Analysis of the paper:

UXO Target Detection and Discrimination with Electromagnetic Differential Illumination – UX1355 – Final Report

Introduction

This paper investigated four different methods to excite a different response in the soil compared to metallic items.

Method 1 - Receiver height
Method 2 – Transmitter field direction

Both receiver height and transmitter field direction assumed that the soil could be approximated by a homogeneous half-space, but this was not successful.

Method 3 – Transmitter loop size

Transmitter loop size was also discarded, as soil and metallic responses scale in the same way as loop size.

Method 4 – Transmitter waveform

This left the final (4^{th}) method which involved varying the transmitter waveform to exploit different responses in metal targets compared to soil through varying the charge-up time.

Analysis of Method 4

In a previous thread Teleno and I discussed this method in theory, and concluded that it may provide a ground balancing technique which does not create a target hole in the response.

Essentially the technique involves using two transmit pulses of different widths. Let's call these T_1 and T_2, where $T_2 > T_1$, and the target tau (τ) is << T_1.

Since the transmit pulses are wide enough to completely saturate any metallic target with $\tau << T_1$, it follows that the received signal will be the same in both cases. However, the signal from ground will be greater in amplitude for T_2 than for T_1.

Then we have:

$$\mathrm{m}_1 = s + g \qquad \text{(narrow pulse)} \qquad \text{(Eq.1)}$$

and:

$$\mathrm{m}_2 = s + kg \qquad \text{(wide pulse)} \qquad \text{(Eq.2)}$$

where k represents the ratio between the ground response to the "wide" and "narrow" pulses, whose formulas are:

$$A(\tfrac{1}{t} - \tfrac{1}{t+T_2}) \qquad \text{(Eq.3)}$$

and:

$$A(\tfrac{1}{t} - \tfrac{1}{t+T_1}) \qquad \text{(Eq.4)}$$

and t is the sampling delay.

Hence:

$$k = \tfrac{T_2}{T_1} \cdot \tfrac{t+T_1}{t+T_2} \qquad \text{(Eq.5)}$$

and solving for s gives:

$$s = \tfrac{km_1 - m_2}{k-1} \qquad \text{(Eq.6)}$$

Further algebraic manipulation also provides equations for T_1 and T_2:

$$T_1 = \frac{-tT_2}{T_2(k-1)+kt} \quad \text{(Eq.7)}$$

$$T_2 = \frac{-ktT_1}{T_1(k-1)-t} \quad \text{(Eq.8)}$$

and the sampling delay (t):

$$t = \frac{T_1T_2(1-k)}{kT_1-T_2} \quad \text{(Eq.9)}$$

Using equation 1, this contains the target signal (let's say 5 units) plus a contribution from the ground (say 1 unit), so the total for m_1 is 6 units.

Then using equation 2, this contains the target signal plus a larger contribution from the ground due to the wider transmit pulse (let's say 3 units). The total for m_2 is then 8 units.

As you can readily see, the ground signal in the second sample is 3 times the ground signal in the first sample. Hence the value of k must also be 3.

Now we're ready to remove the ground signal.

From equation 6:

$$s = \frac{km_1-m_2}{k-1} = \frac{(3\times 6)-8}{3-1} = 5$$

which is the target signal minus the ground signal, but without a hole in the target response.

Teleno gave an example for 2 transmit pulses, where T_1 = 100us and T_2 = 400us with a value for k of 1.1.
The minimum sample delay was therefore (from Eq.9):

$$t = \frac{T_1T_2(1-k)}{kT_1-T_2} = \frac{100\mu\times 400\mu(1-1.1)}{1.1\times 100\mu-400\mu} = 14\mu s$$

Note that the value of k is intrinsically determined by whatever transmit pulse widths are assigned to T_1 and T_2.
Since we arbitrarily set k to a value of 3 in the unitless example, the question now is whether k = 3 represents a sensible value to choose?

Let's first use the values provided by Teleno:

T_1 = 100us, T_2 = 400us, k = 1.1, and (again) s= 5, and g = 1.
The sample delay t is 14us, which is also determined by the values of T_1 and T_2.

$$s = \frac{km_1-m_2}{k-1} = \frac{(1.1\times 6)-6.1}{1.1-1} = \frac{0.5}{0.1} = 5$$

Successfully removing the ground signal. However … "Houston, we have a problem".

Note the final value in the denominator of 0.1. This means that the output of the differential integrator needs to be amplified by a factor of 10 to bring the target signal back to its original value.

It would appear at first glance that we could simply set k equal to 2 and force the denominator to equal unity, and no amplification would be required.

The optimum value for k is readily determined by plotting a graph of T_2 versus k for fixed values of T_1 and t.
Fig-1 uses T_1 = 100us and t = 14us, and shows that the best value for T_2 is 385us when k = 1.1.
(See "T2 versus k.xls")

So is it even possible to realize a gain value of k = 2?
Using Eq.8 with k = 2, t = 14us, and T_1 = 100us, we have the result that T_2 = -32.9us, which is clearly nonsense. This happens because you cannot arbitrarily assign values to these interlinked parameters.

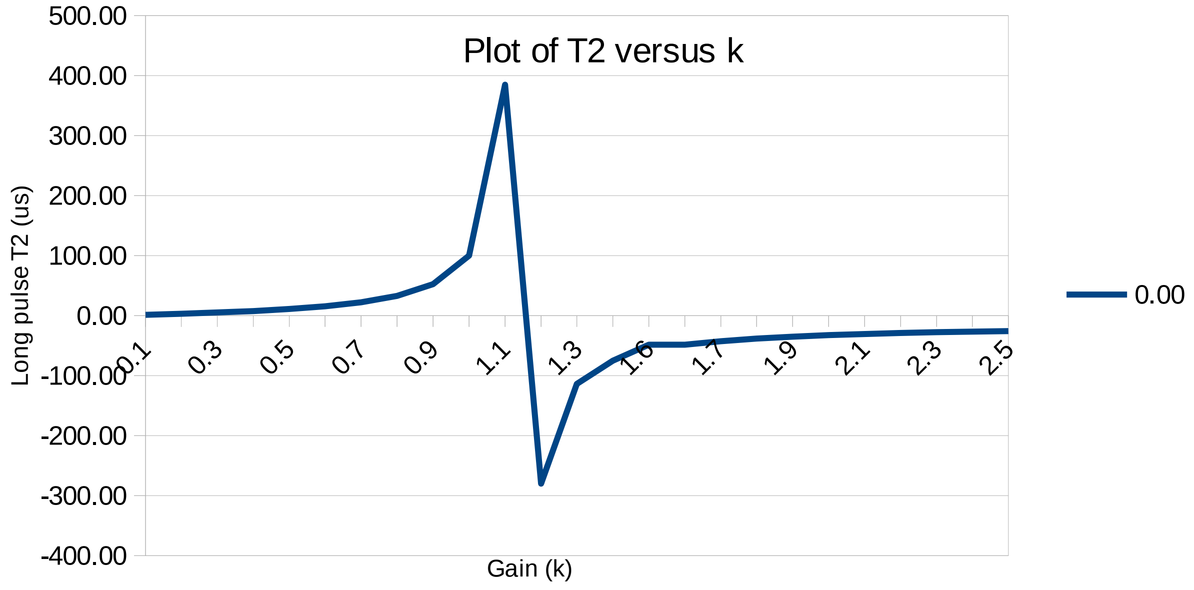

Fig-1: Plot of T_2 (long pulse) versus gain (k) with T_1 = 100us and t = 14us

Since the numerator in Eq.8 is negative, it follows that T_1(k-1) needs to be less than *t* in order for the denominator to also be negative, resulting in a positive value for T_2.

For example, if *t* = 17us, and we want k to equal 2 (to avoid any additional amplification) then T_1 must be less than 17us. But … note that now the sample delay is longer than T_1, with the result that the signal from the target of interest will have essentially vanished before sampling takes place. This leads to the conclusion that setting k to 2 is not a sensible solution.

With T_1 = 20us and *t* = 17us (i.e. ensuring that T_1 is greater than *t*) we can create a second plot (Fig-2) of T_2 versus k, and then use this to determine the optimum values to use.

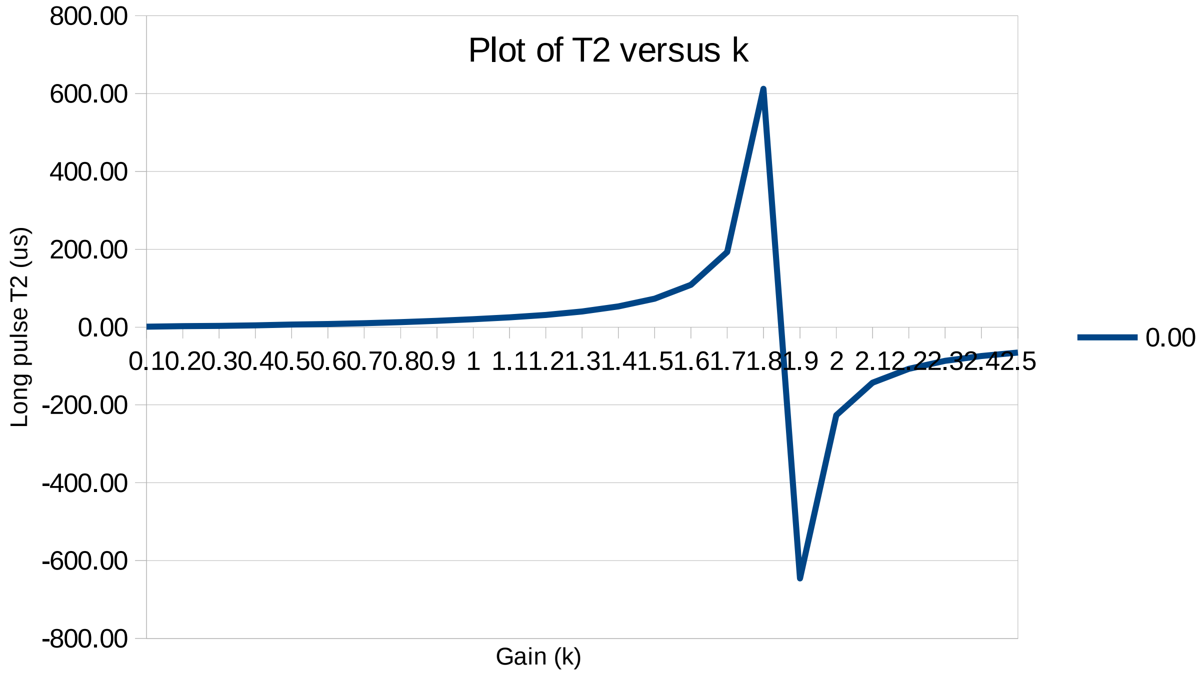

Fig-2: Plot of T_2 (long pulse) versus gain (k) with T_1 = 20us and *t* = 17us

As you can see, Fig-2 indicates that the maximum value for k is 1.8, and that this requires T_2 to be set to 612us. However, a more reasonable value for T_2 would be 193us when k = 1.7.

T_2 can also be calculated by hand as follows:

$$T_2 = \frac{-ktT_1}{T_1(k-1)-t} = \frac{-1.7\times17\mu\times20\mu}{20\mu(1.7-1)-17\mu} = 193\mu s$$

If we then round up T_2 to 200us, the value for k only changes slightly to:

$$k = \frac{T_2}{T_1}.\frac{t+T_1}{t+T_2} = \frac{200\mu}{20\mu}.\frac{17\mu+20\mu}{17\mu+200\mu} = 1.71$$

The authors of the research paper conducted field studies with three different transmitter on-times of 10ms, 4ms, and 2ms. The analysis showed that, for typical UXO targets, differential measurements based on these varying charge times were no more effective at suppressing soil response than coil compensation methods based on a single charge time.

The reason for the failure appears to be because most UXO time-constants are too long for this technique to work. However, it was also concluded that any targets with significantly smaller time-constants would have excited a different response to the soil.

For reference, a small to medium UXO-like object has a time constant of 40ms.

Based on these conclusions it appeared to be worth exploring the differential technique for targets with small time constants. Also, rather than scan the ground twice with different TX pulse widths and analyzing the data later, it should be possible to process the data in real time.

Sensible starting values to use during testing were calculated as: T_1 = 20us, T_2 = 200us, *t* = 17us, and k = 1.71.

A Practical Test

In order to test the theory, an Arduino Nano PI was programmed to generate the required transmit and sample pulses, as shown in Fig-3.

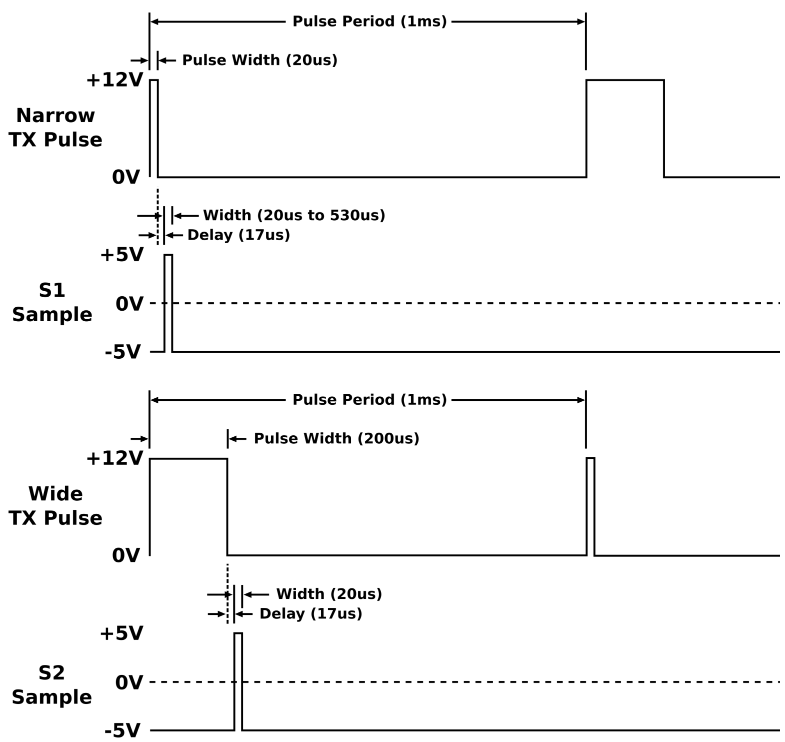

Fig-3: Transmit and sample pulses

The original transmit circuit used a resistor to passively turn off the mosfet. In order to increase the mosfet turn-off speed, and subsequently enable earlier sampling, the transmit circuit was modified for active turn-off. The modified circuit is shown in Fig-4. This involved cutting one track on the top layer, changing R4 from 1k to 10k, and adding a PNP transistor (2N3906) and two resistors (1k and 10k) on the bottom of the board. Using the example test coil with the original TX circuit, the sampling delay was previously set halfway up the decay curve at 24us, but after the modification the sample delay could be set to 17us with the preamp coming out of saturation at 15us. The TX OSC signal at "A" was inverted in the code to account for the signal inversion produced by the 2N3906.

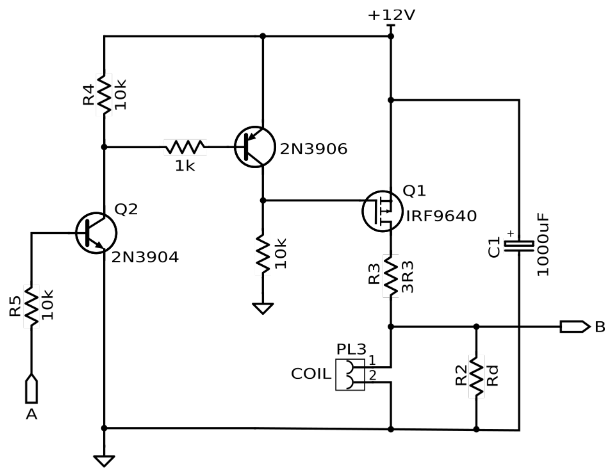

Fig-4: Modified TX circuit

The Arduino sketch used for this test was "Arduino_differential_GB_test.ino".

In the original ANPI code there was extensive use of interrupts to control the detector timings, but this was abandoned in the following tests due to the additional delays that were introduced, and a simple loop in combination with software delays was used instead. In fact, all interrupts were disabled to avoid jitter in the samples.

As you can see from Fig-3, the narrow and wide pulses were interleaved. The S1 gate was used to sample the target signal from the narrow pulse, and the S2 gate sampled the wide pulse. For this initial test, the EF signals were ignored to simplify testing. Equation 6 shows that the signal from the narrow pulse needed to be amplified in order to achieve ground balance, and since the ANPI circuit has one channel the only way to achieve this was to vary the S1 sample width associated with the narrow TX pulse.

Due to the self-adjusting threshold (SAT) of the ANPI, any targets that were small enough to be saturated by T_1 (narrow pulse) should have produced an audio tone as they approached the coil, whereas all unsaturated targets should have produced an audio tone as they moved away. Unfortunately all targets were detected as they moved away, indicating that none of them were saturated by the T_1 pulse.

A second test was performed using the numbers suggested by Teleno as a value for T_1 of 20us was possibly too low. Sadly the result was exactly the same, even with T_1 set to 100us.

Several other combinations were attempted, and in one case it was possible to reject a hammered silver coin. In this instance it would be expected that a Nickel, a one Euro, and a Victorian penny would all give a response when they moved away from the coil, as the hammered silver coin should have saturated before any of these targets. The result was, however, that the Nickel gave a response when moving towards the coil. The conclusion was that attempting to provide amplification by varying the sample pulse width created a situation where a subtractive GB process was taking place, and the rejection of the hammered coin was the result of creating a target hole in the response.

In order to implement the differential illumination theory correctly would require a detector with two separate channels so that the narrow pulse channel could be amplified independently. However, this still leaves the requirement to amplify the overall result to maintain a sensible level of target response. Current tests also indicated that the differential method was not very efficient. Perhaps using direct sampling with a much more powerful processor could achieve a better result, but the results achieved so far are not hopeful.

Subtractive GB Test

As a comparison, it was then decided to attempt an implementation of the standard subtractive GB technique using an ANPI. The Arduino sketch used for this test was: "Arduino-subtractive_GB_test.ino".

As the subtractive method is now widely known and understood, I will not go into detail here. Suffice to say that this was successful on the ANPI using the existing hardware and the small modification to the TX circuit described earlier.

The main sample delay was set to 17us, 10us sample width, 10us GB delay, and 10us GB width. The GB width was variable by the user by an external pot, and EF elimination was also provided in this version.

It was not possible to test the ANPI with real world mineralized soil at my present location, but it was possible on the bench to eliminate small nails in the same way as the TDI. The ANPI responded to higher conductivity targets as they approached the coil, and lower conductivity targets as they moved away.

Anyway ... this is all food for thought, and a basis for further experimentation.