Hammerhead
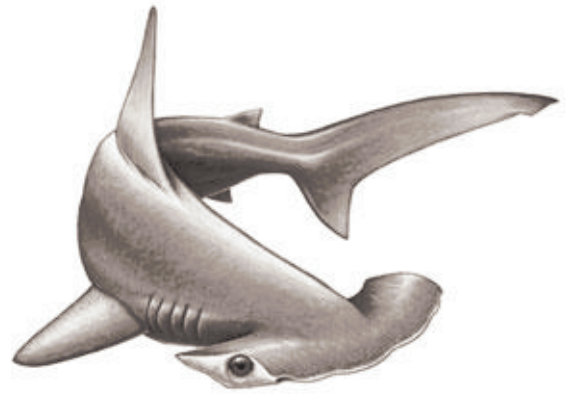## Pulse Induction Metal Detector

by Carl Moreland

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"Hammerhead" is a pulse induction (PI) metal detector design. It is intended primarily as a learning platform for experimenters, and as a base design on which to expand. This design is very much like other commercial PI detectors, which tend to have similar circuit designs, so it has the potential for good performance.

Metal detectors generally are not easy projects, especially the induction balance variety, and usually have performance that falls far short of even the least expensive commercial models. Three goals for this design were: make it easy to build, make it flexible, and get decent performance.

Pulse induction is a good choice for a do-it-yourself project because the circuitry is straightforward, and "mono" coils are easy to make. There are also very few critical internal settings — that is, it's not hard to get the circuit to basically work — although final performance will depend heavily on a number of parameter settings. This project includes a layout for a simple single-sided PCB using common through-hole components, as well as a much smaller two-sided surface mount PCB for those with steady soldering irons.

Flexibility is achieved with several build options. They include:

- Passive or active MOSFET turn-off (through-hole only)
- Generic preamp support for NE5534, LM318, and others
- Single-ended or differential integrator
- VCO or non-VCO audio
- Extra component pads around the preamp to support experimentation (through-hole only)

This design also makes most of the important circuit parameters variable:

- Transmit pulse rate
- Transmit pulse width
- Integrator sample delay
- Integrator sample pulse width
- Secondary integrator sample delay
- Threshold
- Sensitivity
- Autotrack speed
- Volume

Any or all of these parameters can also be set to fixed values, simplifying the control interface. The various design options, and parameter adjustments, will be described as we go.

Circuit

A simplified diagram of the circuit is shown in Fig. 1. It can be divided into five sections: power supply, clocking, transmit plus receiver front-end, receiver back-end, and audio. Each section can be built and tested sequentially. An oscilloscope is useful for probing the circuitry to see what is going on, but

is not absolutely necessary, providing the circuit is built correctly. A digital multimeter (DMM) is needed.

The complete circuit is shown in Fig. 2 and, at first glance, appears to be complicated because of all the options that were designed in. However, the design options really don't add much complexity, and allow for different configurations and performance comparisons. Simplified circuits will be shown in the descriptions of the hook-up options.

Power supply

Power for *Hammerhead* is provided by a single 12-volt battery pack, preferably an 8-pack of AA's. A 9-volt pack can be used with a reduction in battery life, and even a 9-volt transistor-radio-type battery can be used, with a significant reduction in battery life, providing a proper supply tank is used at the coil switch (I'll discuss this later). Combining the surface-mount circuit with a 9-volt transistor-radio battery, results in a very compact detector, ideal for a hand-
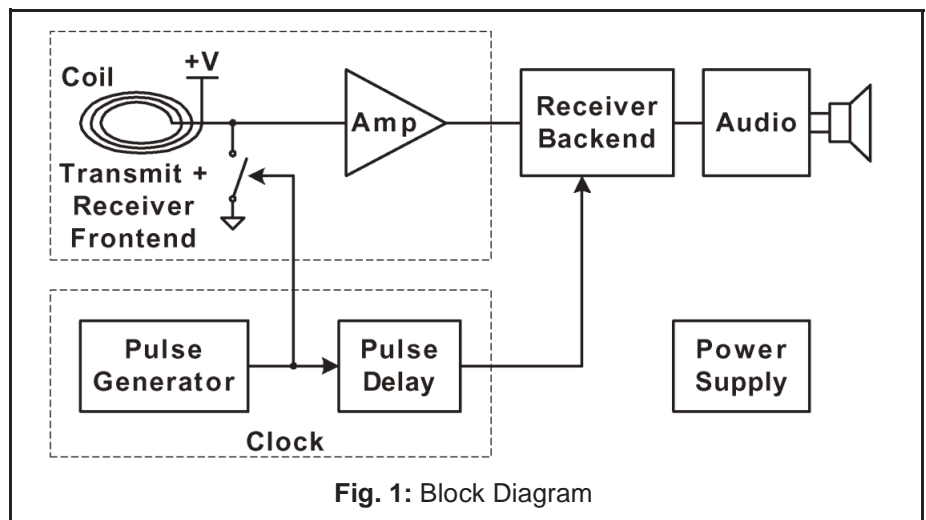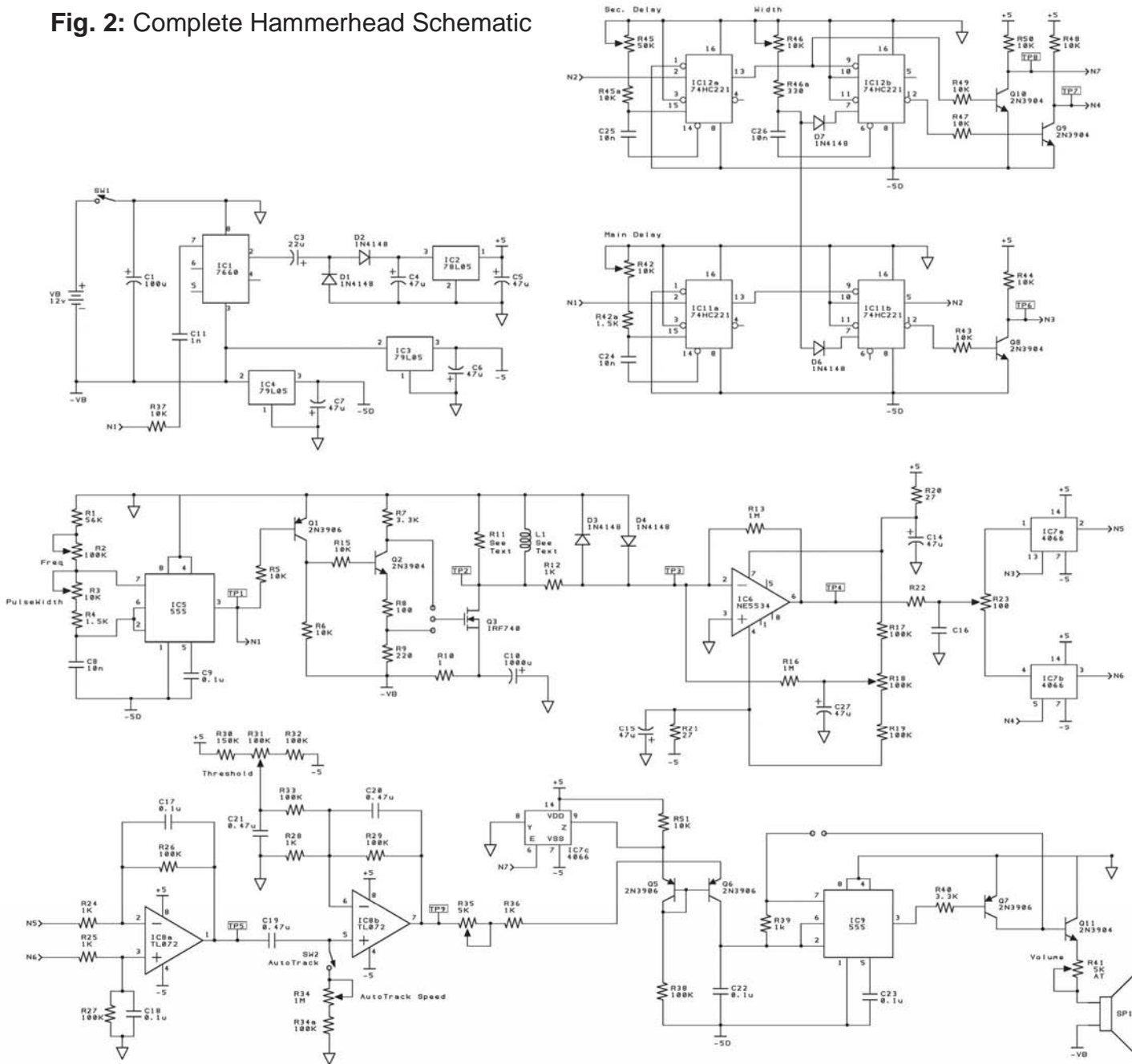

Fig. 1: Block Diagram

Fig. 2: Complete Hammerhead Schematic

held probe.

The power supply circuitry (Fig. 3) consists of a voltage doubler, and 3 regulators. The voltage doubler, built around a 7660 supply chip (IC1), generates a voltage that is roughly twice the battery voltage.

At this point, the easiest way to visualize the supply voltages is to consider the positive side of the battery to be "ground", the negative side of the battery to be the "minus rail" (-VB), and the voltage doubler output to be the "plus rail" (+VB). See Fig. 4. The schematic is labeled as such, with the battery connected between ground and "-VB".

A 7805 regulator (IC2) produces +5 volts from the output of the voltage doubler, and is used as the positive supply for the analog opamps. There are two 7905 regulators, one for the -5 volt opamp (analog) supply (IC3), and one for a -5 volt digital supply (IC4). A separate digital regulator is used to help isolate digital noise from the noise-sensitive analog path.

Voltage doubling by the 7660 is

achieved through the use of a charge pump that must be clocked. Normally, the 7660 is used with its internal clock which operates at around 10 kHz, but it also has an option for overriding the internal clock with an external one. By using an external clock, we can ensure that power supply switching noise is synchronous with the sampling. R37 and C11 couple the clock signal to the 7660 for this purpose. Unfortunately, the 7660 cuts the external clock frequency in half, and at the lowest clock rate may result in poor efficiency. R37
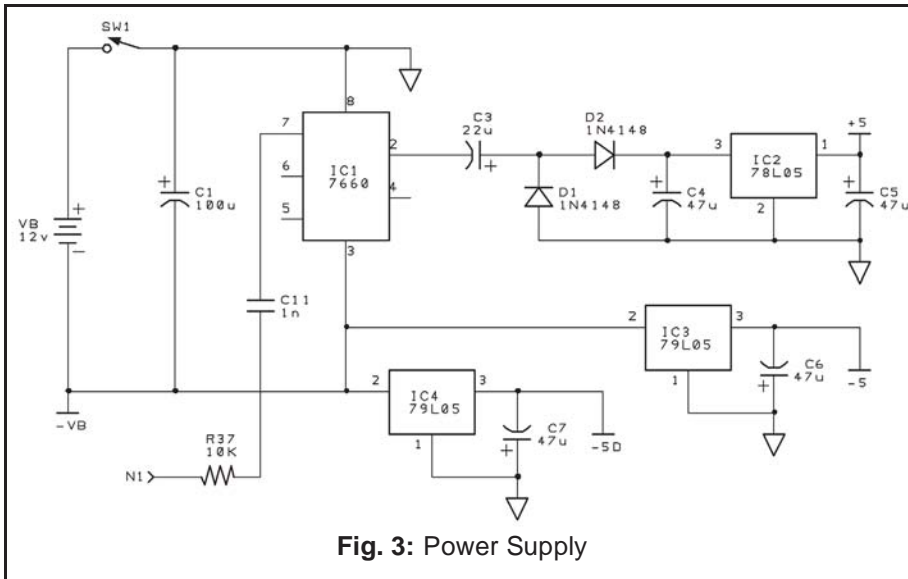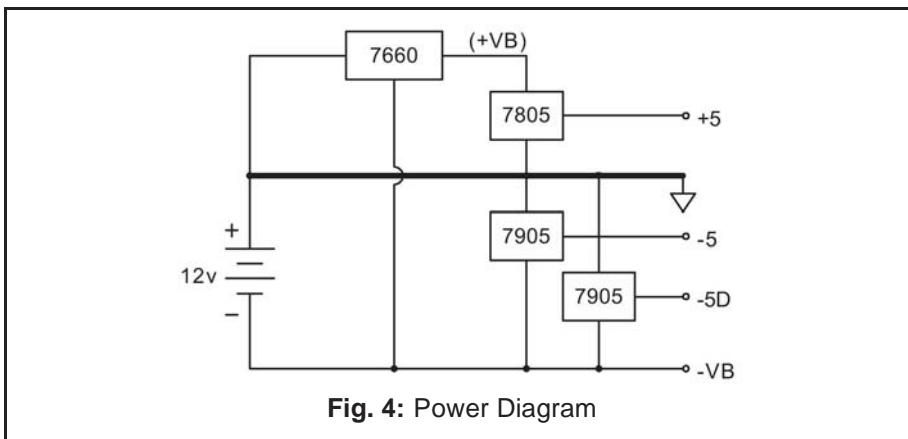
Fig. 3: Power Supply

Fig. 4: Power Diagram

and C11 may be omitted, and the 7660 will run on its internal clock.

Clocking

The master clock generator is a 555 timer (IC5) connected as an astable oscillator (Fig. 5). Four different clocks are potentially needed, depending in the design options used. The main clock drives the coil switch Q3 which pulses the search coil. A second clock, delayed from the trailing edge of the main clock, controls the main sampling switch (IC7a) after the preamp (IC6). A third clock, delayed from the second one, controls an optional secondary sampling switch (IC7b), used for differential integration. Fig. 6 shows a timing diagram of these three pulses. A fourth clock can be used to gate the speaker for non-VCO audio.

The 555 oscillator has two controls. R2 varies the frequency of the main pulse (and all derived pulses), and R3 varies the pulse width of the main pulse only (TP1). There is a slight amount of

frequency variation with pulse width adjustment. The frequency of the main pulse determines how many times per second the coil is pulsed, and also how many samples per second the integrator (IC8a) is integrating. Generally, a higher pulse frequency allows for a faster coil motion and perhaps a little better noise performance, while consuming more power. Varying the main

pulse width determines how long the coil is turned on, which can affect depth of detection (up to a point) and power consumption.

The frequency range for this design is 900Hz to 2300Hz, and the pulse width can be adjusted from 10µs to 75µs. R1-R4 can be modified for other frequency and pulse width ranges. Note that these ranges, and subsequent ones, are subject to variation due to component tolerances. The numbers presented here are measured from a single build and may not be representative of nominal ranges.

The remaining pulses are generated by dual monostable multivibrators IC11 and IC12. IC11 creates the first delayed pulse for the main sampling switch (TP6), and IC12 creates an additional delay for the secondary sampling pulse (TP7). In each case, the first half of the multivibrator chip is used to delay the input pulse, and the second half sets the output pulse width. The delays, and the pulse widths, are set by RC time constants. The R-component consists of a potentiometer for adjustability, plus a fixed resistor to set a minimum delay and pulse width.

For the differential integrator to work properly, both sampling pulses need to have the same pulse width, so both pulse width monostables (IC11b & IC12b) are controlled by the same RC time constant, R46/R46a/C26, by using isolation diodes D6 and D7. This scheme[1] works nicely, as long as the two pulses have a sufficient amount of delay time between them, which is eas-
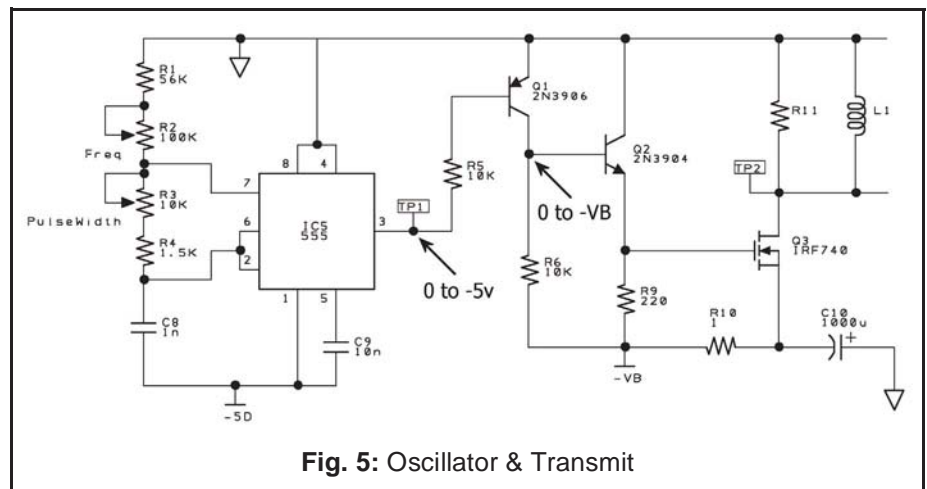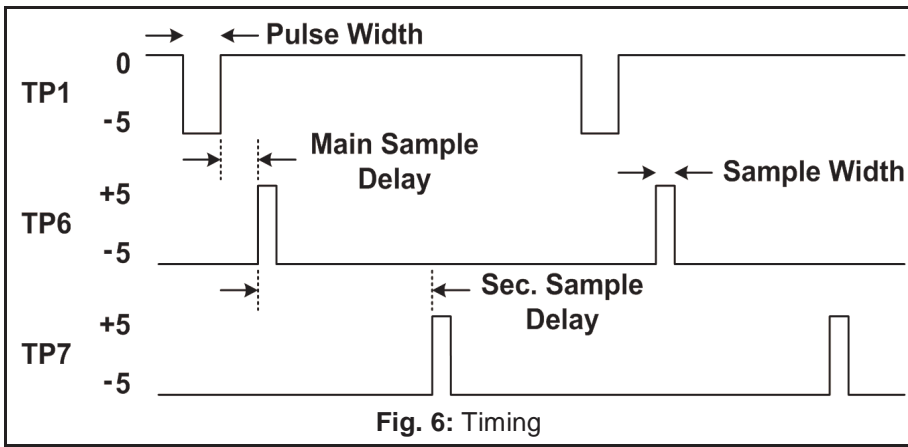
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1. Suggested by Eric Foster.

Fig. 5: Oscillator & Transmit

Fig. 6: Timing

ily met in this application.

Thus, potentiometer R42 sets the main sampling delay, which is variable from around 10µs to 75µs. The secondary sampling delay tracks the delay of the main sample, with an additional delay set by R45, variable from 75µs to 350µs. R46 adjusts both pulse widths from 3µs to 50µs. Note that extreme limits of various settings may not be compatible. For example, at the highest frequency (2300Hz), a combination of high pulse width, large sample delay, and maximum secondary delay might place the secondary sample pulse into the next transmit pulse. There is no danger in this, but it may result in bizarre behavior.

Transistor level shifters Q8 and Q9 convert the 0/-5 volt logic levels of the monostable outputs, into +5/-5 levels needed to drive the sampling switches IC7a and IC7b. Transistor Q10 is also a level shifter, and drives the sampling switch IC7c, which is used for the non-VCO audio option. If the VCO option is used, Q10, R49, and R50 are not needed.

Transmit/Receiver Front-end

The main device in a PI detector is the coil switch, usually a MOSFET or bipolar transistor with a high current capacity and a high breakdown voltage. The coil switch serves two functions: to short the coil across the battery voltage, which creates a large coil current; and to turn the coil current off as quickly as possible. During the "on" time, current flowing through the coil creates a magnetic field around the coil which, when static, does nothing[2]. But when the coil is switched off, the current ceases, and so does the magnetic field. It is the col-

lapse of the magnetic field that induces eddy currents in a nearby metal target which, in turn, generates a counter-magnetic field. The higher the initial magnetic field, and the faster it is collapsed, the greater the target field that is generated.

The output of the 555 oscillator drives buffer/level-shifter transistor Q1, which primarily converts the 0/-5 volt levels of the 555 into 0/-VB levels. Fig. 5 shows an NMOS drive circuitry using passive turn-off via R9. Transistor Q2 is simply a buffer, with low-value emitter resistor (R9) used as a fast pull-down for the main coil switch transistor Q3. For this setup, R7, R8, and R15 are shorted. For other options, see the *Other Options* section.

Coil switch Q3 must have sufficient current capacity during the time it is shorting the coil, and it should also have a high breakdown voltage to allow for a high flyback voltage. NMOS device IRF740 is rated for 10 amps and 400 volts. Other devices can be substituted, including NPN's and IG-BJT's, with slight differences in performance.

R10 and C10 form an RC tank for providing the transient current of Q3. These are not absolutely necessary, but can reduce supply noise, especially when using a 9-volt transistor-radio-type battery[3]. If not used, omit C10 and short R10. In use, C10 should be large enough to supply the needed charge for the time Q3 is on. This depends on three

parameters: the gate pulse width, the average coil current, and the supply voltage. As an example, assume that the pulse width is 25µs, the coil current is 2A (limited by its internal resistance), and the supply is 10v. Furthermore, assume we want the capacitor voltage to ripple no more than 100mV. Capacitor current is given by the equation $i=C\times dv/dt$, so $C=i\times dt/dv$, or $2A\times25\mu s/0.1v = 500\mu F$. To find the value of R10, we assume the remainder of the clock time is available to charge C10 back up, so we can set the R10×C10 time constant appropriately. But this is a circuit that need not be operated optimally, so we can just as easily oversize C10 to, say, 1000µF and set R10 equal to 1Ω. With 100mV of ripple across R10, the battery will source 100mA of current over a longer time period, instead of an instantaneous 2A.

Resistor R11 is the coil damping resistor and prevents ringing when Q3 turns off. Ringing will occur because of the L-C tank created by the inductance of the coil, and the total parasitic capacitance, including the self-capacitance of the coil, capacitance of the cable, and of Q3. The optimal value of R11 is dependent on the coil, and is best determined experimentally. If the resistor value is too low, it will overdamp the coil and reduce sensitivity. Typically, R11 is in the range of 200-800 ohms, with 680Ω used for the coils described in this article.

The coil signal is applied to preamp IC6, which is connected as an inverting opamp. R13/R12 sets the gain to 1000. Diodes D3 and D4 provide clamping to protect the opamp. Because the coil pulse of 200-400 volts will absolutely destroy the opamp, do not attempt to operate the circuit without them!

IC6 needs to be a high-speed opamp, with good transient recovery. The NE5534 and LM318 have been popular choices, but there are many more to choose from now. Different opamps have different schemes for nulling off-

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2. However, the exponential "charging" of the coil current does induce a target field, which can degrade performance if it is not settled out.

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3. This type of battery should be avoided in standard PI detectors because of its relatively high internal resistance. However, for a PI-based pinpointing probe, it would be fine.

> **Important note:** R11 absorbs the energy that was stored in the coil just prior to flyback, and dissipates the energy as heat. The amount of time-averaged energy is dependent on several factors: coil resistance, transmit pulse width (turn-on time), and transmit frequency. Low coil resistance, large pulse width, and high frequency combine to give the highest energy, and R11 can get *very hot*! It is recommended that R11 be no less than a 1/2-watt resistor, preferably metal film. If you intend to run it hot, consider a 1-watt resistor, and/or heatsinking it. Note that Q3 should not run hot, unless it is breaking down during flyback.

sets, sometimes using one or more of the "extra" pins. This design provides a generic method of nulling the offset by applying an offset current to the non-inverting input via R16. Because of the high gain, this current needs to be very small, so R16 must be large. Since this opamp operates on the smallest signal in the circuit, it is desirable to have the cleanest supply voltages possible, so R20-C14 and R21-C15 provide low-pass noise filtering for both rails.

The output signal of the preamp can be optionally filtered by R22-C16, which can be installed as a low-pass filter as shown in Fig. 2, or transposed to provide high-pass filtering. Both filter types have shown up in some commercial designs, and values for R22 and C16 will depend on the application. They are not used in this project so values are not provided; omit C16 and short R22.

The final part of the receiver front-end is the sampling switches. IC7a and IC7b are 4066 gates that sample the same output signal of the preamp, but at different times. Potentiometer R23 provides a method of fine-tuning the signal balance between the two switches, which will be explained in the **Calibration** section. IC7a is the main sampling switch, and will sample the signal during the decay of the target signal. The sample delay and sample pulse width are set by R42 and R46 as described in the **Clocking** section.

IC7b samples the signal at a later time, determined by R45, and is used for interference cancellation in the differential integrator. This scheme is used in many commercial designs, but is often lacking in other PI projects. It is optional, and the **Other Options** section describes how to set up a single-ended integrator.

Receiver Back-end

The remaining circuitry consists of

the differential integrator, amplifier, and audio. The purpose of the integrator (IC8a) is to average the sampled signals from the preamp. Noise, which is random in nature, averages to zero — or so we hope — while even weak target signals will correlate and remain. A short time constant will result in an excessively fast decay of the target signal, while a long time constant will smear adjacent targets and reduce

selectivity.

Fig. 7 shows the differential version of the integrator. Gain is set to 100 by R26/R24. C17 is the integration capacitor, and its value should be chosen to provide a sufficient, but not excessive, integration time constant. For differential integration, the secondary signal from IC7b should be applied to a divider that matches the inverting gain network, such that the non-inverting gain is the same as the inverting gain. Usually, this will call for either precision-valued resistors, or at least well-matched resistors. However, standard 5% resistors are sufficient if R23 is used to calibrate the differential gain. The single-ended integrator option is described in the **Other Options** section.

The output of the integrator is AC coupled through C19 to the final gain
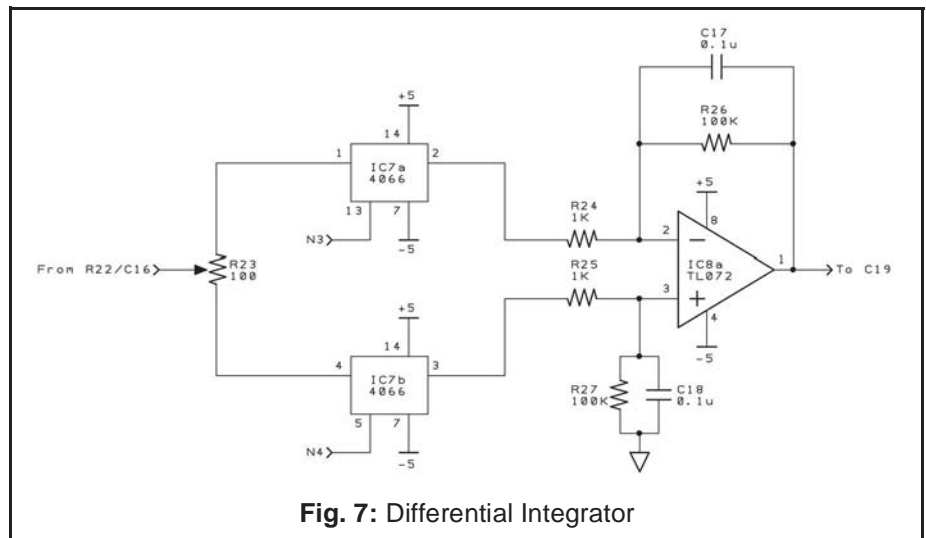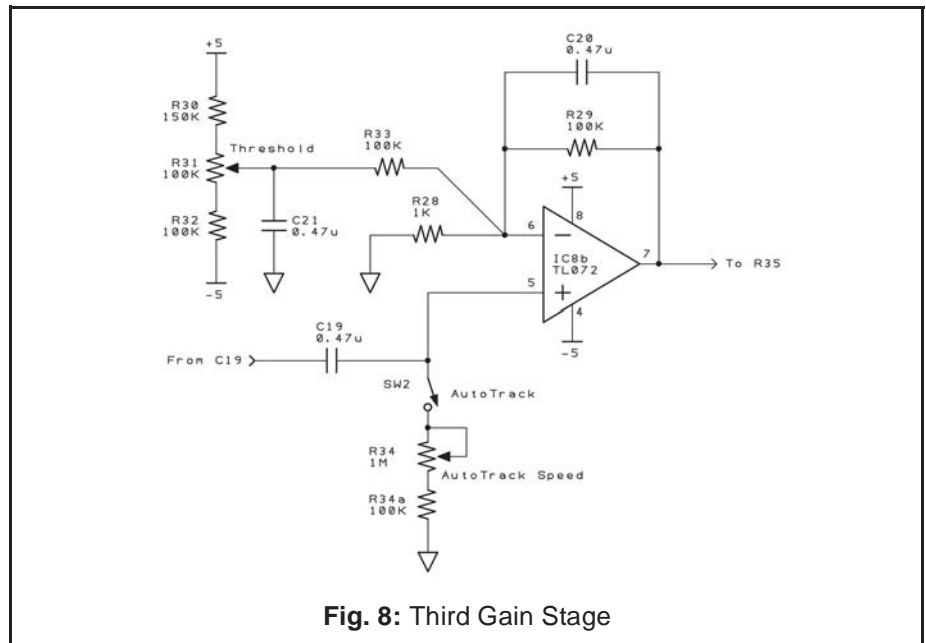

Fig. 7: Differential Integrator

Fig. 8: Third Gain Stage

stage, opamp IC8b (Fig. 8). The gain of this amp is set to 100 by R29/R28. C20 provides some additional low-pass filtering. With the integrator signal AC coupled, resistor R34/R34a is used to provide a discharge path for the non-inverting input of the opamp. Thus, static signals are rejected and only dynamic signals will be amplified. This means that when the coil is swept over a target, the signal will rise and fall and get amplified by IC8b. But if the coil is moved over a target and held steady, the signal will rise and then quickly fall as C19 is discharged[4]. The rate of discharge, or the allowable motion speed, can be controlled by varying R34. Since setting R34 to zero will completely kill the signal (although with no risk of circuit damage), R34a is used to set a maximum discharge rate.

This type of motion circuit is common in PI detectors and helps reject slowly changing ground conditions. However, the need to keep the coil in motion makes pinpointing targets difficult. If R34 is removed (opened), and the inputs of IC8b have zero bias current, then the capacitor will not discharge and even static signals will pass, resulting in a no-motion mode. Therefore, IC8b (and thus IC8a) needs to be either a JFET-input opamp, or a CMOS opamp. Even a JFET-input opamp has a slight bias current, perhaps several picoamps, which will discharge C19 in a short time (15 seconds or so). So this no-motion mode likely is not useful for continuous hunt-

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4. Actually, C19 will *charge* until the input to IC8b saturates.

ing, unless a true zero-bias current CMOS opamp is used.

To easily switch between motion mode and zero-motion mode, the PCB includes pads for a panel-mounted switch. The mode switch should either be a momentary-contact pushbutton switch located for easy thumb access, or a momentary toggle switch for index finger control. If a CMOS opamp is used for IC8, then a SPDT switch with one side momentary (ON-OFF-MOM) can be used, similar to the mode trigger used on White's brand detectors. If there is no desire for a zero-motion mode, then the pads on the PCB can be shorted. R34 can also be panel-mounted to easily change the retune rate, though this is rarely done.

AC coupling the integrator signal into IC8b also causes the output of IC8b to have a quiescent (average) value, plus a dynamic target signal. R30-R31-R32-R33 provide a way to adjust the quiescent output level of the amp which, as it turns out, is a useful way of setting an audio threshold. C21 filters the adjustment voltage applied to R33. See Fig. 8 for an alternate drawing of IC8b, that might be clearer.

The last part of the backend is the audio circuitry. There are two major options for the audio: VCO, and non-VCO. The VCO audio is normally tuned to a low growl, and a target gives a rising pitch, much like the old BFO detectors. The non-VCO audio has a fixed frequency, and a target produces an increase in loudness, much like TR and VLF detectors. Although the human ear is more sensitive to frequency changes than loudness changes, some

people don't like VCO audio. The non-VCO option will be presented in the *Other Options* section.

With the VCO option (Fig. 9), a 555 is used as a voltage-to-frequency converter, such that changes in the voltage level from IC8b result in changes in the audio frequency. R35 (plus R36) drives the common-base transistor Q6, whose emitter is biased to 0v by Q5-R38. Since R35 has signal on one side and virtual ground on the other, it acts as a voltage-to-current converter. Q6 passes this current to the 555 oscillator's RC timing, making the oscillator frequency increase with increasing current. The output of the 555 drives buffer transistor Q7, which drives a speaker or headphones.

Normally, the output audio frequency is adjusted to a certain quiescent value, and a target signal causes the frequency to increase. Setting the quiescent audio frequency is done with the threshold adjustment R31, described previously. The value of R35 determines the amount of VCO current that is generated for a given target signal, therefore it can be made variable for adjusting sensitivity. R36 sets the maximum VCO current.

The addition of NPN transistor Q7 provides current boosting for driving the speaker, in case of weak volume (Q6 & Q7 form the equivalent of an SCR). There is no provision on the PC board for connecting Q7 in this configuration, so *it must be kludged in*. If volume is adequate, Q7 may be omitted and the volume pot driven directly with Q6's collector. A similar boost transistor may also be added to the real Q7 in
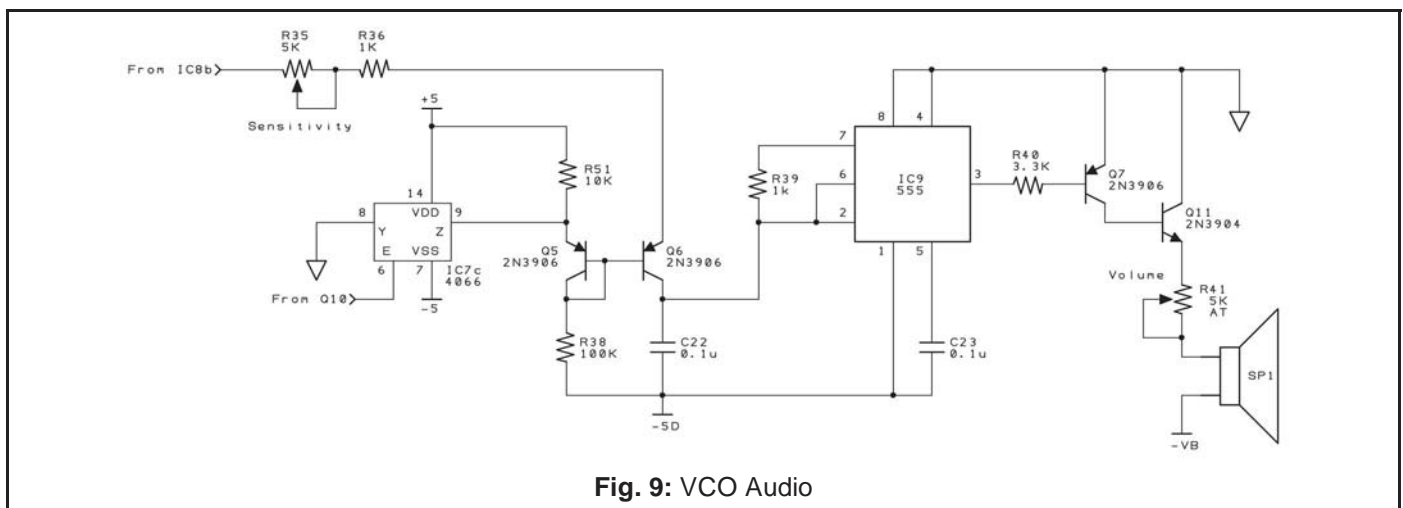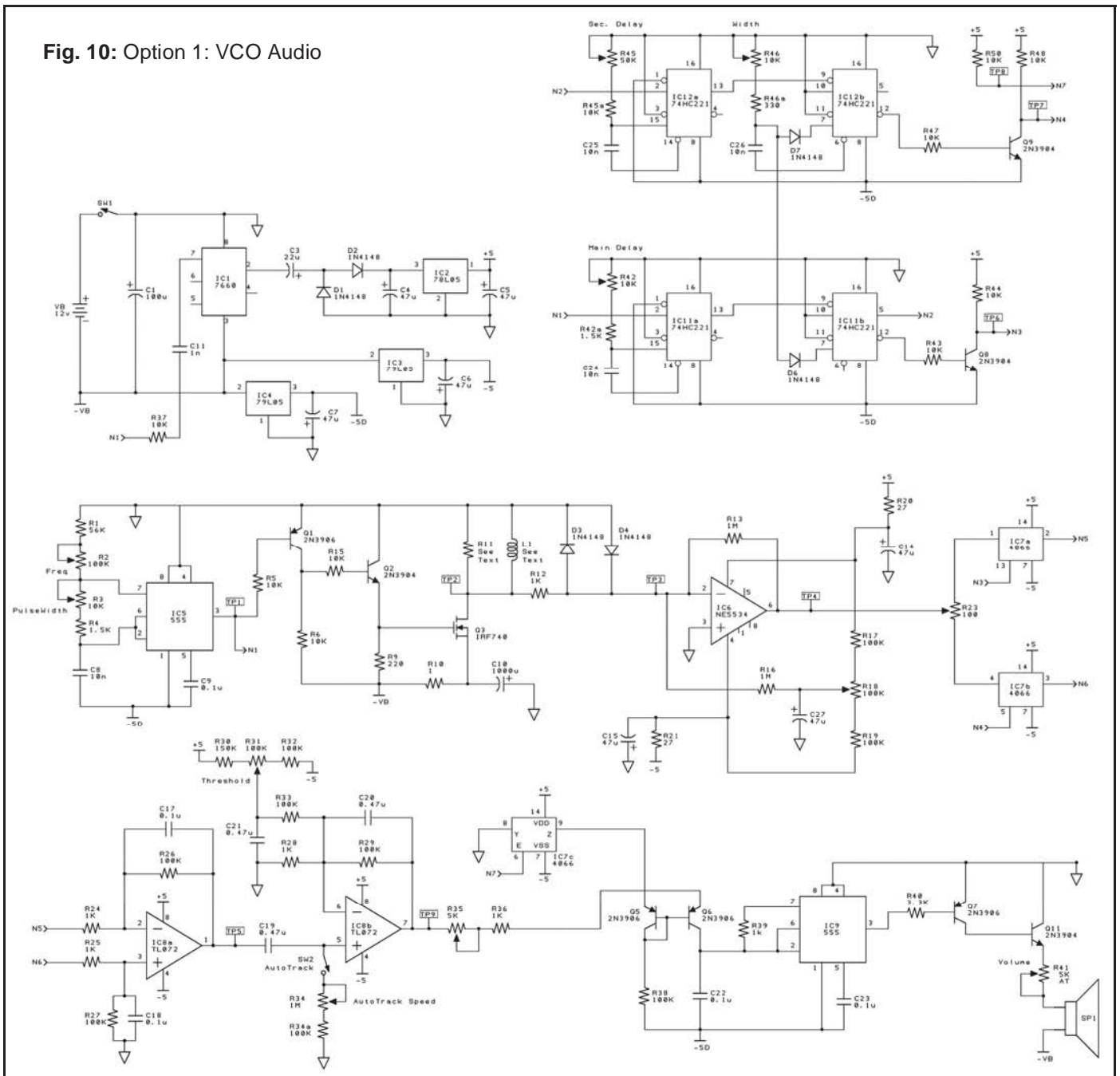

Fig. 9: VCO Audio

Fig. 10: Option 1: VCO Audio

Figs. 9 & 10 for louder volume. Again, it must be kludged in.

Once the threshold loudness is adjusted for the non-VCO option, a target signal will cause an increase in loudness. The non-VCO option potentially offers better performance than the VCO option. Driving a speaker (or headphones, to a lesser extent) creates large current spikes that can feed through to the supply voltages, and cause interference with the receiver. With the non-VCO option, the audio frequency is synchronous with the sampling frequency, and if feedthrough occurs, it can be moved in time by

delaying the chopping signal until it is placed at a non-sensitive point in the sampling period. With VCO audio, the interference is asynchronous and cannot be controlled. No tests have been performed to see if this is really a problem.

Construction & Calibration

Building the *Hammerhead* project is fairly straightforward, and can be done in discreet stages. As already mentioned, a DMM is needed, and while an oscilloscope is useful, it is not necessary. Waveforms will be shown so those with an o-scope can verify circuit oper-

ation, and those without can see what the circuitry is supposed to be doing. The remainder of this section will describe the construction of the VCO audio option. Other options will be discussed in the *Other Options* section.

In building circuits, I generally like to use IC sockets. It allows for the re-use of ICs if you decide later to scrap the circuit, and it enables the easy swapping of ICs if one is bad, or if you decide to experiment with a different IC. In this design, I would suggest socketing at least IC6, and perhaps IC8. These opamps are the most likely candidates for experimentation.

Also, there are several resistors and capacitors that can be experimented with. To make these easy to swap out, pin sockets can be used, or any other component socket that can be split into single pins. Make sure to use sockets that are big enough for the component leads, as there are sockets available for several different lead sizes. In building the surface-mount version, sockets are not an option, so SMT is best for those who don't wish to experiment with components.

The schematic for Option 1 is shown in Fig. 10, and a complete list of components for this option is given in the sidebar. Resistors are 1/4-watt 5%, except for R11 which should be 1/2-watt, preferably metal-film. Electrolytic caps should be rated for at least 16v on the VB lines, and 10v elsewhere. For the other caps, polypropylene and polystyrene offer the best stability, but monolithic is generally sufficient.

As with the circuit description, we'll start with the power supply section. Install IC1-IC4, C1, C3-C7, and D1-D2. Watch the polarities on the electrolytic caps, as well as the diodes. C11 and R37 can be installed at any time, or omitted entirely. Temporarily short SW1, apply 12v to the circuitry and use a DMM to measure the voltage outputs of IC2 (pin 1 = +5v), IC3 (pin 3 = -5v), and IC4 (pin 3 = -5v), with respect to ground. Remember that "ground" is the positive side of the battery, not the negative. Since IC1 is a voltage doubler, the input to IC2 (pin 3) should be roughly equal to the battery voltage, but could be as low as 80% or so due to the inherent inefficiency of the chip. Battery voltages drop quickly from their rated voltage, so the output of IC1 could be as low as 8 or 9 volts for a 12v battery. Other measured voltages should differ by no more than a few percent.

Next is the clocking circuitry. Install IC5, R1-R4, and C8-C9. Also install IC11-IC12, R42-R48, R50, C24-C26, and D6-D7. Do not install Q8-Q9. Make sure all appropriate shorting wires are placed for this option. Power up the circuitry again, and measure the supply voltages on IC5 (pin 1 = -5v), IC11 (pin 8 = -5v), and IC12 (pin 8 = -5v). The output of IC5 (TestPoint 1) should mea-

sure slightly negative, and vary with the Frequency and Pulse Width adjustments. It should fall between -0.25 and -1.25 volts, and be roughly -0.5v with both adjustments centered.

The transmit circuitry and the receiver preamp are next: IC6, R6-R21[5], C10, C14, C15, C27, D3-D4, and Q1-Q3. Do not install R5. Remember to install only the components needed, and jumpers where appropriate. As mentioned before, R9 normally sees short pulses of current, and should not overheat. However, if the output of IC1 should get stuck in a low state, R9 can destructively overheat (*burn up*), as well as MOSFET Q3. Therefore, make sure IC1 is always operating, or pull R5 (or R9 or R15) out if you need to debug the circuit (this will also protect Q3).

Damping resistor R11 will depend on the coil used, but for the 500uH coils described in the **Coil** section, it should be 680Ω. R11 should also be rated at 1/2-watt, as it can get a bit warm, especially when both the frequency and the TX pulse width are set high. Leave the coil L1 off for now. Set R18 to its center position. Power up the circuitry and check the supply pins on IC6: pin 7 = +5v and pin 4 = -5v (roughly; R20 and R21 will slightly reduce these values). Adjusting R18 should vary output of IC6 (pin 6, TP4) from about -1.6v, to +1.6v.

Continue with the remainder of the receiver: IC7, R23-R34, and C17-C21, plus any needed jumpers. *Do not install IC8 at this time.* Temporarily short SW2 and set R34 to its maximum value. Again, apply power and measure the power pins on IC7 (pin 14 = +5, pin 7 = -5v) and the power pins on IC8 (pin 8 = +5, pin 4 = -5v).

For proper differential integration, the differential gain paths of IC8 should be reasonably well matched. The inverting path gain is $A_{inv} = \frac{R26}{R24}$. The non-inverting path gain is

$$A_{noninv} = \frac{R27}{R25 + R27} \times \frac{R24 + R26}{R24}$$

which simplifies to R26/R24, when

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5. R7, R8, and R15 may be shorted. See the **Other Options** section

Parts List (Opt. 1)

Resistors (5% 1/4-watt)

R1	56k
R4, R42a	1.5k
R5, R6, R15, R37, R43, R44, R45a, R47, R48, R50	10k
R9	220
R10	1
R11	See Text
R12, R24, R25, R28, R36, R39	1k
R13, R16, R17, R19	1M
R20, R21	27
R17, R19, R26, R27, R29, R32, R33, R34a, R38	100k
R30	150k
R46a	330
R40	3.3k

Potentiometers

R2, R18, R31	100k
R3, R42, R46	10k
R23	100
R34	1M
R35	5k
R41	5k Audio Taper
R45	50k

Capacitors

C1	100µF elect.
C3	22µF elect.
C4, C5, C6, C7, C14, C15, C27	47µF elect.
C8, C24, C25, C26	10nF poly.
C9, C17, C18, C22, C23	0.1µF poly.
C10	1000µF elect.
C11	1nF
C19, C20, C21	0.47µF poly.

Diodes

D1-D4, D6, D7	1N4148

Transistors

Q1, Q5, Q6, Q7	2N3906
Q2, Q8, Q9, Q11	2N3904
Q3	IRF740

Integrated Circuits

IC1	ICL7660(Voltage inv)
IC2	78L05 (+5v ref)
IC3, IC4	79L05(-5v ref)
IC5, IC9	NE555 (Timer)
IC6	NE5534(Opamp)
IC7	4066 (Bilateral switch)
IC8	TL072 (Opamp)
IC11, IC12	74HC221 (Multivibrator)

Misc

J1	Audio jack
SP1	Speaker
SW1, SW2	SPST switch
SP1	Speaker

Search coil (see text), 12v battery, battery clip, housing, knobs, coax, etc.

R25=R24 and R27=R26. Therefore, when the resistor ratios are matched, the inverting and noninverting gains will match. One way to match resistors is to use 1% or 0.1% precision resistors. Another way is to calibrate the gain. In the spirit of making this project easy to build, without specialty parts, we will calibrate.

Short pad 1 of IC8 to a convenient ground (simple to do when using IC sockets — IC9 pin 4 is ground). *This should never be done with IC8 installed.* R24-R26 is now a simple voltage divider, the same as R25-R27. A DC voltage can be applied to R23, and if there is a mismatch in the two dividers, R23 can be adjusted to null it out. This should be done with the analog gates turned on, which will be the case as long as Q8 & Q9 are not installed.

Use a voltmeter to measure the voltage at TP4. Adjust R18 until this voltage is maximum. Now measure the voltage <u>across</u> pins 2 and 3 of IC8, and adjust R23 until it is zero. Readjust R18 until the output of IC6 (TP4) is 0 volts. Remove power to the board, remove the ground short to IC8's pad 1, and install R5, IC8, Q8, and Q9. Set R31 to its midpoint.

At this point, we're ready to install the audio circuitry. Refer to the *Other Options* section for details on building the non-VCO option. Install R35-R41, Q5-Q7, Q11, C22-C23, IC9, and necessary jumpers. Set R35 to its midpoint and R41 to maximum value. At this point, the circuitry is ready to be packaged and completed. Using a suitable enclosure (remember to allow for a battery pack) add SW1, SW2, the speaker and/or headphone jack, and mount whichever pots will be user-accessible.

Coil

This design, like most other PI designs, is set up to use a simple mono coil. A mono coil has only one winding, as opposed to coils with multiple windings, which often require delicate alignment. Important coil parameters are coil diameter, number of windings, and wire gauge.

For all-purpose coin hunting, a good coil size is 10 inches (25cm) in diameter. A smaller coil will be more sensitive to smaller targets, but will achieve less depth. A larger coil will gain depth, but lose sensitivity to small targets. One popular setup for PI detectors is to use a very large coil, such as 1 meter, for deep cache hunting. This design can be adapted for this; see the *Substitutions* section.

The number of windings affects the strength of the magnetic field that is generated. Theoretically, field strength is proportional to the square of the number of turns, so doubling the number of turns results is four times the field strength. This seems to be a fantastic return on wire investment, except for three drawbacks; more windings results in more coil weight, higher coil resistance, and more parasitic capacitance.

Coil weight must be kept reasonable for comfortable usage. Coil resistance can easily limit the amount of "on" current, which is one of the limitations on the initial field strength. Resistance can be reduced by using a larger wire gauge, but this again adds to the weight of the coil. Another effect of additional windings is an increase in interwinding capacitance, which tends to limit dI/dt during turn-off, again reducing the transient field strength dB/dt.

The standard coil for this design has a diameter of 10-inches (25cm), with 26 turns of 26 AWG[6] enameled wire. A simple way to wind a coil is to drive a circle of nails of the correct diameter into a piece of plywood, and wind the wire around the nails. Then, pull out a few nails and slide the coil off the jig.

Before removing the coil, ensure that both ends have loose leads (pigtails) at least 2 to 3 inches (5-8 cm) long. Also slide some short pieces of tape under the wire, between nails, and wrap tightly to keep them bundled after the coil is removed from the jig. It is best to overlap the pigtails and wrap a piece of tape at the overlap, as shown in Fig. 11.

This is really all that's needed to wind a mono coil, and the pigtails can be soldered to a length of coaxial cable that feeds the main circuitry. However, a critical addition is a ground shield which, for PI detectors, is mostly

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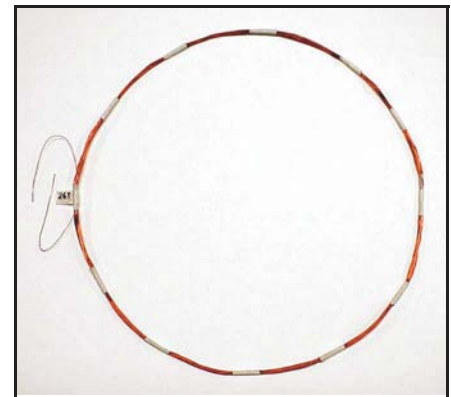6. 26AWG = 27SWG = 0.4mm. A slightly larger wire gauge is fine.

Fig. 11: Wound coil

Fig. 12: Notched aluminum tape

Fig. 13: Applying the tape

Fig. 14: Shielded coil

needed to shield from outside electrical interference.

There are a number of ways to shield coils, including foil, wire wrap, metallic tape, and conductive spray coatings. A simple method is to wrap the coil with aluminum duct tape, the kind easily found at the local home improvement center. This is the tape that is true aluminum, not the silvery metallic-looking fabric duct tape. Standard duct tape is slightly conductive,

but not enough for shielding.

Begin by cutting a length of tape equal to the coil circumference, minus about 1/4" (6-7mm). Duct tape is usually wide, so cut lengthways to get a piece about 1/2" (12.5mm) wide. Now cut notches every inch or so along both edges of the tape, such that the notches are about 1/3 - 1/2 the width of the tape, and are staggered with the other side. See Fig. 12 for details.

Remove the backing and, starting at one of the pigtails, lay the tape around the outside of the coil, sticking the coil in the center of the tape (Fig. 13). When the shield is placed all the way around the coil, stop just short of the pigtails, such that the two ends of the shield wrap do not touch. If the shield completes a short all the way around the coil, it will allow significant eddy currents to flow, which will severely degrade performance. Now begin folding down the 1-inch tabs along one side of the tape, and then fold the tabs on the other side, such that they overlap slightly.

One end of the coil shield will be connected to the cable shield. Since aluminum forms a thin oxide very quickly, soldering to it is not easy, and the solder joint can be unreliable. Instead, wrap a few turns of tinned wire tightly around the shield, and solder this wire to the cable shield. See Fig. 14.

The final challenge of coil-building is to mount it to something rigid. This is actually the biggest challenge, as there is a limited selection of decent coil housings available. Metal detector manufacturers use vacuum-formed plastic shells. The coil is placed in the shell, and liquid epoxy (or some other filler) added to secure it and provide rigidity. For homebrewers, contact information is given at the end of the article for a source of coil shells.

Besides using an epoxy-filled plastic shell, there are some other alternatives. One of the simplest solutions is to epoxy the coil winding to a round piece of plywood of roughly the same diameter. Although this is an easy solution, it is not especially attractive or durable, and it would not be advisable to submerge it in water. But it is sufficient for experimentation.

Another solution is to simply buy a PI coil from a detector manufacturer. Some PI detectors use plug-in coils, and have accessory coils available. Other models have hard-wired coils, but a replacement coil should still be available. In most cases, the value of the damping resistor (R11) will have to be tailored to the coil used. The best value to use for R11 is the same value used for the damping resistor in the detector that the coil was made for, as most front-end designs are the same. Contact the manufacturer for this information.

Once the coil construction is complete, solder the pigtails to a length of coaxial cable, with the coil shield connected to the cable shield. Make sure the cable is securely clamped to the coil in some manner, so that there is no stress on the solder connections. Do not use any metal fittings in the construction of the coil, as they will desensitize the detector. Use plastic and nylon fittings instead. Connect the other end of the coax to the circuit at L1, with the shield soldered to the ground side and the center conductor connected to Q3.

Adjustment & Usage

With the detector completely assembled and packaged, make sure the volume is turned down and apply power. SW2 should be closed. You should be able to adjust the Threshold and vary the audio tone from dead silence to a high pitch. Set the Threshold to get a very low frequency puttering audio. Wave a metal target close to the coil and the audio frequency should increase. If the metal is held absolutely still over the coil, the audio should retune itself back to the threshold tone.

With all the other pots set to the positions prescribed in the *Construction & Calibration* section, you should be able to detect a medium-sized coin several inches from the coil. Increasing the Sensitivity (by decreasing R35) might slightly improved depth, but the detector quickly becomes unstable, especially in noisy environments[7]. Increasing the

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7. Such as inside a house, which is a poor environment for testing a PI detector. You might experience significant instability due to interference.

Pulse Width also improves depth slightly, at the expense of power consumption.

The most interesting controls are the Sample Delay (R42) and Sample Pulse Width (R46). Varying these can change sensitivity, even to different types of metal. In general, a short delay (around $15-20\mu s$) gives the best sensitivity to low-conductance metal like gold.

Once the detector is operating and stable, you can turn SW2 off and test the non-autotrack mode. Now when a metal target is held absolutely still over the coil, the audio should not retune to the threshold tone. This is normally used for pinpointing targets, not for general searching. In fact, unless a CMOS opamp is used for IC8, it is likely that this mode will become unstable after 15 seconds or so. Even JFET-input opamps have a small input bias current that will quickly charge C19.

This design is intended to be a learning platform for how a PI detector works, so it has a lot of knobs to turn. Thus, it is quite easy to loose track of how adjustments interact, so when testing different settings it is best to keep a good record. As you find an optimal setting for a certain knob, mark the position on the panel.

Other Options

The article has primarily covered the standard setup with the VCO audio option. Other build options will be described here. Some options are only available with the through-hole PCB.

In the standard setup, Q2 actively pulls up the gate of Q3 (with almost the full battery voltage applied) to turn it on, while R9 passively turns Q3 off. An additional resistor, R8, is available to divide down the voltage applied to the gate (or base) of Q3. This is more useful if an NPN transistor is used for Q3 (see *Substitutions*). The default is to short R8.

In a PI detector, the turn-off of the coil switch should be done as quickly as possible. If passive pull-down is used, then different resistor values for R9 can be tried. Because the signal applied to R9 is a low duty cycle pulse, even a low value like 100Ω will not cause excessive average power dissipation.

However, an active device pulling
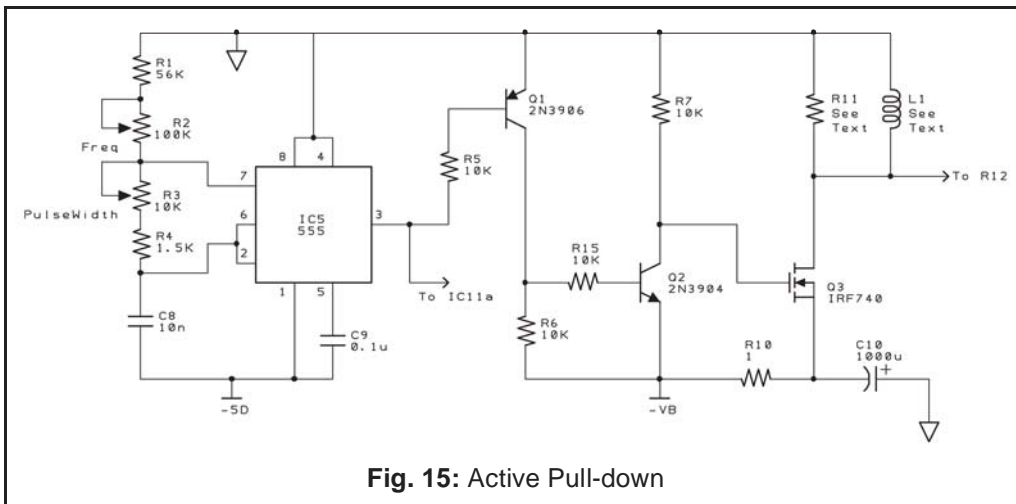
Fig. 15: Active Pull-down

down the gate/base of Q3 will achieve faster turn-off than a resistor. Q2 offers the experimenter the option of investigating active pulldown, with R7 providing passive pull-up (see Fig. 15). The value for R7 is a bit of a guess, and may need adjusting depending on the gate capacitance of Q3. Also, Q2 should have base resistor R15 of about 10kΩ, which can be shorted for the normal passive pull-down option.

This configuration inverts the pulse applied to Q3, so the timing of IC5 will need to be modified to produce an inverted ("positive") pulse at TP1. I have not worked out the resistor values (R1-R4) for this. Furthermore, the pulse will need to be delivered to pin 1 of IC11 instead of pin 2, and this will require a minor PCB modification.

R22/C16 can provide for low-pass filtering, as shown in the complete schematic (Fig. 2), or high-pass filtering by transposing the two components. Normally, R22 is shorted and C16 omitted. If filtering is desired, component values will be need to be determined for the desired corner frequency.

IC8a can be configured as a differential integrator (standard setup) or a single-ended integrator. For single-ended, omit R25 and C18, and short R27 (or use a 1kΩ resistor). R23 is not needed, and can be replaced with a short from IC7a, pin 1 to R22. There is also no need for IC12 and its assortment of components unless the non-VCO audio option is being used, in which case only R47, R48, and Q9 can be omitted.

For a quick comparison between single-ended and differential modes, try building the standard setup, and place a shorting switch (e.g., toggle) across R27-C18. Then single-ended or differential mode can be selected with a flip of the switch.

Autotrack may be permanently configured to auto mode by shorting SW2. It can also have a fixed setting by replacing R34 with a fixed-value resistor. The resistor value can be determined by initially using a potentiometer to find the desired setting.

The non-VCO audio circuit, shown in Fig. 16, produces a change in loudness instead of frequency. IC7c chops the output signal of IC8b, so the audio frequency is constant and equal to the master clock frequency. Keep in mind that if the sample frequency is varied (via R2), the audio frequency will follow. They cannot be set independently in this design.
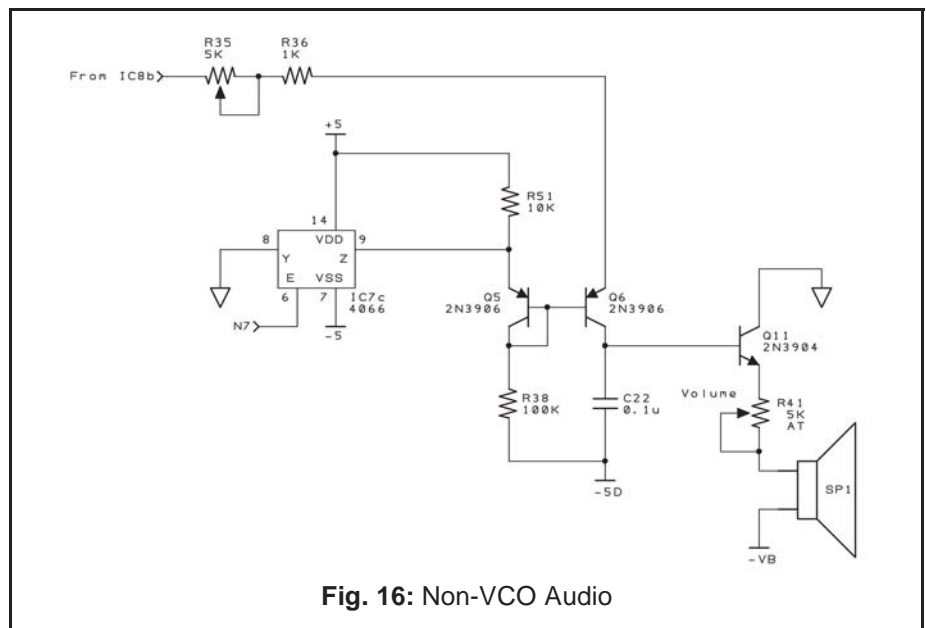
As with the VCO option, R35 (plus R36) converts the output voltage of IC8b to a current. Q6 is a common-base transistor whose emitter is biased to virtual ground, and IC7c shorts the base to +5v, thereby chopping the current. This produces a constant-frequency tone that varies in loudness in response to the variation in R35's current.

Q6 then directly drives Q11 in the same SCR configuration that was shown in Fig. 9 with Q7/Q11. For the non-VCO option, R49, R50, and Q10 must be installed as shown in Fig. 2.

Substitutions

Component substitution options will be described here.

If a large coil is desired (1 meter square) then R1-R4 should be modified to give a lower clock frequency, such as 100 Hz. You will also need to run a higher pulse width, and possibly heat sink Q3 and R11. R11 may need to be a 1-watt resistor.

For IC1, a number of manufacturers make 7660-compatible chips; most have "7660" as a portion of their part number, but some may not. The 7660 is available with different voltage ratings, and for this design, you will need the one rated for at least 12 volts.

IC2-IC4 are 100mA regulators (TO92 for the through-hole board). Any compatible regulator may be substituted. A

Fig. 16: Non-VCO Audio

low dropout voltage will result in longer usable battery life.

IC5 should be a CMOS version of the venerable 555 timer. A TTL version might work, but might need a pull-up resistor (to ground) on pin 3.

Most "small-signal" devices are not critical. About any signal diode may be used in place of the 1N4148's (avoid rectifier-type diodes, i.e. 1N400x). Likewise, NPN & PNP transistors are fairly non-critical.

Transistor Q3 can be just about any 700-series NMOS device, and can also be an NPN transistor like a 2N3055. Though I haven't tried one, an insulated-gate BJT might also work. Generally, try to use a fast transistor with lowest junction capacitances (especially drain capacitance), while meeting the current and breakdown voltage constraints. When using a bipolar device for Q3, it is possible that applying the full 12 volts across the base-emitter could damage the part. Therefore, use R8-R9 as a voltage divider — R8=330Ω results in a little less than 5 volts and a Thevenin resistance of 130Ω.

Some experimenters have had better success at running a lower gain in the preamp. Try using a 2kΩ (or 2.2kΩ) resistor for R12.

D3 & D4 should be low-capacitance fast-recovery diodes. 1N4148's are commonly used here, but there are faster diodes that might improve transient settling. I've tried Schottky diodes and found they offered no improvement.

IC6 can be just about any fast-recovery opamp. The NE5534 is popular, but there are many newer opamps that are faster and lower noise. Avoid current-feedback opamps.

A CD4016 can be used in place of the CD4066.

IC8 can be just about any FET-input opamp. The TL072 and TL082 are popular but, as in the case of IC6, many newer opamps are available. Performance is not as critical as with IC6, either in speed or noise. The lower the input bias current, the longer the no-motion mode will operate, so a true CMOS-input opamp will be best.

You cannot substitute a TTL-compatible 74221 (such as a 74LS221) for the 74HC221. You can substitute other CMOS compatible versions, such as the 74C221.

The listed component values for the pulse timing offer quite a bit of adjustment range. If a 1kΩ resistor is used for R42a, the minimum pulse delay can be taken down to 8μs. Reducing R45a to 5kΩ results in a minimum secondary delay of about 45μs. If R46=2kΩ and R46a=220Ω then the resulting pulse width is 3 - 20μs, probably a more practical range.

PC Boards

Although this project can be built on perf board using point-to-point wiring, it is much easier to use a PC board, and the layout is already done. Fig. 17 shows the PCB layout; because it is single-sided, it is very easy to fabricate. However, a ready-made PCB is available, see the **Sources** section at the end
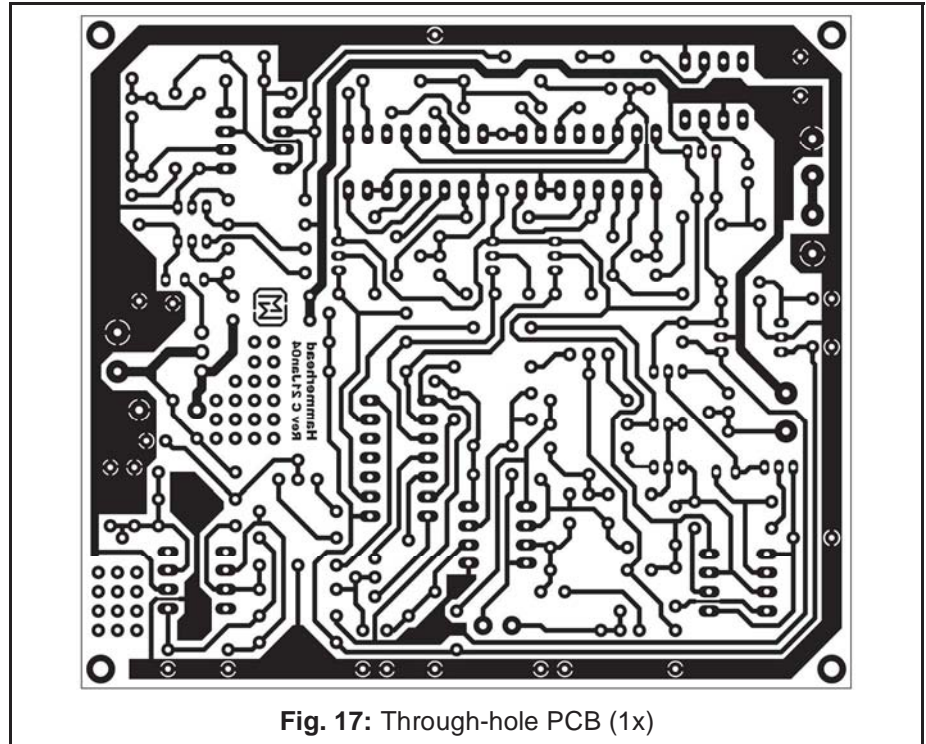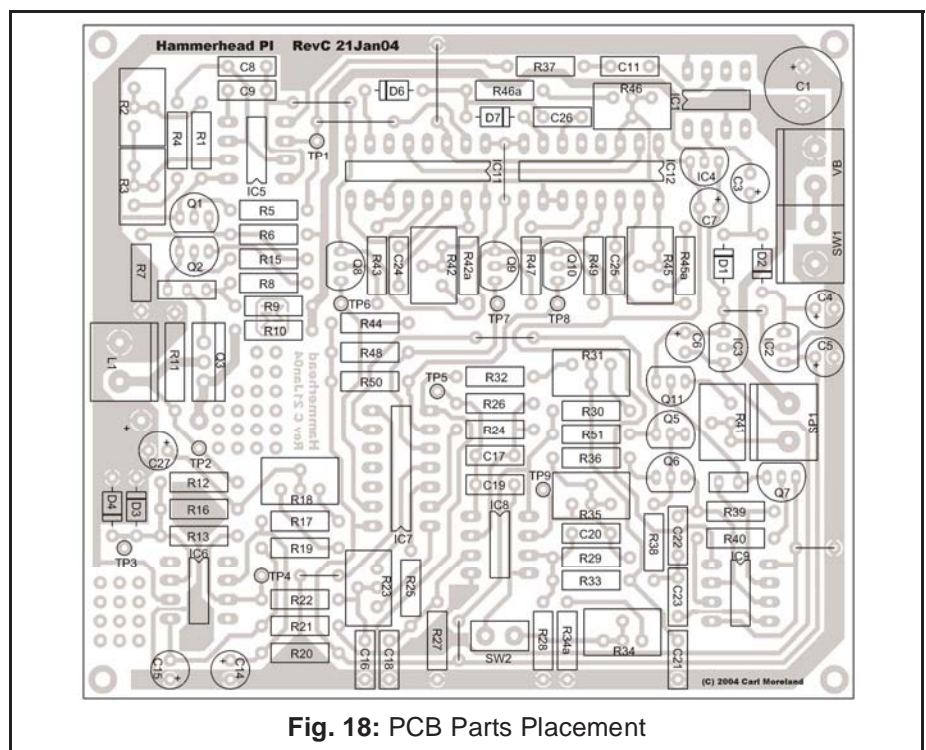

Fig. 17: Through-hole PCB (1x)

Fig. 18: PCB Parts Placement

of the article. Fig. 18 shows the parts placement for all the possible parts. Remember, though, that some parts are omitted, and some shorted, depending on the option.

This project is an ideal candidate to build using surface-mount components. Fig. 19 shows both sides of a surface-mount (SMT) PC board (shown 2X the actual size), which is also available. It is roughly one-third the size of the normal PC board. Fig. 20 shows the parts placement, again for all the parts.

Troubleshooting

Here are some common problems and potential solutions.

Output voltage of the 7660 is not right.
- Check the polarity of the diodes.
- Check the polarity of the electrolytic cap C3.
- Try disconnecting C11.

No pulses or strange pulse widths coming out of the 74221's.
- Make sure they are CMOS versions of the 74221 (C, HC, AC). TTL versions such as the 74LS221 will not work.
- Check polarities of D6 & D7.

Coil pulse is ringing badly
- Oscilloscope probe capacitance is loading the coil. Use a low-capacitance probe.
- Incorrect damping resistor value.
- Excessive cable or shield capacitance.

Valid pulse on the coil, but no output on opamp IC6:
- Misadjusted offset R18 can saturate the output.
- An incorrect (low) value for R16 can saturate IC6.
- Bad clamping diode D3/D4 can fry the opamp.

Calibration of IC8a via R23 doesn't work:
- For this procedure, R44 & R48 should be installed, but Q8 & Q9 should NOT be installed. If Q8 & Q9 have been installed already, simply short R44 & R48.
- R5 (or R15) should not be installed. If they are installed and Q3 is being pulsed, then the coil should be
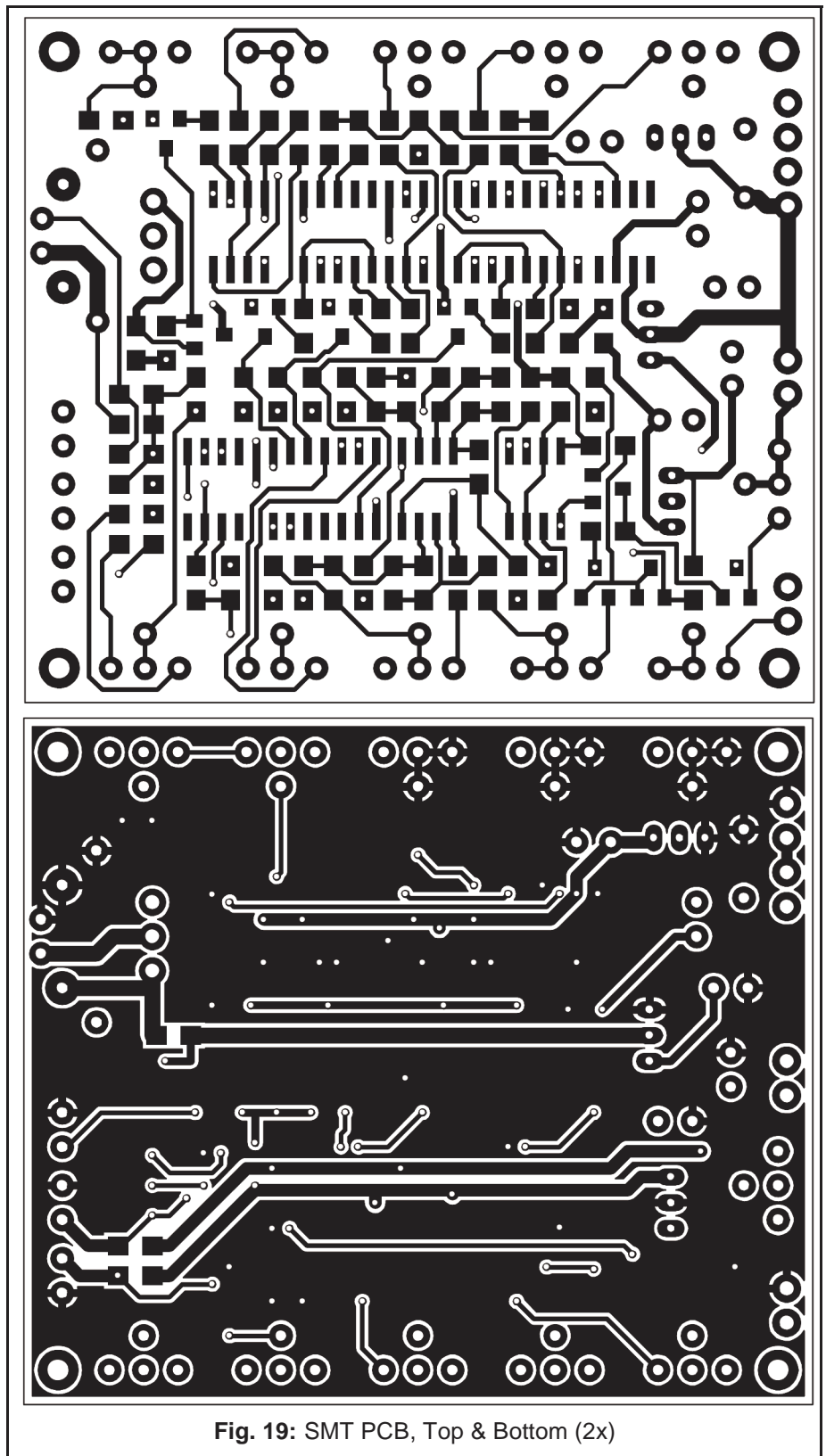
Fig. 19: SMT PCB, Top & Bottom (2x)

disconnected. There will be a slight (but acceptable) error in calibration.
- Is R22 installed (low-pass filter) or shorted (no filter)?
- If R22/C16 was installed as a high-pass filter, temporarily short C16.

Audio is not working or is erratic:
- Make sure TP9 is close to zero volts for no target.
- Try reducing sensitivity via R35.
- If testing indoors, try going outside, well away from noise sources.

Detection depth is poor:
- If testing indoors, try going outside, well away from noise sources.
- Make sure autotrack speed (R34) is not too fast.
- Try reducing the pulse delay (R42).
- Try increasing pulse width (R3).

The last page of this article shows various waveforms as probed with an oscilloscope, including the relationship between waveforms, and how they vary with potentiometer settings.

Sources

Either a through-hole PC board, or a SMT PC board, (etched, drilled, nickel-plated, & silk-screened) is available from:

Geotech
P.O. Box 184
Oak Ridge, NC 27310

Cost is $10 (US/Canada/Mexico) and includes S&H. Cost to other locales worldwide is $12, including S&H.

Most through-hole components can be purchased from the local Radio Shack (some must be special ordered). The following mail-order companies have an extensive selection of both through-hole and SMT components:

Digi-Key: http://www.digikey.com

Futurlec: http://www.futurlec.com

Jameco: http://www.jameco.com

Mouser: http://www.mouser.com
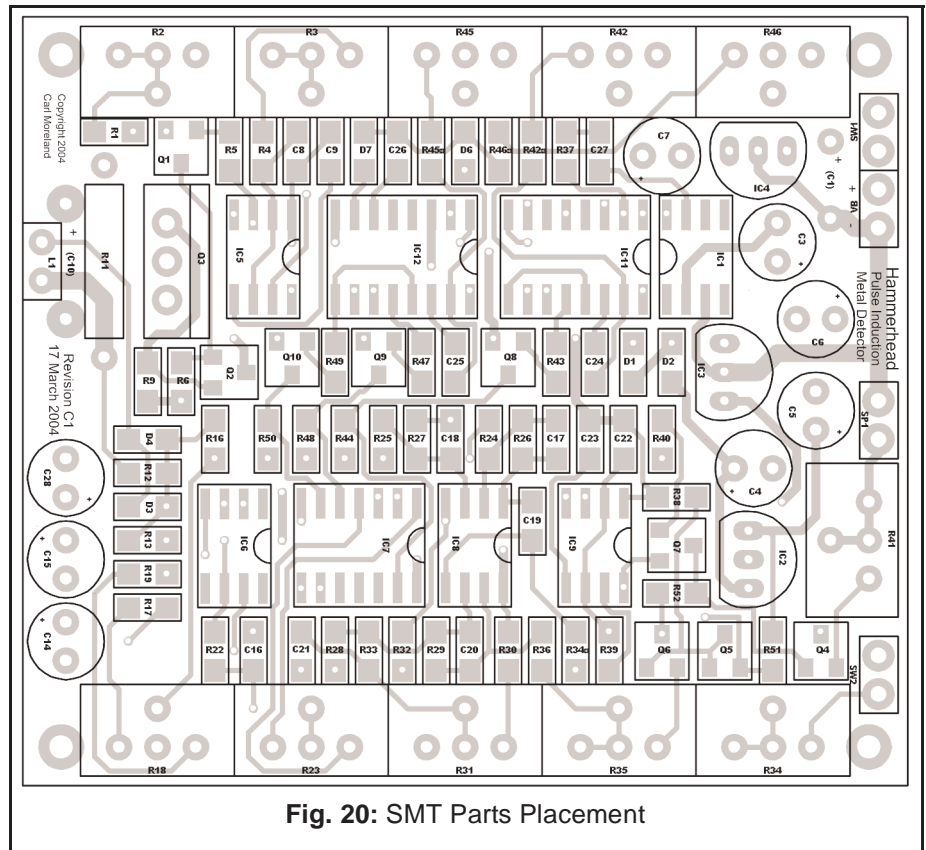
Fig. 20: SMT Parts Placement

Coil shells are available in several sizes from:

Hays Electronics
P.O. Box 26848
Prescott Valley, AZ 86312
http://www.hayselectronics.com

Further information is available on the Geotech web site:
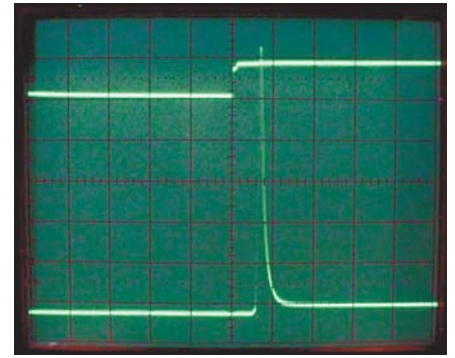
http://www.thunting.com/geotech

- Latest version of this article
- Technical help forums
- More info on building coils
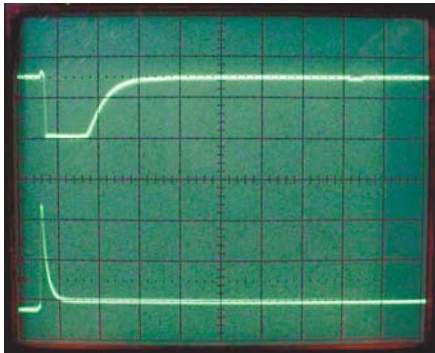- Other detector projects
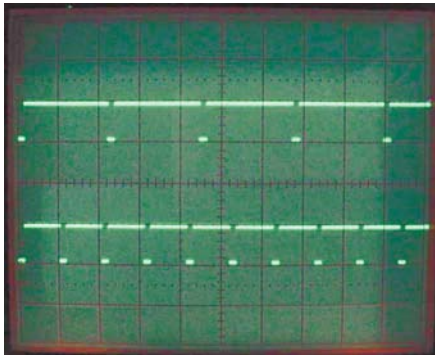
Fig. 21: Output of IC5 (TP1) — top trace is low freq (~900 Hz), bottom trace is high freq (~2kHz).
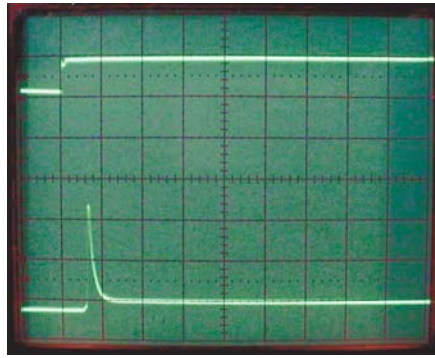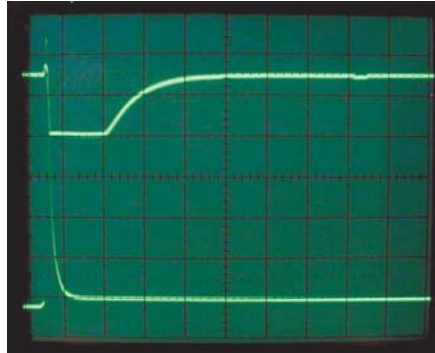

Fig. 22: Output of IC5 (TP1) and coil flyback signal (TP2). 10us pulse width results in ~120v flyback peak.
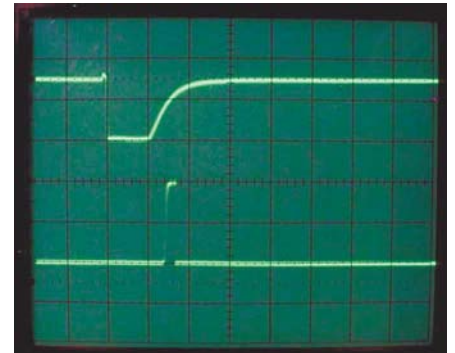

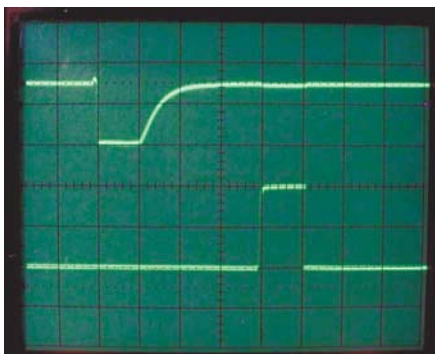**Fig. 23:** Same as Fig. 22, but now 50us pulse width results in ~320v flyback peak.

Fig. 24: Output of the preamp (TP4) in relation to the flyback signal (TP2).
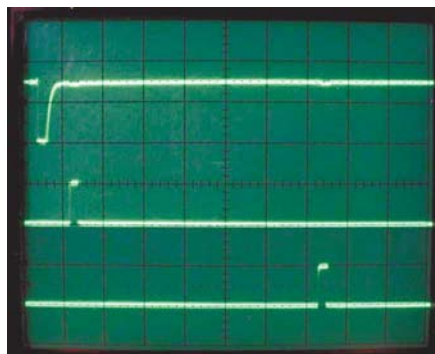

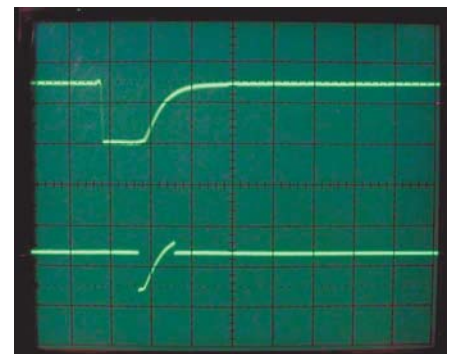**Fig. 25:** Same as Fig. 24, but pulse width is now 50us. Note that preamp decay is extended.

Fig. 26: Preamp output (TP4) and main sampling pulse (TP6) with ~15µs delay and narrow pulse width.
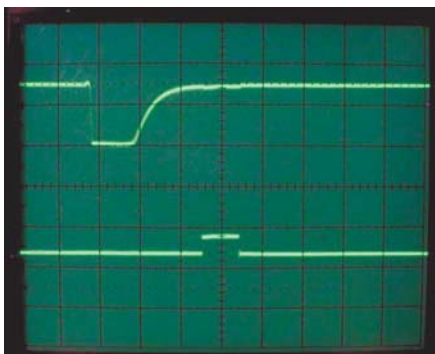

Fig. 27: Same as Fig. 26, but now the sample pulse is delayed further, and pulse width increased.

Fig. 28: Output of the preamp (TP4), along with the main (TP6) & secondary (TP7) sampling pulses.

Fig. 29: Output of the preamp(TP4), and output of the main sampling switch (IC7 pin2).

Fig. 30: Same as Fig. 29, sampling further out.