Flux-gate magnetometer sensor plans.

© RHR Laboratories, (905)884-2392, www.rhrlaboratories.com

Welcome to the fascinating endeavor of magnetic field measurements!

You are privileged to have in your possession plans for making very sensitive magnetometer sensors, similar in capability to the ones used in the Pioneer spacecraft, which first mapped out the magnetic fields of our Solar System's outer planets. Many hundreds of hours of engineering time have been expended by *RHR Laboratories* to obtain the special manganese-zinc ferrite material, determine its optimal shape, develop the coil winding configuration, and optimize its operating frequency. The plans described here refer to a particular magnetometer device developed by *RHR Laboratories*, using special ferrite core material; however, you can experiment with other, similar cores, or consult the References for related information. Please be aware that the ferrite material and its shape are crucial to proper magnetometer operation; you can save yourself much development effort by purchasing the required ferrite cores from *RHR Laboratories*.

In addition to measuring weak static magnetic fields, you will be able to intercept ELF (extremely low frequency) electromagnetic waves, both naturally occurring, and man-made. Naturally occurring ELF disturbances are closely correlated to ionospheric activity, and thus to solar flares. An increase in ELF energy has been observed prior to strong earthquakes. The chief man-made ELF source is the ubiquitous 60 Hz power-line signal. ELF waves are quite penetrating, and are not easily blocked by soil, rock, or seawater, and have been used for low data-rate communications in those environments.

Two identical magnetometer sensors are extremely useful in making differential measurements (referred to as gradiometer operation). The basic magnetometer sensor produces a large signal due to the Earth's field, but its absolute magnitude depends on the sensor's orientation in the Earth's field, as well as on its temperature. By making two identical sensors, and mounting them in the same direction some distance apart, you will be able to detect minute differences in magnetic field between the two locations. Since you are using two identical detectors, which are at the same temperature and point in the same direction, you do not need to worry about temperature compensation, or making corrections due to sensor orientation. By walking around with such a two-sensor device, or by trolling it under water, you will be able to detect the presence of magnetic materials when those materials produce a gradient in the local magnetic field.

Pairs of cores can be stacked on top of each other to increase the sensor's sensitivity. The table below summarizes the options open to you for constructing suitable magnetometer sensors.

# of cores used	Typ. Input signal	Typ. output in Earth's field	Typical application	Cp range, Pri. turns	Cs range, Sec. turns
2	10V rms 80 kHz	2.5 V p-p, 160 kHz	Standard flux-gate magnetometer (see Fig. 3). Use two such devices to make a temperature-independent gradiometer.	4,700 - 10,000 pF, 14 turns	220 - 270 pF, 500 turns
4	10V rms 34 kHz	7 V p-p, 68 kHz	More sensitive magnetometer, requires temperature compensation. (see Fig. 4)	5,600 - 47,000 pF, 14 turns	220 - 270 pF, 1000 turns
8	10V rms 22 kHz	12 V p-p, 44 kHz	Super-sensitive magnetometer capable of putting out over ten volts in the Earth's field, and detecting variations on the order of a few parts-per-million.	0.01 µF - 0.1 µF, 9 turns	470 - 820 pF, 1100 turns

Table 1. Summary of flux-gate magnetometer possibilities.

Regardless which magnetometer sensor you choose to construct, you will need a sine- or square-wave signal to excite it, and an oscilloscope to detect the second harmonic of the excitation signal. The second harmonic amplitude is proportional to the instantaneous magnetic field passing through the long axis of the detector. Recommended sensor connection is shown in Figure 1.

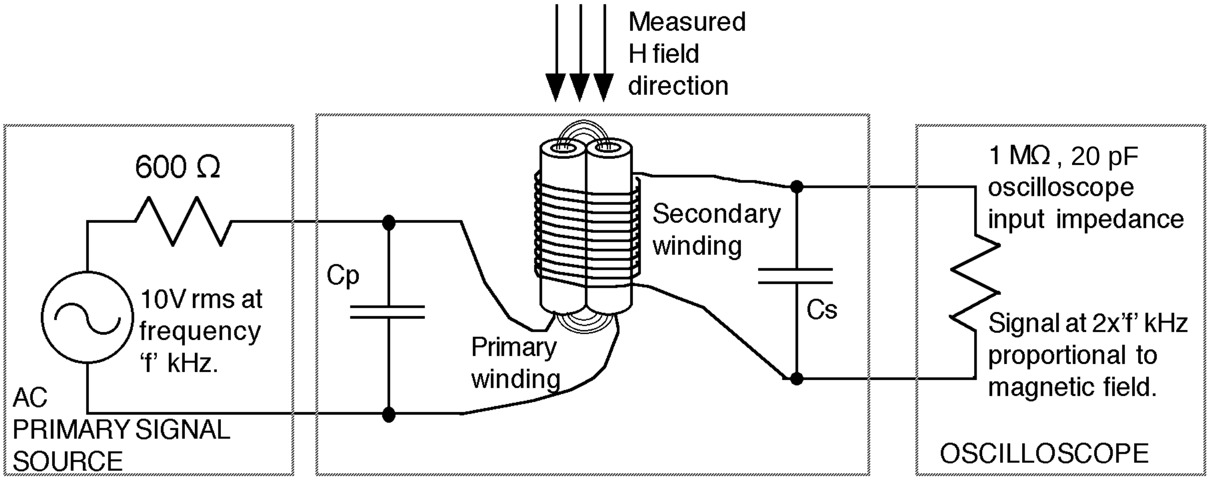


Fig. 1. Recommended flux-gate magnetometer connection.

The primary signal saturates the ferrite cores twice per each AC cycle, since there are two current peaks, one positive and the other one negative. When the cores saturate, their permeability decreases. When core permeability is high, any external ambient field is drawn inside the ferrite material, and when permeability is low, less of the ambient field is drawn inside the ferrite. This action produces changing magnetic flux through the secondary winding, if an external DC, or slowly varying magnetic field is present. Since the magnetic flux due to the ambient H field changes at twice the rate of the primary signal, a voltage at the second harmonic of the primary signal is induced in the secondary winding.

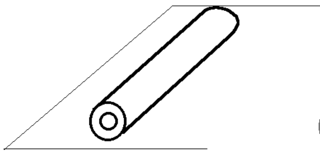
Resonating the secondary winding with a small capacitor at the second harmonic markedly improves the detector's sensitivity. The primary capacitor C_p forces higher saturation current to flow through the primary windings. The exact value of this primary capacitor will depend on the particular generator that you use; the supplied value works well with the Hewlett-Packard HP200CD Widerange Oscillator - feel free to experiment with the value of the primary capacitor. If your signal source cannot produce the required high frequency signal, you can operate the detector at any even sub-harmonic frequency of the secondary resonance, with reduced sensitivity.

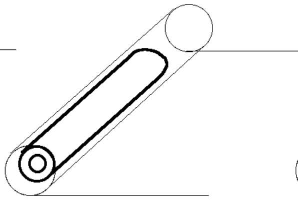
Second harmonic content of the primary signal source must be very low, otherwise it will mask the second harmonic signal produced by any ambient magnetic field. A 50% duty cycle, AC coupled square wave contains no even harmonics, and can therefore be used as the driving signal, if a pure sine wave source of the required amplitude is not available. The sensor is sensitive to direction and polarity, maximum output is obtained when external magnetic field is along the long axis of the ferrite sleeves, and produces no output if external field is perpendicular to it. There is no lower frequency limit and the detector will respond to a DC field as well as to a slowly changing field.

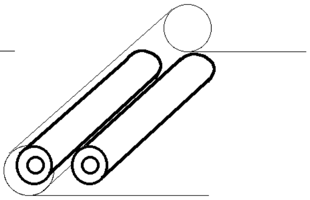
Standard two-core flux-gate magnetometer sensor construction.

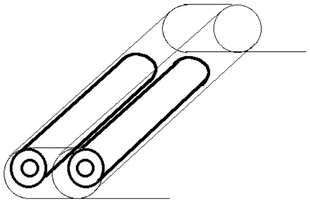
The standard sensor has 14 turns of wire in the primary winding through ferrite core holes, and 500 turns in the secondary wound around outside of ferrite cores, at right angles to the primary winding. Such simple detector construction is allowed by the special ferrite material, which exhibits a large change in its permeability when saturated.

1. The ferrite cores need to be insulated from the secondary winding, and from each other; the best way to do this is to wrap one ferrite core in one turn of insulating tape (ordinary Scotch tape is fine), add the second parallel core, and finish winding the tape around both cores:


Lay one core on sticky
side of Scotch tape.


Wrap one turn of tape
around ferrite core.


Lay second core
parallel to first one.


Wrap tape around
both cores.

2. Trim edges of tape so they protrude about 1/8'' past the edge of the ferrite cores.

3. Use about 2 ft of AWG#38 insulated magnet wire to wind 14 turns of primary winding through both ferrite core holes (see Fig. 2.).

4. Wind 500 turns (about 15 ft length of AWG#38 magnet wire) of secondary winding on the outside of ferrite cores, perpendicular to primary winding direction. Secure end of winding with fast-drying varnish, or nail polish (see Fig. 3). More turns will give you higher sensitivity at a lower operating frequency, but there is a practical limit on how many turns can be wound on the small cores.

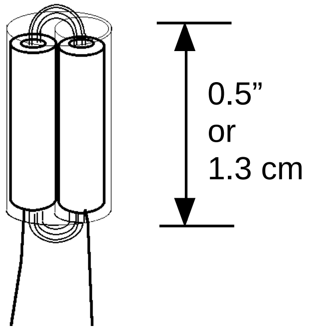
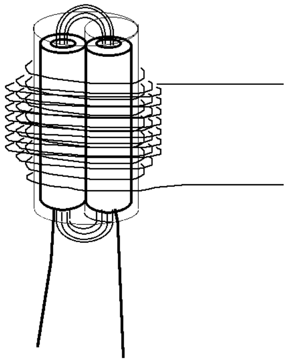


Fig. 2. Primary winding consists of 14 turns of wire through both ferrite core holes.



Outside end of secondary winding is the 'hot' high-impedance node for measurement of second harmonic.

Inside start of the secondary winding should be connected to ground, to provide shielding for the rest of the secondary winding from the high-amplitude primary signal.

Fig. 3. Secondary winding consists of approximately 500 turns of wire around the outside of the ferrite cores.

5. Connect sensor to the test setup as shown in Figure 1; use 6,800 pF capacitor in the primary, and 270 pF capacitor to resonate the secondary. The magnet wire insulation can be removed by heating the wire ends with soldering iron and solder.

6. Vary the AC signal generator frequency around 80 kHz to locate the peak second harmonic signal amplitude using the Earth's field as the test signal (sensor oriented almost perpendicular to ground). Second harmonic amplitude shown on the oscilloscope should be between 2 and 3 V p-p. Wave a permanent magnet near the sensor and verify that signal amplitude on oscilloscope display changes. Point the detector's axis in an East-West direction and observe that the oscilloscope amplitude decreases. Keep in mind that steel objects, instruments, desks and chairs will almost certainly affect the local field direction, and you may encounter locations where the East-West direction may not produce a null in the magnetic field.

Multiple-core flux-gate magnetometer sensor construction.

You can stack pairs of ferrite cores on top of each other to produce longer sensors, with 1,000 or more secondary turns. Use the same construction techniques as outlined above, and select capacitor values from Table 1. Feel free to experiment with capacitor values and operating frequencies. These multiple-core sensors will exhibit amazing sensitivity, but will require more primary energy to saturate the larger volume of ferrite material.

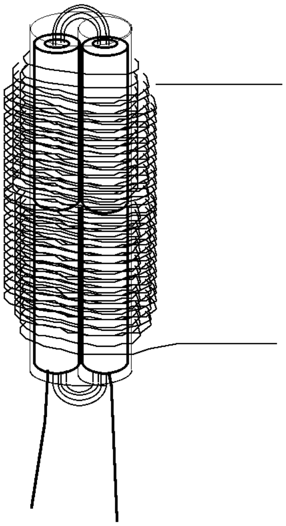


Fig. 4. Four-ferrite stacked construction with 14 primary and 1,000 secondary turns.

General Notes.

General Notes.

Fluxgate sensors are affected by temperature; therefore, they should be operated in a temperature-controlled environment. For sensors which are subjected to temperature changes, proton precession devices are preferred.

The ambient field can be conveniently cancelled by a suitably placed permanent magnet, in order to increase detector sensitivity. The oscilloscope display will then show some leakage signal at the primary, fundamental frequency which is capacitively coupled from the primary winding to the secondary through the high dielectric constant of the ferrite material. This leakage signal can be decreased by slightly moving the primary winding, where it protrudes past the edges of the ferrite. You should be able to null the ambient signal to the level that you can detect amplitude changes on the order of 0.1 mV. Assuming that the detector amplitude is 2 V p-p in the Earth's 0.5 Gauss field, a 0.1 mV change represents 1 part in 20,000, or 50 ppm without any additional amplification.

Instead of using an oscilloscope to detect the second harmonic signal, you could use a low-capacitance Schottky diode rectifier to give you a direct DC voltage proportional to the ambient magnetic field. Local field nulling with a permanent magnet cannot be used with Schottky rectifiers, since the rectifier will not work with AC amplitudes below about 0.5 V.

The detection method which produces the best results is synchronous detection, where a second harmonic signal derived from the primary sine wave is used to demodulate the detector's second harmonic signal. The output of such synchronous demodulator can be further amplified and fed into an audio spectrum analyzer, which will then display the ELF frequency components, with a prominent peak at 60 Hz.

An interesting technique for nulling the ambient field involves feeding a DC current into the secondary winding to produce an equal and opposite cancelling field. However, the secondary winding operates at a very high impedance, and any current source circuitry connected here will compromise the detector sensitivity by lowering the operating impedance. A good compromise is to wind another winding (tertiary) with about 100 times fewer turns than the secondary. Any impedance connected to the tertiary will therefore be multiplied by the square of the (secondary/tertiary) turns ratio, or 10,000 and will therefore be less likely to affect the sensitivity.

As a rough guideline using the standard two-core sensor, you will need about 40 mA of DC current through 10 turns of tertiary winding to cancel the Earth's field. This can be obtained with a supply voltage of about 9 V feeding a 220 Ω resistor in series with the tertiary winding. The effective resistance appearing at the secondary will be $(500/10)^{\wedge 2}$ x 220 = 550 kΩ, which is lower that the normal 1 MΩ, and will cut the detector sensitivity by about 25%. Direct connection of a cancelling current to the secondary would require about 1 mA of current, produced by a resistance of 9 kΩ from a 9 V source. Such a low secondary impedance will make the detector unusable.

Since the tertiary operates at a low impedance, a high inductance choke can also be used in series with the bias resistor to further minimize its effect on secondary impedance.

The Earth's field is about 0.5 Gauss = 50 µTesla = 50,000 γ, and is inclined about 75^{o} down from the horizontal in most of continental US and Canada. There is about 40 γ daily variation in the field's strength. There are additional monthly cycles, disturbances due to Solar flares, ocean and air tides, and there may be some correlation to weather. The Earth's field drifts westward by about 90^{o} of longitude per 400 years, and its magnitude decreases by 5% per century. This means that the Earth's magnetic field is about half of what it was during the Roman Empire times, and some early Chinese compasses no longer work due to the weaker field. It may very well be that in a few hundred years, the weakening magnetic field will present a threat to human survival, as charged particles in the solar wind and cosmic rays will no longer be deflected by the Earth's magnetic field and may present an increasing radiation and environmental threat to all life on the surface.

Scientifically feasible applications of flux-gate magnetometers:

1. Electronic compass – you need three sensors for the three axes of a true vector field indication.
2. Measure currents without direct contact, and without breaking the circuit.
3. Measure variations in Earth's field, with possible correlation to earthquake prediction, or correlation to other as yet unknown phenomena.

4. Detect iron, nickel, cobalt and gadolinium ore bodies, and their companion minerals.
5. Detect ferromagnetic metals, objects, property line markers by means of a gradiometer device.
6. Measure magnetization direction of rock samples and archeological artifacts.
7. Detect ELF waves, set up ELF communication link.
8. Measure strengths of permanent magnets, magnetization of compass needles, etc.
9. Measure ground currents induced by ionosphere, by distant thunderstorms, etc.
10. Determine if a concealed or inaccessible power line is ‘live’ and carries current.
11. Measure CRT magnetic emissions.
12. Detect proximity of steel objects, such as cars, weapons, ships.
13. Set up a security scheme based on the magnetization of a concealed magnetic strip, similar to the ways some libraries place magnetic tape in books’ spines.
14. Space and planetary magnetic field measurements.

Applications which are not feasible with flux-gates, but have been attempted:

1. Analysis of brain-wave patterns. The resolution of a two-core magnetometer is about 5 nT, while the brain generates 2 fT fields (2.5 million times smaller).
2. Determination of biological attributes, such as sex of birds.
3. Location of underground water sources.
4. Detection of distant airplanes and UFO’s.

References:

1. *Scientific American*, “The Evolution of the Earth’s Magnetic Field”, Dec./89, p.68,”Broadcast Warning: Did Radio Waves Portend the Loma Prieta Quake?”, Mar./90, p. 27, “Contented Cows?”, Sept./93, p. 147, “SQUIDS”, Aug./94, p.46, “Building World-Record Magnets”, Jun./95, p. 58.
2. *McGraw Hill Encyclopedia of Science & Technology*, McGraw-Hill, New York, 1987, 6th edition, “Magnetometers”, “Geomagnetism”.
3. Lerner, R. G., G. L. Trigg, editors, *Encyclopedia of Physics*, VCH publishers, Inc., 2nd ed., New York, 1991, p. 439, “Geophysics”.
4. Acuna, M. H., “Fluxgate Magnetometers for Outer Planets Exploration”, *IEEE Trans. on Mag.*, Sept. 1974, p. 524.
5. Gordon, D. I., “Recent Advances in Fluxgate Magnetometry”, *IEEE Trans. on Mag.*, Mar. 1972, p. 76.
6. Marshall, S. V., “An Analytic Model for the Fluxgate Magnetometer”, *IEEE Trans. on Mag.*, Sept. 1967, p. 459.
7. Kraus & Carver, *Electromagnetics* , McGraw-Hill, p.148.

Common questions and answers:

Q. Given the magnetometer’s excellent sensitivity, why can’t I detect a car passing down the street 100 ft away?
A. Magnetic field is always a dipole field (it always has a North and a South pole). This means that the magnetic field strength of a magnet decreases as $1/d^3$ in the North/South direction, and as $1/d^2$ perpendicular to the North/South direction (‘d’ is the distance from the magnet). This means that the field decreases with distance very rapidly - much faster than the electric field from a charged object, for example. Cars, which are not usually fully magnetized, can be detected at close distances because they tend to influence the ambient field’s direction and magnitude. Such passive influence decreases with increasing distance even faster than $1/d^3$.

Q. My sensor’s second harmonic output is lower than numbers shown in Table 1. Why?
A. The numbers supplied in Table 1 apply when using a signal generator with 600 Ω output impedance, when the detector is pointed in the direction of a local maximum of the Earth’s field. If your generator’s impedance is different from this, the detector’s sensitivity will be affected. Try changing the primary circuit capacitor value, or use an inductor in series with the generator’s output to increase its impedance. Another, less common, cause of a low reading is a cracked ferrite core; any air gap in the magnetic path will prevent the ferrite from saturating. You could also be inside a structure which shields, or opposes the Earth’s magnetic field - this is highly unlikely but theoretically possible.

Q. Why is there is no second harmonic output when I build the sensor?
A. Your magnetometer could be oriented in a direction where there is no magnetic field. Try re-orienting it by 90

degrees to get away from a null direction. Your primary and secondary windings could also be mis-wired. Check the resistance of each winding with an ohmmeter. The primary resistance should be very low, near 1.1 Ω, while the secondary resistance should be about 16 Ω. An open-circuit indication could mean that you crossed the connections, or that the wire varnish covering has not been sufficiently removed by heat to form a good electrical contact.

Q. I noticed that any metal object will affect the detector's reading when brought really close to it. Does this mean that all metals are somewhat magnetic?
A. No. Metal objects placed very close to the magnetometer will shift the secondary's resonant frequency, so what you are observing is a shift in operating frequency, rather than a changed level of second harmonic signal. Keep all objects further than two inches from the detector to avoid detuning the secondary resonant circuit.

Q. My detector does not show a null no matter in which direction I point it. Why?
A. The most common reason is that your signal generator is putting out a distorted waveform, containing second harmonic, which is then picked up by the secondary even in the absence of magnetic field reading. Another reason could be that the ferrite material in your detector has become permanently magnetized and your input signal amplitude is insufficient to saturate it. You should be able to demagnetize the ferrite by slowly decreasing the frequency and amplitude of the input signal source down to as low as your signal generator can go.

Q. Is there a natural limit to any magnetic field's value?
A. While there is a limit to the magnetic field strength that you can measure with your magnetometer, this is due entirely to the sensor's construction. Magnetic field is the only energy field in nature that does not seem to have an upper limit to its value. Large electric fields cause breakdown and arcing; large gravitational fields cause space to collapse into a black hole; no corresponding phenomenon has been predicted or observed for strong magnetic fields, such as are observed near neutron stars or near huge currents in the laboratory. If you wish to store arbitrarily large amounts of energy, magnetic field seems to be the best choice; this capability is exploited by proposed superconducting energy-storage rings and by high velocity electromagnetic railguns.

We would like to hear from you, if you find a novel application for flux-gate magnetometers, or if you can break our record for flux-gate magnetometer sensitivity which currently stands at 160 V p-p in the Earth's field obtained from an 8-core detector operating at 22 kHz and loaded by 10 MΩ secondary impedance, with no additional amplification.

RHR Laboratories offers special hollow ferrite cores suitable for constructing fluxgate magnetometers described in these plans. The cores are about 0.5" long with 0.06" diameter (13 x 1.5 mm). Five cores are supplied, together with a gradiometer schematic.

RHR Laboratories
207 Harding Blvd. W.
Richmond Hill, ON L4C 8X6
Canada

tel. 905-884-2392
fax. 905-884-6843
104673.3110@compuserve.com
www.rhrlaboratories.com

Items	US $	CDN $
Five special manganese-zinc ferrite cores + + Gradiometer schematic and parts list	30.00	45.00

Please phone (905) 884-2392, or fax your VISA number, expiry date, name on card, and your mailing address to (905) 884-6843; do not send VISA number by e-mail.

Shipping by regular mail included for continental US & Canada. Payment by VISA or cheque. VISA credit card purchases are billed in equivalent Canadian currency. Please allow two weeks for delivery.