coil or mode, the source is magnetic. However, if the use of a figure “8” receive coil or “cancel” mode does not reduce the interference, then the source is non-magnetic, but is probably transmitters or static electricity..

The following table lists the differences between the most common man-made interference, mains electricity, and the most common natural interference, sferics.

Property	Mains	Sferics
Sound	Distinct pulsing; usually varies slowly in rate (frequency of pulsing)	Random unstable threshold, sometimes with occasional short-duration pulses.
Tuning	Can be very effectively tuned out.	Tuning makes absolutely no difference
Coil orientation	Usually fairly independent on whether the coil is horizontal or vertical.	Highly dependent on whether the coil is horizontal or not. Even small deviations from the horizontal will increase interference very significantly (unless near a long electrical conductor; e.g. fence)

2.2 Signal strength decrease with depth.

Most detector operators would have noticed that the target signal strength is highly dependent upon the distance of the target from the coil. This is because the magnetic field decreases very quickly with increasing distance between the transmit coil and the target ; so too does the magnetic field decrease very quickly with increasing distance from the target to the receive coil. Suppose the transmit and receive coil are one and the same, as in a mono-loop. Suppose the target is directly on the central axis of the coil. If the coil radius is a, and the target distance from the coil z, then the field at the target is

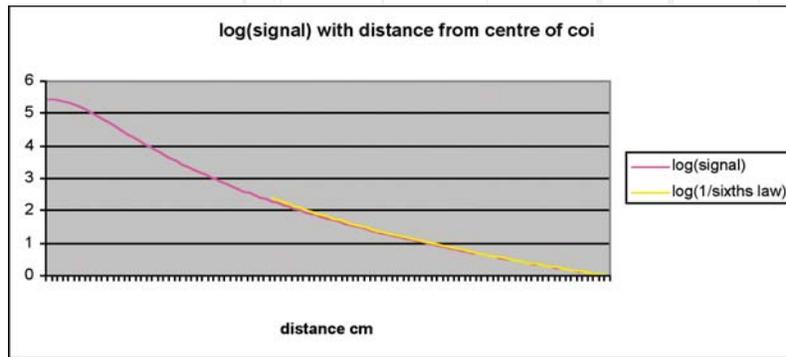
$$H=2nIa^2/(a^2+z^2)^{3/2}$$

where I is the transmit current and n the number of transmit coil windings (and thus receive too, as this is a mono-loop wound coil). Assuming that the target is small, the signal from the target back to the coil is similarly detected in proportion to

$$2na^2/(a^2+z^2)^{3/2}.$$

Thus the there-and-back signal is proportional to

$$1/(a^2+z^2)^3.$$



**Figure 6. Logarithm of receive signal strength for an 11” mono-loop with distance from the centre of the coil.
Note that the signal is close to being a $1/z^6$ law for distances greater than 40cm.**

Thus, suppose that the winding radius a is 12.5cm (11”) mono-loop, and a small target is on the central target axis; then, the target signal will decrease by several hundred thousand times from the coil to 1 metre away as shown in the figure. As an example in the $1/z^6$ region, an increase in depth of 12% will result in the signal halving in strength, and an increase of 47%, that is say 40cm to 59cm, results in the signal being 10 times smaller.

Different technologies.

Metal detectors transmit a variety of different waveforms all with different advantages and disadvantages. The most common waveform is VLF which is basically a single frequency sine-wave. The next most common is PI, the basics of which are given in section 1.2.1. Minelab’s “Broad Band Spectrum” and “Full Band Spectrum” products transmit yet another waveform which is composed of multi-period rectangular-waves.

Definitions given below:

$\tau = L/r$ = mean metal target time constant, where L is the effective mean target series inductance and r the effective mean target series resistance.

$\omega = 2\pi/\tau$ = frequency of target resistive component (R) peak value (characteristic frequency).

t = time variable.

2.3 Single frequency sine-waves (VLF).

The resistive component R of a first order time constant non-ferrous metal target with $\tau = L/r = 2\pi/\omega$ (first order meaning that the time constant is not distributed), is proportional to

$V\omega\omega_0/(\omega^2+\omega_0^2)$, and the target reactive component X for a non-ferrous target is proportional to

$V\omega_0^2/(\omega^2+\omega_0^2)$, for a sinusoidal transmitted signal of frequency ω_0 and strength V . (Actually, the sign of X is negative.)

The following figure shows this relationship graphically.

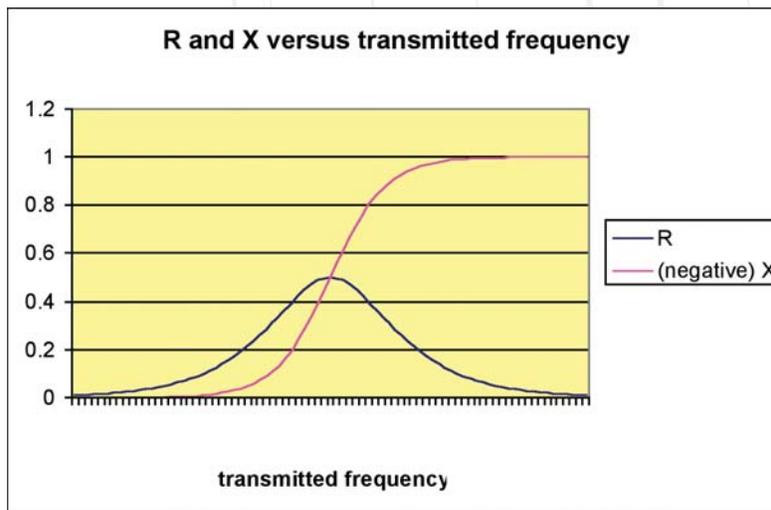


Figure 7. VLF X and R responses to a first-order time constant target versus transmit frequency ω_0/ω .

In essence, the resistive component has a broad peak at $\omega_0 = 2\pi/\tau$ (frequency=1 in the figure), whereas the reactive X component has a relatively fast transition centred about $\omega_0 = 2\pi/\tau$. The resistive component is associated with energy loss (electrical heating in the target) and the reactive component X is the extent to which the target “reflects” the transmitted magnetic field by eddy current re-transmission without losing energy. Loosely speaking, this is diamagnetic-like, although from a scientific point of view, diamagnetic usually means something else. At high applied frequencies ($\omega_0 \gg \omega$), the reflection is near 100% and the transmitted magnetic field applied to the target does not effectively enter the target. At low applied frequencies ($\omega_0 \ll \omega$), metal targets are approximately transparent to the transmitted applied field, and at $\omega_0 = 2\pi/\tau$ half the energy of the applied transmitted field is reflected and half absorbed.

However, if a metal target is ferrous, then the target has two competing magnetic X components; the same eddy current diamagnetic component as in non-ferrous targets, with negative X values, and a ferromagnetic component which enhances the magnetic field with positive X values, (very loosely speaking, a kind of opposite of diamagnetic). The ferromagnetic component alone, excluding any eddy current contribution, is approximately independent of frequency at typical metal detector frequencies ω_0 . At low frequency applied fields ($\omega_0 \ll \omega$), the target looks magnetic (ferrous), as the diamagnetic component is approximately zero and the ferromagnetic component dominates. At high frequencies ($\omega_0 \gg \omega$), the reflection is near 100% and the transmitted magnetic field applied to the target mostly does not enter the target because the eddy currents are constrained to the target’s surfaces; this is called the “skin effect.” Thus the magnetic field does not encounter the bulk internal ferrous nature of the target but, rather, only the surface ferrous components which are much smaller in magnitude than the diamagnetic eddy current component. Hence, for ferrous targets, the X component changes sign from ferromagnetic (+X) to diamagnetic (-X) or from “ferrous” (+X) to apparently “non-ferrous” (-X) at a particular frequency ω_0 .

It follows that a problem with ferrous discrimination of large ferrous targets, having long mean time constants, is that the possible larger diamagnetic response may make a detector indicate that the target is non-ferrous.

Another problem of discrimination is when large targets are close to the coil. Receive coils are “nulled” relative to the transmitted field, that is, the transmitted field half induces a “positive” transmit magnetic field contribution to the receive coil and half induces a “negative” transmit magnetic field contribution to the receive coil. If the target is mostly within the region of the “positive” transmit magnetic field contribution to the receive coil, then the received signal contributes mostly “positively” to the receive signal, both for X and R. Similarly if the target is mostly within the region of the “negative” transmit magnetic field contribution to the receive coil, then the received signal contributes mostly “negatively” to the receive signal, again both for X and R. Because both X and R present the same relative signs in each region, the ferrous/non-ferrous nature is assessed to be the same in both regions. Many targets are not symmetrical, though, and the location within the target which produces the biggest R signal is often not in the same location of the biggest X signal. A problem occurs when the different location of the target dominant R signal adds a receive signal in the opposite sign sense to the dominant X of the target. This makes the metal detector respond in the reverse ferrous/non-ferrous sense to the target when it is in the coil’s sign-reversing region.

Luckily, this region is small in size so the detector should respond mostly correctly. However, one may falsely think that the detector has located a non-ferrous target amongst ferrous targets when a large ferrous target is close to the coil, or worse, that a large gold nugget close to the coil is ferrous! Hence, great care should be taken when large targets are close to the coil.

2.4 Multi-frequency systems.

The term “multi-frequency” applies to multi-frequency sine waves, PI, square waves, multi-period rectangular waves etc, in short, any transmit signal other than a single frequency sine wave.

Technology that transmits multi-frequencies has several advantages over single frequency sine waves:

- Improved discrimination (see 1.1.3)
- Ability to cancel mineralisation signals well.

2.5 Multi-frequency sine-waves.

At typical metal detector effective transmit frequencies (1-100kHz), the R component of mineralised soils is approximately independent of frequency. The X component is also almost independent, but has a slight frequency dependence.

Assuming that soil electrical conductive is insignificant at typical metal detector frequencies, the relationships between R and X, in magnetic mineralised soils at different frequencies, are:

If ω_l and ω_h are transmit frequencies with $\omega_h > \omega_l$, then

$$X_l - X_h = k \ln(\omega_h/\omega_l)$$

$$R_l = R_h$$

$$(X_l - X_h)/R_l = (X_l - X_h)/R_h = 2\ln(\omega_h/\omega_l)/\pi$$

where X_l is the low frequency soil reactive component,

X_h is the high frequency soil reactive component,

R_l is the low frequency soil resistive component,

R_h is the high frequency soil resistive component,

ln is the natural logarithm,

And k is an arbitrary constant and a function of mineralisation and proximity of coil to the soil etc.

As noted earlier, soil R/X is random, and typically R/X in mineralised goldfields is of the order of 1% (most often a bit less). In other words, only a small part of the soil magnetic signal reacts to the history of the applied field (R). Most of the soil component signal reacts instantaneously to the applied magnetic field and is thus X. Suppose R/X is 1% at say 1kHz, so $X/R = 100$, then the decrease per decade in frequency of X/R is $2\ln(10)/\pi = 1.466$. Thus at 10kHz, $X/R = 100 - 1.466 = 98.53$, and at 100kHz = $98.53 - 1.466 = 97.07$ etc. This relationship does have an upper limit of the order of 100s of kHz or MHz depending on the particular material. (The distribution of “time constants” of individual microscopic magnetic “particles,” which is a function of the “particle” size and shape distribution, determines at what frequency this relationship ceases to be accurate. See 2.6. Similarly at extremely low frequencies, this relationship ceases to be accurate too, at frequencies of the order of hundredths of a Hz. However, what matters, is that these relationships hold well at typical metal detector effective operating ranges (e.g. 1-100kHz).

Hot rocks” are rocks with R/X significantly different from the average local soil R/X as detected by VLF detectors, or with significantly different but very small R frequency dependence compared to the local soil as detected by multi-frequency detectors (including PI) with the above mathematical expressions satisfied (see 2.6).

For time constant discrimination, just R or ground balanced R from at least two frequencies can be used for accurate determination with minimal soil X interference:

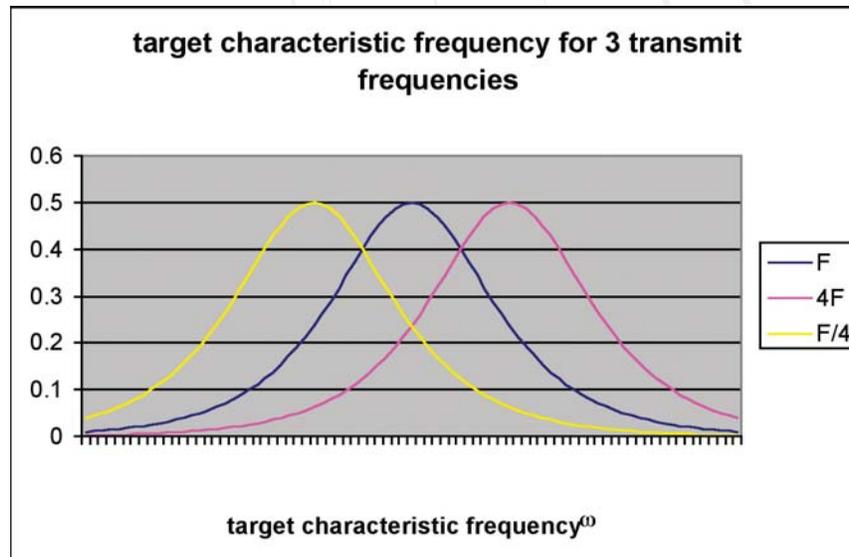


Figure 8. For a target characteristic frequency $\omega = 2\pi/\tau$, the resistive component R is different for each transmitted frequency.

2.6 Pulse induction (PI).

In terms of PI, the X component of magnetic soils simply responds directly to the transmit field as defined above. The R component of the magnetic soil response, resulting from “superparamagnetic viscosity” as mentioned above, results from the time for microscopic magnetic non-interacting single-domain particles⁴ to overcome their associated small energy barrier, which is related to their thermal energy, and align with the applied magnetic field. This (Arrhenius) thermal energy is well known to scientists and equal to kT where k is Boltzmann’s constant and T is the absolute temperature. The size of these particles is of the order of 10 nm. This is less than the wavelengths of visible light; such a particle cannot even be seen with a light microscope! After the cessation of the transmission, these magnetic particles randomise again because of temperature, and in doing so produce a “demagnetising” decay signal.

In simple, common terms, “viscous” refers to the particles being suspended in a “sticky” substrate, but being “shaken” by heat which randomizes these magnetic particles. The single magnetic domains are not joined together as in multi-domain iron, but are effectively physically separated, so they are not directly magnetically interacting. “Paramagnetic” is an extremely weak magnetic enhancing property of some materials which is related to the Bohr magneton of atoms, a magnetic moment well known to physicists. Again because of temperature, the atoms contributing to this do not align well with an applied field because they are randomized by temperature. That is, the magnetic field causes a force to magnetically align the atoms/molecules with the applied field, but temperature competes simultaneously to randomize them. The temperature effect is considerable and so the attraction to a magnet is so weak that it cannot be noticed in everyday human experience. The magnetic susceptibility of paramagnetic materials approximately follows Curie’s law and is thus proportional to $1/(\text{absolute temperature})$. In superparamagnetic materials, the phenomenon is basically the same, but much larger single domain particles are responsible for the magnetic enhancement, instead of individual atoms, and thus the magnetic moments are gigantic in comparison because of the cooperating atoms in the single domains. Hence, the term “superparamagnetic” refers to a much stronger “paramagnetic-like” phenomenon.

Superparamagnetic particles of a specific size and shape have a “time constant” exponential decay. Superparamagnetic usually arbitrarily is defined as having a time constant of less than 1 minute. This time constant is highly dependent on size and temperature.⁵

⁴ The superparamagnetic “particles” are often referred to as “grains.”

For example, 28nm magnetite particles at 20C behave superparamagnetically with an exponential decay of about 1 minute, but slightly larger viscous particles may exhibit amazingly longer decays: magnetite particles of about 32nm exhibit decays of the order of an hour, and particles of size 37nm decay over a time of about a billion years! However, at an elevated temperature of 100C, the 32nm particles will exhibit a time constant of <1minute! Viscous single domain particles with a random particle size distribution, that is, resulting from a log-uniform time-constant distribution, will show a logarithmic magnetic decay for a magnetic step function (the 1/t component in the PI response given below).

Interestingly, superparametric grains are employed biologically: Some birds with excellent navigation have a membrane surrounding a superparamagnetic ferrofluid containing approximately 3nm magnetite crystals suspended in a liquid. The magnetic field distorts the ferrofluid and thus the membrane to an ellipsoidal shape with the long axis aligned with the field. Nerve fibres sense this shape change and associated change in osmotic pressure across the membrane, thus enabling a sense of terrestrial magnetism.⁶

Most single-domain particles are not viscous, as they are too large to be thermally “bumped out” of magnetic alignment. Thus, they may exhibit stable magnetism. The more slowly decaying particles will produce an X response in metal detectors because of their slowness compared to the transmit frequency. Most of the X component arises from particles bigger than the superparamagnetic particle range that decay at rates much slower than the transmit fundamental frequency, or are magnetically stable. These materials detected as X only consist of the slower viscous particles, stable single domain particles, pseudo single domains, and multi-domains. Superparamagnetic particles exhibit both X and R responses during the transmit on period in PI detectors for similar reasons why a metal target does in a VLF detector as described above, except that the time constant distribution is log-uniform over the effective time-constant range of the receive circuitry.

There are many superparamagnetic materials; magnetite, maghemite and titano-hematite particles being the most common.

Superparamagnetic particles ideally exhibit no hysteresis, and thus no remanent magnetism, and they magnetically saturate easily (compared to multi-domains or even pseudo single domains). “Saturate” means that the received signal is not linearly related to the transmitted magnetic field; if the field doubles in strength at a particular magnetic domain in the soil, the X and R received response do not double, which they would were the relationship linear. This saturation causes the mathematics of the soil decay response given below to lose accuracy. This is because the different sized particles saturate differently. This means that there is no straightforward way of accurate ground balance.

The magnetic strength to cause noticeable saturation to a sensitive metal detector depends on the magnetic chemical. Most of the superparamagnetic particles found in the goldfields require intense fields to cause saturation whereas, ironically, some more benign mineralised soils saturate more easily, and thus may cause worse spurious signals than the highly mineralised goldfields. Double-D coils are excellent for suppressing the effects of near-surface saturation, whereas mono-loops are poor at this. Thus, this saturation can most easily be noticed when using a mono-loop coil as one “pumps” the coil up and down, causing varying field strength in the soil. In easily saturable soils, good ground balance is not possible because of saturation, whereas accurate ground balance may be achieved in soils that require more intense fields to cause saturation. However, the Minelab GPX- 4000 (“Smooth” and “Specific” modes), and de-mining detectors (F3 and HSTAMIDS) uniquely provide modes insensitive to saturation effects, so mono-loops can be used in saturable soils with these Minelab units without problems.

As implied above, all soils and particularly hot rocks, do exhibit a very small degree of R frequency dependence, because the superparamagnetic decay time distribution is not perfectly log-uniform over the range which effect metal detectors. The soils and hot rocks

⁵ It would be a mistake to assume that because the time constant of a particular size superparamagnetic particle is highly temperature dependent, that the soil's response is also highly temperature dependent. Basically, as the temperature changes, so too does the size of the particles contributing to a particular time constant merely change, right across the continuum time constant range.

⁶ Further, one type of bacterium produces stable single domain crystals which it stores internally. Another type produces random small sized single domains, including superparamagnetic grains, which it expels into the environment.

with relatively larger R frequency dependence (still very small in absolute terms), will exhibit an R permeability frequency spectrum that is noticeably temperature dependent too, for the reasons given above. Some rare extreme “super-hot-rocks” exhibit very significant R frequency dependent permeabilities, and these are thus highly temperature dependent because the time constant spectrum is not log-uniform. Such rocks exist in some areas in the Golan Heights in the Middle East, for example.

Suppose a PI transmit coil system has an ideal transmit system, that is zero transmit system “on” resistance, and the whole back-emf duration is extremely short and any delays in the receiver transfer function are also extremely short. If the “on” period is T with a voltage V applied across the transmit coil, then for a single transmit “on” pulse followed by a back-emf pulse, the received voltage signal across the receive coil from magnetic soils is

$$kV\{ T/t - \ln[(t+T)/t] \},$$

where k is a function of coil distance from the ground and the local concentration of mineralised soils. This decaying signal is purely the R component which results from the history of the applied field.

The important issue is that the above soil response is predictable and, to a high degree of accuracy, soil invariant. Thus, by subtracting one part of the signal from another, it is possible to cancel the soil response.

For a first order metal target, that is a target with a non-distributed time constant, the target response is proportional to

$$V\{T/\tau - 1 + \exp(-T/\tau)\}\exp(-t/\tau).$$

This is different from the soil equation, so the subtraction of one part of the signal from another to cancel the soil response will, in general, not cancel the target signal.

If for example, samples were taken at $t=0.02T$, to give a signal S1, and at $0.5T$ to give S2, and at T to give S3, then the value of $S1 - 76.97S2 + 75.97S3$ will cancel signals from the soil for this “ideal” PI system, and also cancel signals induced by static magnetic fields such as the earth’s field.

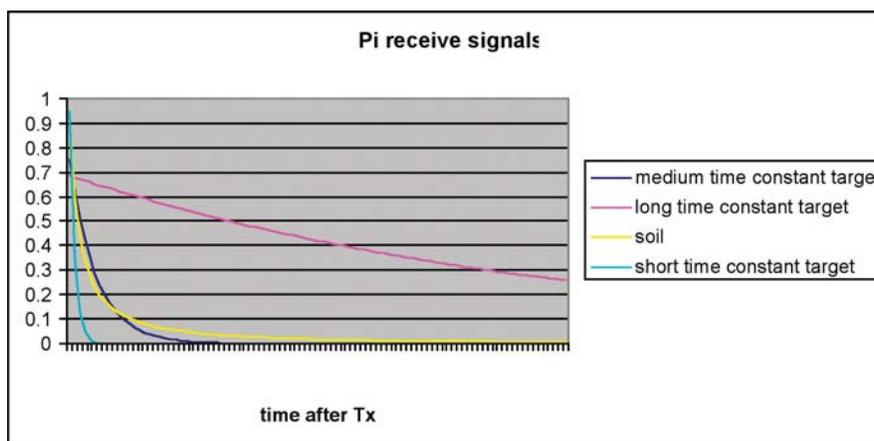


Figure 9a. Comparison between a long, medium and short time constant target, and mineralised soil signal decay from a PI pulse.

Some texts present this graph as a log-log scale, so for comparison, this is given below.

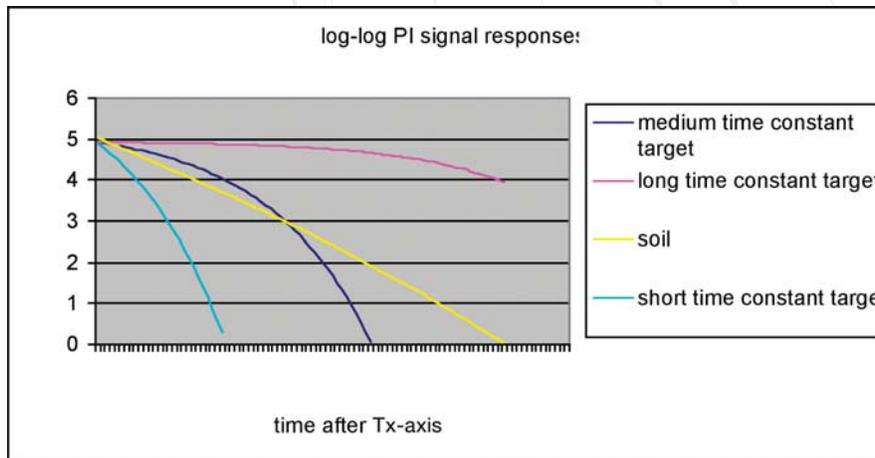


Figure 9b. Same as figure 9a but log-log scale.

Note that the soil signal is scale invariant in time, that is suppose $T = 1$ and $t = 0.1$. Then if $kV = 1$, the value of the signal at $t=0.1$ is $1/0.1 \cdot \ln(1.1/0.1) = 10 \cdot \ln(11)$. Compare this to time scaled up by 2 times, that is $T = 2$ and $t = 0.2$, which is still the same, namely $2/0.2 \cdot \ln(2.2/0.2) = 10 \cdot \ln(11)$. This is what one would expect from a log-uniform distribution of time constants.

However, the target response is not scale invariant with time, that is for $T=1$, $t=0.1$, the response for say $\tau=0.05$ is $\{1-0.05[1-\exp(-1/0.05)]\}\exp(-0.1/0.05) = 0.14$, whereas for $T = 2$, $t=0.2$, the response is $\{2-0.05[1-\exp(-2/0.05)]\}\exp(-0.2/0.05) = 0.037$. This is because the target time constant is literally, as said, "constant."

{For readers interested in state-of-the-art mathematics, I have a paper published in the prestigious applied maths journal SIAM J. Appl. Math., Vol 66, No 2, pp. 468-488 2005, which discloses a solution using non-linear mathematical techniques to a problem which eluded engineers for many decades.}

As stated above, the range of time constants of the magnetic particles is log-uniform over a certain range of values. This range sets an upper frequency limit for the accuracy of the relationships given in 2.5. For the same reason, the soil signal decay, shortly after the cessation of the transmit period where this high frequency soil behaviour is manifest, ceases to be predictable owing to random variation in soil magnetic particle time constant distributions from location to location. Hence, this sets a lower limit to the delay before receive measurements commence following the transmit signal in order that soil signals may be cancelled accurately. Thus this also sets a lower limit to the time constant and hence size of the nugget that may be detected whilst still rejecting soil signals accurately.

However, there are other reasons why measuring too close to the transmit pulse is a problem. First, transient signals from the transmit and receive electronics may cause a problem. This can be reduced by careful electronic design, but there is always a limit. Second, conductive components of soil may cause interference. The intensity of these conductive soil components is dependent on coil size; large coils detect these far more overtly than small coils. In practice for inland "non-salty" soils, this becomes a problem for the PI units with similar gains and delays to Minelab PI units in many areas if the coil (mono-loop) is about a metre (3ft) or more in diameter. The effect is pronounced for a 4' diameter mono-loop. In salty soils, the effect is far greater because of increased soil electrical conductivity. This soil conductive response roughly follows a $kt^{-5/2}$ law, which is a far more rapid decay than the $T/t - \ln[(t+T)/t]$ response. The term k in $kt^{-5/2}$ is a function of the local soil conductivity and coil size. This dominates for very large coil loops, and for ore prospecting when loops of the order of 100 metres diameter are laid on the ground surface. As long as the receive loop is about a metre bigger or smaller than the transmit loop, that is spaced away from the transmit loop by >1 metre, then the soil magnetic signal becomes insignificant compared to conductive ore signals. This is because the ore signal is so much stronger, and because the soil magnetic materials are typically shallow, most effectively less than a metre.

The SD2000 detector was developed by deriving the above mathematical expressions, first in 1987, then checking the validity of these with a simple electronic circuit. The reason for doing the maths resulted from a realisation that if the soil R signal was independent of frequency, then it must necessarily follow that the pulse induction soil signal must be of an invariant shape, and therefore capable of being cancelled. About a month later, a prototype was tested in the goldfields; it worked far better than a multi-frequency sine-wave prototype which had already been significantly more successful at finding gold than any VLF detector. This was developed further into a robust prototype for further checking. A patent was then filled and thereafter several prototypes built and used to find gold on a regular basis. These prototypes were upgraded a few times and tested by the so-called "12 Apostles." (The number "12" was a myth; there were fewer than 12 in reality.) All this work on this PI development was done purely by me "after work hours" during a very busy period, hence the relatively long delays. The improving prototypes resulted in the SD2000.

In terms of discrimination, obviously all multi-frequency technologies have the ability to relatively accurately discriminate time constants without significant X component soil interference. PI is no exception. The figure shows the response produced by subtracting one sample from another at the times indicated. The black curve, S1, is the response from the difference between a sample at $t=0.02T$ from a sample at $t=0.1T$ where $t=0$ at the end of the back-emf pulse. The yellow curve, S2, is the difference between a sample at $t=0.05T$ from a sample at $t=0.3T$ relative to the result S1. The red curve is the difference between a sample at $t=0.2T$ from a sample at $t=T$ relative to the result S2.

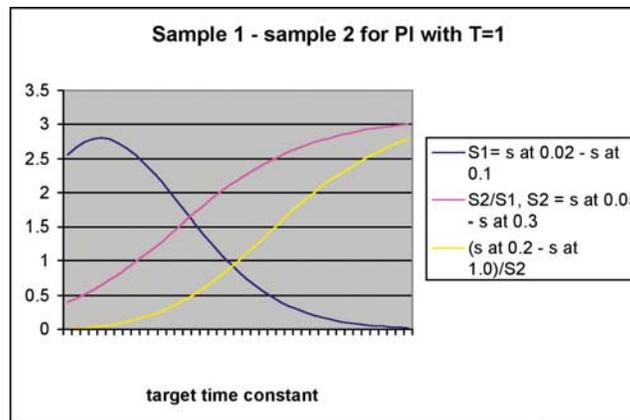


Figure 10. Responses to different sampling times for a PI transmit signal.

In the figure, "s" stands for "sample at time xx after the transmit pulse." As can be seen, the ratio varies very substantially for different target time constants t which basically means well-defined differentiation between different targets. For reference, the figure below is for sine waves, and shows the relative response for 3 different frequencies, each separated by a factor of 4 to be consistent with Figure 10. This shows a similar degree of t differentiation but with the advantage of greater values of R at the target characteristic frequency extremes, thus yielding a greater advantage over PI for discrimination, as will other multi-frequency CW systems with a similar spread of "effective" transmit/receive frequencies, such as the Minelab multi-period rectangular-wave detectors (e.g. Sovereign/Explorer).

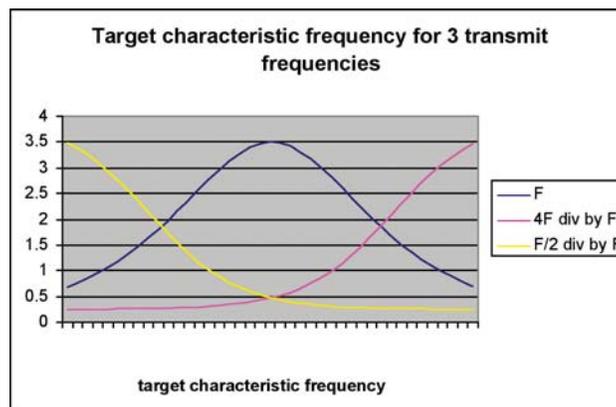


Figure 11. Relative R component response for 3 simultaneous sine-waves. Compare with figure 10.

2.7 Multi-period PI; Multi-Period Sensing (MPS).

According to the above expression for magnetic soil viscosity, the shorter the transmit ON time, T , the greater the low frequency attenuation of the viscosity signal, relative to the high frequency viscosity. In terms of magnetic viscosity, this greater attenuation of low frequencies results from the shorter time available for the particles to overcome their energy barriers. From a statistical mechanical point of view; the corresponding demagnetisation signal will also decay correspondingly faster. Hence, the longer pulses produce soil viscosity decay signals which decay significantly slower than the short pulses. However, (first order) target signals simply decay as $\exp(-t/\tau)$ regardless of "ON" time, but their magnitudes are affected by transmit "ON" time. Thus, having a mixture of long and short transmit "ON" periods in the transmit waveform sequence enhances the difference between target and soil viscosity decay signals. This feature aids the detection capability of Minelab PI gold series and de-mining detectors significantly.

2.8 Multi-voltage, multi-period PI; Dual Voltage (DVT) and Multi-Period Sensing (MPS).

The energy associated with the short "ON" pulses of the multi-"ON"-period system of 2.7 above are low compared to the long "ON" pulse, simply because the transmit current has a shorter time to build in value during the short pulses compared to the long pulse. Thus, by increasing the voltage applied to the transmit coil during the short pulses compared to the long pulse makes the associated energy more equal. This further helps differentiate between target signals and the soil viscosity decay signals, and again aids the Minelab PI detectors significantly.

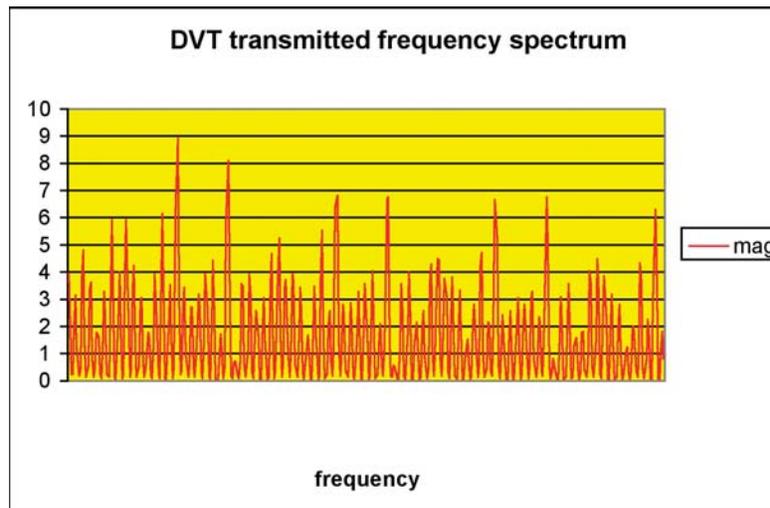


Figure 12. Multi-voltage, multi-period PI transmit spectrum. Note very broad spectrum.

All metal targets have distributed time constants: the only targets that have first-order-like time constants are non-ferrous rings. Even coins do not approximate first-order targets particularly well, and irregular shaped targets such as gold nuggets certainly do not. Hence, these behave like several different time constants mixed together. Some gold nuggets with fairly widely distributed time constants may produce signal decays that are similar to the soil decay signal, and hence these gold nuggets produce relatively weak responses because their signals are mostly cancelled just as the soil signal is cancelled. However, the vast majority of decay signals from nuggets are not similar in shape to the soil signal, so the nuggets are detected well.

2.9 Multi-period rectangular waveforms FBS, BBS and Iron Mask;

As stated, these metal detectors produce many transmit frequencies simultaneously (see figure 3). Thus, it is easy to extract high frequency, medium and low frequency components for accurate target time constant discrimination (see 1.1.3).

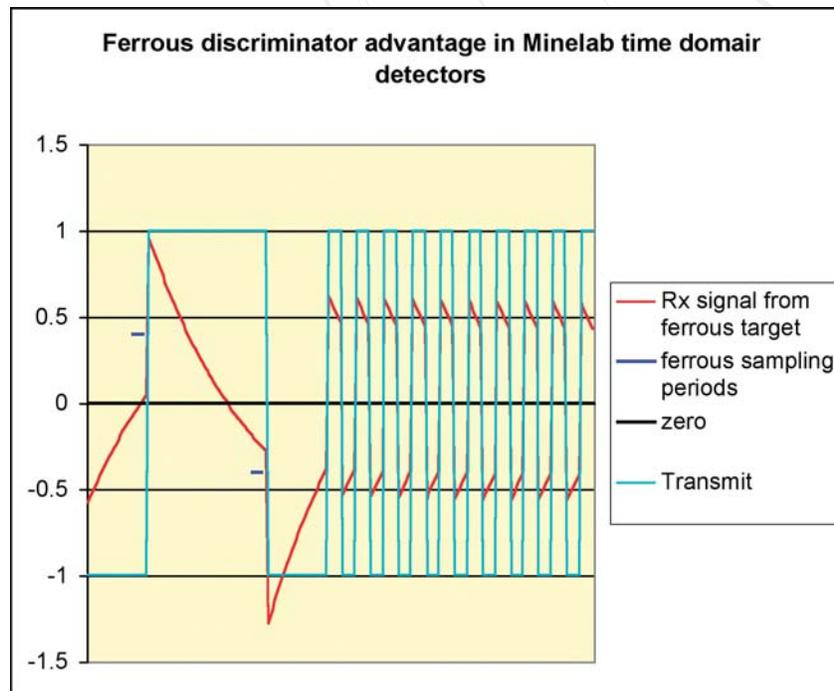


Figure 13: BBS receive waveform of a long time-constant (e.g. large) ferrous target. The sampling of is shown when the ferrous response is strongest and least contaminated by eddy current “diamagnetic” components.

During a long pulse, a ferrous target eddy current signal in the receive coil decreases in magnitude (voltage). {Actually, the signal in the receive coil responds to how quickly the eddy currents change in strength, not their magnitude.} As stated in 2.3, field X components, generated by eddy currents, oppose the “ferrous” X components of metal targets. The signal from these “diamagnetic” X components decreases with time during a pulse, whereas the ferrous X signal merely gets stronger as the transmitted magnetic field enters the target during a pulse. Hence, the ferrous (+X) signal is relatively strongest, and “diamagnetic” (-X) is weakest at the end of long periods pulses. Thus measurements at the end of long period pulses give a relatively uncontaminated by signals from eddy currents, producing excellent information about the ferrous nature of metal targets. This does not eliminate the problem of soil X mineralisation signals, but because the ferrous signal is strong during these periods, the capability of ferrous discrimination is significantly improved. This “Iron Mask” feature benefits the Minelab Full Band Spectrum (FBS) and Broad Band Spectrum (BBS) technologies.