

# Fluxgate Magnetometer

by Carl Moreland

The instrument of choice for the modern treasure hunter is no doubt the metal detector which has the capability of not only finding precious metals but most can also provide some level of discrimination against unwanted targets such as pulltabs and foil. The metal detector operates by generating a dynamic electromagnetic field and looking for perturbations in the field due to conductive objects. Another instrument, called the magnetometer, looks only at static magnetic fields (namely, earth's) for perturbations. Not all metals affect magnetic fields in an easily measurable way; the magnetometer is sensitive only to ferrous targets such as iron and nickel.

In most cases the treasure hunter is trying to eliminate ferrous targets, or at least those that contain iron (such as nails), and detect only gold, silver, and copper and their alloys. So why would anyone want a magnetometer that can only locate iron while totally ignoring gold? The answer lies in the things that sometimes accompany treasure. For example, a cache might be buried in a steel or iron container; placer gold is often found in highly magnetic black sand; and sunken treasure is often accompanied by iron artifacts. In fact, most of the sunken treasure ships found in the last 30 years were pinpointed with a magnetometer, and the mag is an obvious choice in detecting steel-hulled ships. So while the mag is not the sort of instrument a weekend coin hunter might use, it is certainly a valuable tool for other treasure hunters.

## The Basic Mag

The basic magnetometer consists of sensor which produces a signal that is proportional to the strength of the magnetic field around it. One type, the proton precession magnetometer, uses a sensor which consists of a bottle of distilled water or a hydrocarbon such as kerosene around which a coil of wire is wound. The coil is periodically energized to produce a strong magnetic field which aligns the "spin" of the hydrogen protons and effectively magnetizes the liquid. When the coil field is removed the protons precess, sort of an atomic wobble that occurs with a frequency that is dependent on the strength of the surrounding ambient magnetic field.

Another type of magnetometer uses a device called a fluxgate sensor. The fluxgate consists of a magnetic core which is periodically hard saturated by a first coil (much like the proton liquid), while a second coil senses the resulting electromagnetic field. Figure 1 shows one such device which is a toroid core with the energizing coil wound toroidally and the sense coil wound flat around the outside. Under normal conditions, the sense coil will not detect the field that is generated by the toroid because it will be balanced, assuming the sense coil is symmetrically wound. However, an additional external magnetic field can cause an imbalance in the toroid's hysteresis which results in a net field that is detected by the sense coil. In this particular configuration, the sensitivity to the external field is sensitive to the orientation of the sense coil with respect to the field.

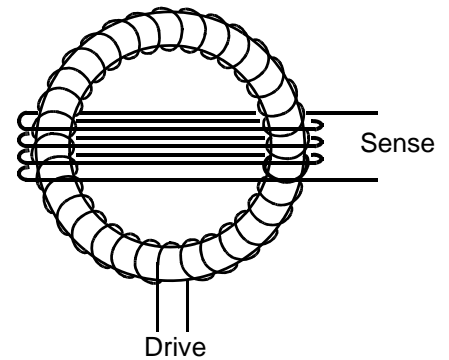


FIGURE 1. Fluxgate Sensor

## A Cheap and Easy Sensor

The fluxgate sensor is a little tedious to construct and the sensing circuitry is rather difficult and requires an oscilloscope for proper adjustment. Fortunately, a ready-made fluxgate sensor (Figure 2) that is incredibly easy to use is made by Speake & Co. in the UK and distributed by Fat Quarters Software in the Americas. Both addresses are given at the end of the article. The sensor is small - 62mm x 16mm (d) or 2.44" x 5/8" - and has four 100 mil-spaced pins at one end. It can operate over a range of  $\pm 50$  microteslas ( $\mu T$ ) with a resolution on the order of about 10nT. This makes it extremely sensitive to very small field anomalies. The pinout, shown in Figure 3, includes a feedback connection which is useful for making linearity corrections to the device. In this application, linearity is not a concern as we will use the sensor to detect the presence of field anomalies, not to accurately measure their value. Therefore, in this design the fluxgate sensor is truly a three-terminal device: 5 volt supply, ground, and output.



FIGURE 2. Speake & Co. FGM-3

The output of the sensor is an easy-to-use 5 volt pulse waveform whose frequency varies with the strength of the surrounding magnetic field, generally from about 50KHz to 120KHz. As mentioned of fluxgate sensors, the device is highly directional, meaning that it responds differently as it is rotated in free space. This poses a problem because directional variations with respect to the earth's magnetic field can easily swamp out any small anomalies that we might be looking for. One possible solution is to use two fluxgate sensors that are aligned in the same direction. They will both "see" the same absolute magnetic field regardless of orientation as long as they remain aligned to each other; however, if there is a local anomaly present it will affect the closer sensor by a greater amount. Technically, this type of arrangement is known as a *gradiometer* because it detects magnetic field gradients, but we will still refer to it by the more general term *magnetometer*.

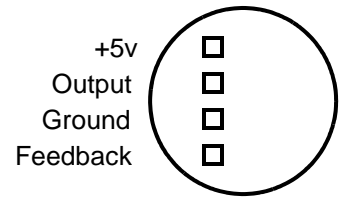


FIGURE 3. FGM-3 Pinout

Recall that the output of the FGM sensor is a pulse train in the 100KHz range. By using two sensors we can mix the two pulse waveforms and obtain a low frequency difference signal. This type of arrangement is reminiscent of the BFO metal detector where two oscillators are mixed together and we look for a shift in one of the frequencies caused by a metal target. Like the BFO, we can directly mix the output frequencies of the two fluxgate sensors to produce an audible indication of a target. Figure 4 shows the schematic for such a digital "mixer". However, there is a better way.

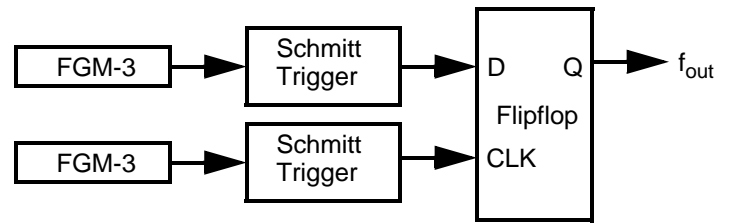


FIGURE 4. Digital Mixer

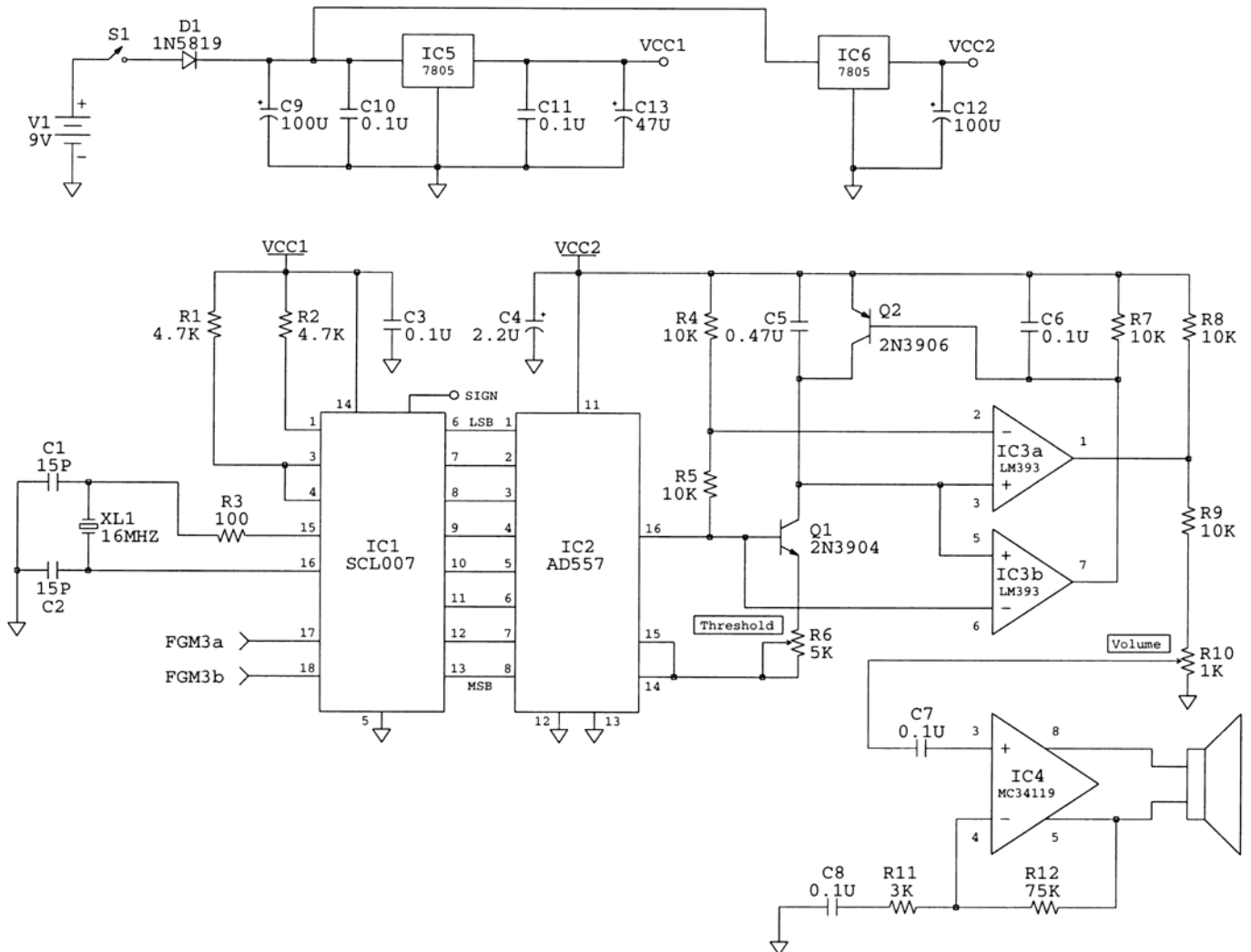


FIGURE 5. FMX-1 Schematic

## The Circuit

Speake & Co. also makes a chip called the SCL007 gradiometer. It accepts the inputs from two fluxgate sensors and does the digital mixing for us. The output of the gradiometer chip is an 8-bit parallel word which corresponds to the mix frequency. A zero output means the sensors see the same field, a full-scale output means there is a large difference. The SCL007 also has a “sign” bit which can tell us which of the two sensors is detecting an increase in the magnetic field, making the total output a true offset binary 9-bit word. We are not particularly concerned with the sign bit, although it could be used to determine which sensor is closer to the target.

To make immediate use of the 8-bit digital output, we must use a digital-to-analog converter (DAC) to produce an analog signal, then use this voltage to produce an audible or visual signal. Since direct digital mixing will produce an audio frequency signal without all of the intermediate mess, why bother using the gradiometer chip? Because it also provides a power-up calibration of the two sensors which improves the sensitivity dramatically. The DAC can also directly drive a voltmeter and the 8-bit parallel output is useful for data logging to a computer.

Figure 5 shows the schematic for the final design. The gradiometer chip is basically connected per the Speake & Co. data sheet. The Analog Devices AD557 DAC converts the 8-bit word to an analog voltage with a range of 0-2.5 volts. This voltage is then used to drive a voltage-controlled oscillator (VCO) which produces an audible tone that drives a speaker. Note that the sensors and gradiometer chip are powered by one regulator, while the DAC, VCO, and audio output have a separate regulator. This is an absolute necessity as any supply fluctuations that get to the sensors will cause them to misbehave. Further isolation is provided at each sensor with an L-C filter on the supply line.

## VCO

The VCO is the only part of the circuit that requires any further explanation. While there are integrated circuit VCOs available, it is difficult to locate any that are very low power (<1mA) and readily available from common sources (i.e., mail-order houses). Thus a simple but effective VCO was designed around the LM393 dual comparator. Figure 6 shows a simplified diagram of the VCO. Q1 is inserted into the feedback path of the DAC output amplifier so that, via the DAC feedback resistors (about 1.6K total), it performs a voltage-to-current conversion for driving the integrator capacitor C5. Therefore, the current drive from Q1 is directly proportional to the DAC output voltage. Interestingly, the true DAC output voltage is not seen at the output pin (16) but at the feedback pins (14/15). This signal is brought out to a separate pad on the PC board (with an adjacent ground pad) so that it can be used as a true analog output. However, with the addition of the threshold adjustment R6 this voltage is not low impedance and should be buffered with an op-amp.

Integrating capacitor C5 generates a descending ramp voltage that is sensed by comparator IC3b; when the ramp voltage at node A falls below the reference on the negative input (B), the comparator output (C) goes low and turns on Q2. Q2 short-circuits C5 which pulls the voltage at node A up to VCC2, shuts off, and the ramp starts all over again. Comparator IC3a compares the resulting sawtooth waveform at node A with a midpoint level (D) to generate an approximate square wave (E). Figure 7 shows the various waveforms that have been described.

The minimum output voltage of the DAC is 0v (when the sensors are balanced) which should result in a silent VCO. In reality, the sensors are never perfectly balanced so the VCO is always running at some low frequency. It is actually desirable to have the VCO idle at a very low frequency. The reason for this is partly why the old BFOs were tuned up to run at a slow putt-putt frequency: the human ear is very sensitive to frequency changes. By running at a very low rate we can discern very minute changes; if we run it too low we risk getting a rate change that is actually too low to distinguish. A nominal rate of 5-10 Hz is a good operating point. Obviously this is below the frequency range of average human hearing (about 20Hz on a good day) but remember that the speaker waveform (E) is a square wave, not a single tone, so what we hear are “clicks.”

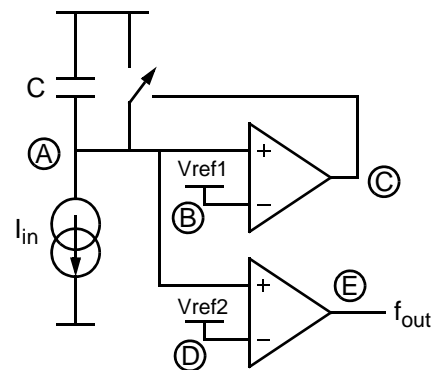


FIGURE 1. Simplified VCO

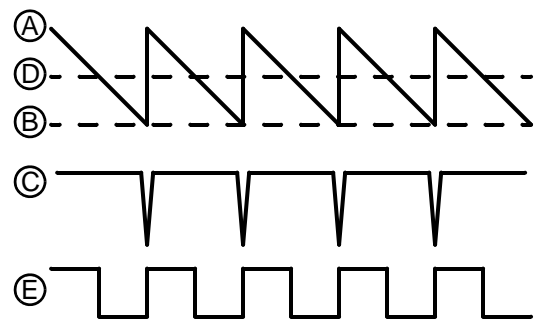


FIGURE 2. VCO Waveforms

Because the square wave is rich in harmonic energy slight variations in the fundamental mean larger variations in the harmonics which gives us an even more effective frequency change.

The resultant VCO frequency depends on the integrator current and capacitor value according to the following equation:

$$f = \frac{I}{\Delta V \times C} \quad (\text{EQ 1})$$

where  $\Delta V$  is the full excursion of the ramp voltage and, as already mentioned,  $I$  is  $V_{DAC}/R_{DAC}$ . The reference to IC3a is derived from a level-shifted version of  $V_{DAC}$ , so  $\Delta V$  ends up being roughly equal to  $V_{CC}-V_{DAC}-0.7$ . Ignoring  $R_6$  the frequency is:

$$f = \frac{V_{DAC}}{(4.3-V_{DAC}) \times R_{DAC} \times C} \quad (\text{EQ 2})$$

When  $V_{DAC}$  is zero the minimum frequency is zero. When the DAC is 1LSB from zero (00000001b, or 2.5v/256) we want a very low frequency, say 5Hz. This means that

$$5 = \frac{9.76mV}{4.29 \times 1.6K \times C} \quad (\text{EQ 3})$$

or  $C = 0.28\mu F$ . The design uses 0.47 $\mu F$  for  $C_5$  so the LSB frequency is actually 3Hz. Again, you will probably find that the DAC output nominally runs a few LSBs above zero. The maximum frequency occurs when  $V_{DAC}$  is ~2.5v and is

$$f = \frac{2.5}{1.8 \times 1.6K \times 0.47\mu F} = 1850Hz \quad (\text{EQ 4})$$

So we end up with a full frequency range from DC to nearly 2KHz which corresponds to the strength of the detected gradient.

## Construction

A full list of components is given in the sidebar. Figure 8 is a 2X scale PC board layout for the mag and Figure 9 is a parts placement diagram. Components and board are available from Fat Quarters Software; information is in the sidebar. There is absolutely nothing difficult about the circuit portion of this project; just solder everything in place and you're done. You may use IC sockets if you wish (I do whenever possible) and the use of 100-mil headers for plugging in the sensors leads makes assembly and disassembly (if ever necessary) a bit easier. Note that the board includes pads for directly taking off the 9-bit data word (including the sign and a ground) and the DAC analog output for interfacing to other circuitry.

Building up the enclosure and tube is not difficult either, but it does require more time and effort. You will need to obtain some 1-1/2" PVC from your local home improvement center along with two end caps plus a few other PVC components for the sensor modules. The length of the PVC will roughly determine sensitivity (up to a point) and 5-6 feet is a very practical length. You do not want it so long that the tube flexes; it is very important to maintain rigidity! For the main circuit box I used an almost perfectly sized plastic case from Radio Shack (see the parts list). You will want to avoid the

## Components

### Resistors (1/4W 5%)

R1,R2	4.7K $\Omega$
R3	100 $\Omega$
R4,R5,R7-9	10K $\Omega$
R11*	3K $\Omega$
R12*	75K $\Omega$
R6	5K $\Omega$ Linear Taper
R10	1K $\Omega$ Linear Taper

### Capacitors

C1,C2	15pF ceramic disc
C3,C6,C10,C11	0.1 $\mu F$ monolithic
C4	2.2 $\mu F$ 10v tantalum
C5	0.47 $\mu F$ monolithic
C7-8*	0.1 $\mu F$ monolithic
C7**	10 $\mu F$ 16v electrolytic
C8**	100 $\mu F$ 16v electrolytic
C9,C12	100 $\mu F$ 25v electrolytic
C13	47 $\mu F$ 10v tantalum
C14,C15	33 $\mu F$ 10v tantalum

### Inductors

L1,L2	56 $\mu H$
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### Semiconductors

D1	1N5819
Q1	2N3904
Q2	2N3906
XL1	16MHz crystal
IC1	SCL007 Gradiometer
IC2	AD557 DAC
IC3	LM393 Comparator
IC4*	MC34119 Audio amp
IC4**	LM386 Audio amp
IC5,IC6	7805 Regulator

\* MC34119 option

\*\* LM386 option

### Misc.

(2) FGM-3 fluxgate sensors, 9v battery and battery clip, SPST switch, 8 $\Omega$  speaker (opt), headphone jack (opt), PC board, enclosure (Radio Shack 270-1803), 1-1/2" PVC pipe 5ft long, (2) 1-1/2" PVC end caps, (2) 1" slip couplers, (4) 1"x1/2" SxS bushings, (3) 1/2" PVC pipe 1" long, IC sockets (opt), pin headers (opt), wire.

Sensors, components, and PC board are available from Fat Quarters Software. Please see the contact information at the end of the article for details.

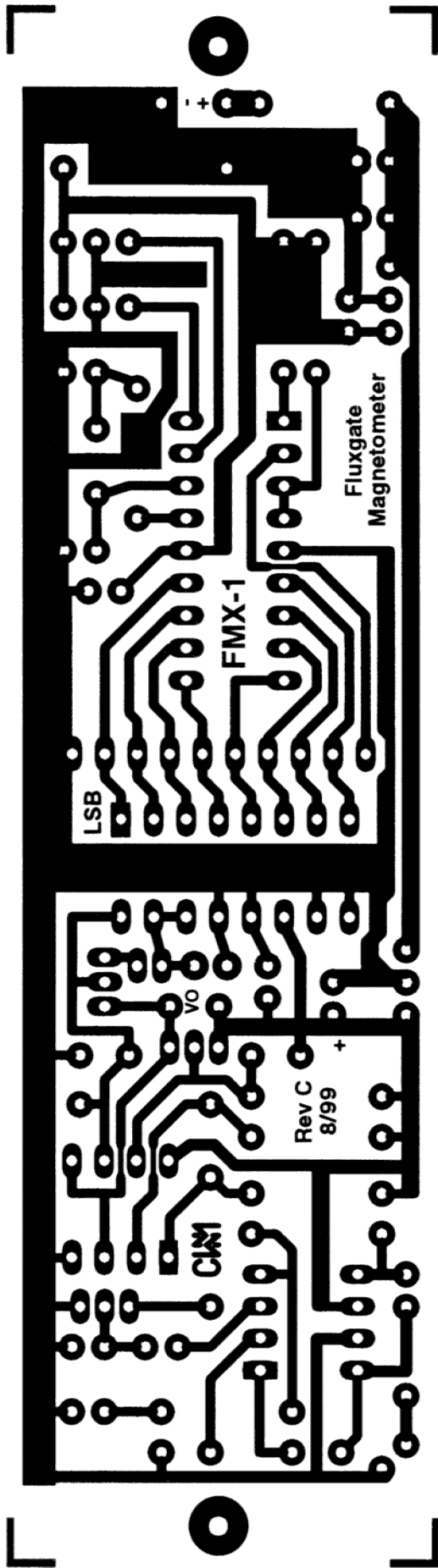


FIGURE 8. PC Board

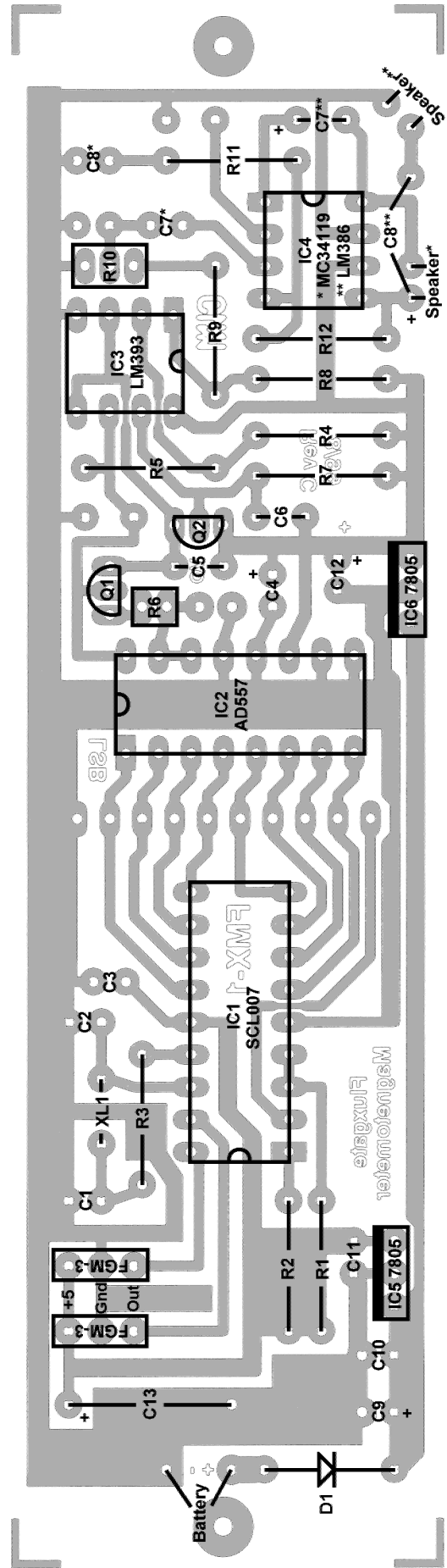


FIGURE 9. Parts Placement

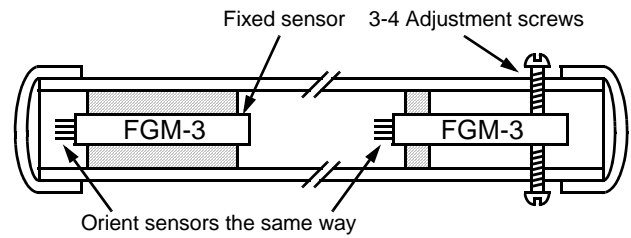
use of any ferrous material in the construction of the mag, and the main tube should not be metal of any kind as eddy currents will be generated and seriously degrade performance.

Fasten the box to the center of the tube with two aluminum sheet metal screws. Drill a 1/2" hole through the center bottom of circuit box and into PVC tube. Next, cut a three-wire cable for each of the sensors; I peeled off 3 leads of a ribbon cable. The cables need to be about 12" longer than half the tube length. Thread the cables from the circuit box out to each end of the tubes and temporarily tape them in place. With the 3-lead cables pulled into the circuit box, finish the hookups to the board including the volume pot/switch, threshold pot, speaker, battery clip, and sensor leads. You may want to trim off some of the excess sensor leads, but leave them long enough so they project at least 8-12" from than the tube. You should also mark on the sensor end which wire is supply, ground and signal. Mount everything according to your preferences; my non-ideal solution is pictured in Figure 8.



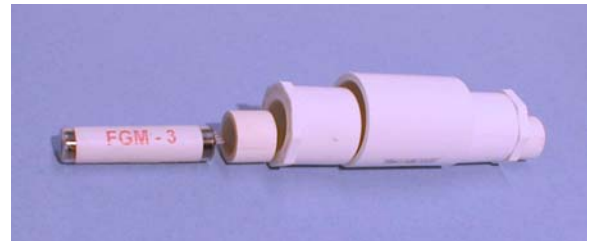
**FIGURE 8. Box Assembly**

The final step, and the most difficult of the whole project, is to install the sensors in a way that they can be mechanically aligned. Sensor alignment consists of adjusting one of the sensors until it is perfectly on-axis with the other sensor. The method described by the Speake & Co. literature is to fix one sensor into the tube with "o-rings", and to mount the other sensor with an adjustment mechanism as shown in Figure 9. The "o-ring" provides a pivot point, and four external non-magnetic (nylon, aluminum, or brass) screws are used to make the necessary adjustments. I found this approach to be unsightly with the screws sticking out of an otherwise sleek-looking tube, and also subject to damage.

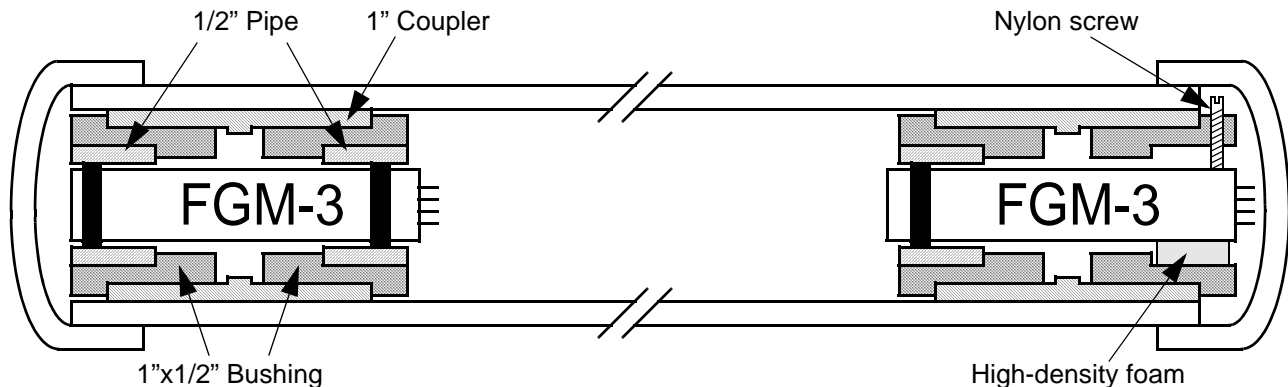


**FIGURE 9. Speake & Co. Adjustment Method**

A better method is to place the adjustment mechanism entirely inside the tube. It so happens that a 1" PVC coupler will very nearly slide into the inside of 1-1/2" PVC pipe (this may vary slightly among manufacturers). Two modules, one fixed and one adjustable, can be made from couplers that are reduced to slide into the pipe - a cross-sectional diagram is shown in Figure 10. To reduce the couplers they can be turned in a lathe, sanded in a drill press, or shaved with a Sur-Form rasp. Just make sure that they fit snugly, and remember that turning or sanding will warm the PVC coupler and cause it to expand slightly - let it cool before checking the fit. For the fixed module, 1"x1/2" bushings are inserted into both ends of a coupler and short pieces of 1/2" PVC pipe are inserted into each bushing so they are flush. The FGM sensor will now slide into the assembly with a slight amount of clearance to the inside of the 1/2" PVC. One or two wraps of electrical tape around the FGM sensor will result in a snug fit. One potential problem with the FGM sensors is that the plastic covers eventually loosen (probably due to thermal expansion cycles) and the exposed sensors slide out, so you should watch for this and apply some glue if necessary. Figure 11 shows the pieces of the fixed module disassembled but properly aligned for assembly.



**FIGURE 11. Fixed Module Prior to Assembly**



**FIGURE 10. Sensor Module Cross-sectional**



The adjustable module is made in a similar manner. One end of the module pivots so it uses a bushing and 1/2" PVC just like the fixed module. One minor difference is that this module will be installed with the connecting pins pointing out of the tube, so we need to provide a path through the module for the wiring. Therefore, the 1/2" PVC pipe has a notch cut lengthwise in it for the wire to run past the sensor. When using electrical tape to shim the pivot end of the sensor keep the width of the tape narrow, 3/16" or so, so that the sensor will easily pivot. The other end of the sensor needs some room for movement in the module so the 1"x1/2" bushing is used but the 1/2" PVC is not. The bushing is drilled and tapped to accept two non-magnetic screws at 90° angles to each other - I used 6-32 nylon screws cut to length with heads removed and new screwdriver slots melted in with a hot screwdriver. Opposite the screws is a piece of high-density foam to keep the sensor pushed against the screws. Figure 12 shows the adjustable module from the end with the adjustment screws. Note the notches that were cut in the coupler for accessing the screws.



FIGURE 12. Adjustable Sensor Assembly

The final step is to connect the sensors to the wires and slide the modules into the tube. The wires are connected to the sensors through an L-C filter (L1-C14 and L2-C15, as shown in Figure 13). I used a 100 mil header socket, also shown in Figure 13, which simply plugs onto the sensor pins. Again, watch your hook-up on this which is why the leads should have been labeled. If you're not sure, use an ohmmeter to check your connections from board to sensor before power-up. When you have the sensors connected to the wires carefully insert them into their respective modules. The fixed sensor should be snug and secure fit with the lead connections pointing inward toward the control box as in Figure 10. The adjustable module will be installed so both the lead connections and the adjustment screws are toward the outside end of the tube. The sensor wiring folds back through the module between the screws and through the slot in the pivot end. Slide both modules into the tube making sure the adjustable module protrudes just enough to access the screws. One advantage of the sensor modules is that you can easily switch between tubes of different lengths. Both modules should have a fairly tight fit in the tube so they do not slide easily. If there is any looseness, apply some non-permanent adhesive before sliding the modules into the tube. We are now ready for power-up and test.

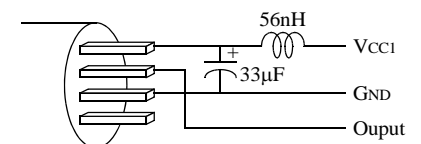


FIGURE 13. Sensor Connection

## Adjustment and Cal

At this point you could run off and start using the mag, but for optimal performance we need to make one easy mechanical adjustment. Recall that a single sensor is sensitive to its orientation within the magnetic field. For the two-sensor arrangement, the mixed-frequency output is sensitive to their misalignment to each other. If they are perfectly aligned, then each sensor will detect the exact same magnetic field (in the absence of a target) and the gradient will be zero even if the whole tube is rotated. If they are not aligned, then one sensor could detect a slightly different field, and this will change with the movement and orientation of the tube. *All calibration and alignment procedures should be done well away from undesirable magnetic fields, including iron targets and electrical (AC) lines.*

Before we can align the sensors, we first need to allow the SCL007 to perform a sensor calibration. According to the literature, the calibration is done during the first 10 seconds or so after power-up during which time it expects the sensors to see a minimum and maximum earth field. The described method is to hold the tube in a north-south orientation pointing the north end upwards at the angle of the field's inclination, about 67° to the horizontal in the UK, a little less in the US, and 0° at the equator. Switch on the power and slowly rotate the tube, head over heels, through 360° during the first 10 seconds. That's all there is to it; *this procedure should be done every time the mag is turned on for use.*

To align the sensors, turn on the unit and go through the sensor calibration described above. Place the tube in an east-west orientation (and level) in a way that you can rotate or roll the tube. I built a simple wooden "U" stand with "V" notches cut in the uprights. With the tube in a starting position listen to the output frequency. If there is no output sound or the frequency is less than 10Hz you may need to go ahead and adjust the VCO to get an appropriate frequency. Now slowly rotate the tube by about 180° and listen for a frequency change. If there is one, it indicates that the sensors are misaligned. I found an effective method is to rotate the tube to find the highest output frequency; with the tube held at this position adjust the sensor to reduce the frequency. Continue this until you can rotate the tube with little or no frequency change.

## Options

This mag has only two knobs: volume and “threshold.” The threshold knob can be used to reduce the minimum frequency at idle for better sensitivity. Doing this creates non-linearities in the DAC voltage to VCO current translation and reduces the maximum frequency somewhat, but neither effect is important for an audio mag. You may choose to omit this potentiometer and put a short in its place. As mentioned before the PC board includes extra solder pads at the digital outputs of the SCL007 for interfacing to a computer. This permits use of the mag design for more accurate mapping with appropriate software. The analog output of the DAC also has convenient solder pads for driving another analog indicator but it is important to use a high input impedance buffer for this signal as any current drawn from this node will get applied directly to the VCO capacitor and cause large frequency errors.

The Motorola MC34119 was used for the audio amplifier and is the amp supplied by Fat Quarters. This device is a little difficult to find so the PC board has been laid out to accommodate the more popular (and slightly higher power) LM386. Figure 14 shows the schematic for this as well as the parts placement. Note that you need to clip pin 7 off the LM386 and add a ground short for pins 2 and 4 (pads are provided).

The fluxgate sensors are extremely sensitive to magnetic fields and the use of a moving coil speaker caused initial concern. However, I’ve found that the dynamic electromagnetic field of the speaker does not seem to affect the sensors. You may choose to use headphones instead of or in addition to the speaker, or to use a piezo-based audio device or a meter driven from the DAC analog output.

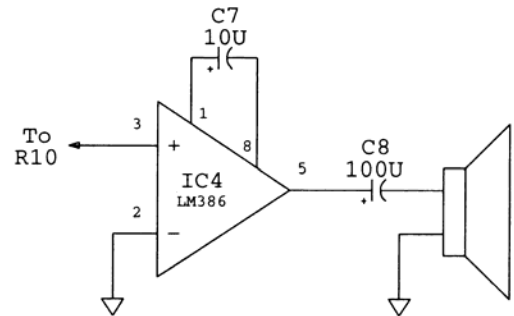


FIGURE 14. Alternate Audio Amp

## Usage

You can carry the mag one of two ways: horizontal or vertical. Vertical orientation seems to be more sensitive while horizontal can allow you to cover more ground by making a wider swath. In the vertical position the sensor with the wires coming out towards the end cap (the adjustable module) is more sensitive and should be the one nearest the ground. When using the mag in the horizontal position, remember that a target signal could be coming from either of the two sensors. You will either have to determine this by moving the mag around, or you can use the sign bit from the SCL007 to drive an LED to distinguish the sensors. With a little practice you should be proficient in no time. The fluxgate mag is extremely easy to use and will make a nice (and inexpensive!) addition to your treasure hunting arsenal.

## Contacts

The fluxgate sensors and gradiometer chip are manufactured by:

Speake & Co. Ltd.  
Elvicta Estate  
Crickhowell, Powys  
NP8 1DF  
United Kingdom

Tel/Fax: 01600 780150 (auto-senses fax)  
Web: <http://www.speakesensors.com>  
Email: [billspeake@btconnect.com](mailto:billspeake@btconnect.com)

Only the sensors and SCL007 are available from Speake, please call for pricing. For all customers in North & South America the distributor for Speake & Co. products is:

Fat Quarters Software  
24774 Shoshonee Dr.  
Murrieta, CA 92562

Tel. (909)698-7950



Web: <http://www.fatquarterssoftware.com>  
Email: [ekern@fatquarterssoftware.com](mailto:ekern@fatquarterssoftware.com)

Fat Quarters has the following items available:

PC board	\$7.75
FGM-3	\$38.50 ea.
SCL007	\$26.75
AD557	\$10.75
Parts Kit	\$12.75

Checks and money orders only, please add \$5.50 priority mail/handling, California residents add 7.75% sales tax. The parts kit contains all PC board components and IC sockets; it does not include the SCL007 and AD557, nor the potentiometers, switch, battery clip, or misc. hardware.

Author's home page is:

<http://www.geotech1.com>

Please check here for the latest version of this article. Other projects are also available and there is a discussion forum to post help questions. Components and boards are not available from the author.