Practical Guidelines for building a Magnetometer by Hobbyists

Part1 : Introduction to Magnetometer Technology

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Version 1.2

22 June 2008

1. Foreword

The concepts and facts described in this paper are not new and they are probably quite obvious to specialists in geomagnetism. However, they were quite mysterious for the standard hobbyist like myself.

This description tries to demystify some of these, making the difference between the critical working conditions and the auxiliary aspects only subject to some optimization.
It should be taken by the reader as MY current understanding of the most important concepts required for the building of a magnetometer. I am quite sure that I missed some points and that I even misunderstood others. In advance, I apologize for any possible incoherence or misunderstanding and I am completely open to any remarks and comments from knowledgeable people.
This was the result of reading a lot of papers on the Web (the best and the most accurate being the paper of **James Koehler** available here) and numerous experiments that I have done in the last months but also a lot of precious information from my temporary or permanent project team members, more specially:

- My French friend **Philippe Marie** with whom I designed and implemented an all-digital PI metal detector with discrimination properties.
- **Steve Brekke**, my best Californian partner who designed our current PPM amplifier chain and guided me on the routes of FFT calculation.
- **Joe Geller**, my occasional partner near Albany,NY with whom I exchanged very interesting messages comparing his design with ours.
- **John Oldham,** a precious Canadian partner with a long experience and actual practice of magnetometers in the field (the sea). He has given me so much good advice during my long period of unsuccessful testing, when the damned precession signal was not showing up.
- **Carl Moreland,** our well-known mag technical site and forum hosting partner who has gathered so many pieces of data giving so many people a playground around which to share their experiences (good and bad) on the technical aspects of all kinds of treasure hunting.

The version 1.2 of this document reports the result of the experience acquired during the last two years on this subject.
I want to specially add my thanks to:

- **James Koehler,** my best Canadian partner and now friend with whom I spent the last two years improving our PPM project putting our two long past experiences in common for the sake of this hobby project.
- **Paul Cordes,** my second partner working with me on an alternative PPM instrument implementation selecting different hardware and software solutions. See more about that in Part 3 of the whole document.

In advance, I am grateful to those who will accept to proofread this paper and remove its most visible conceptual and syntactical bugs.

2. *Introduction to the Magnetic World*

The Earth's magnetic field can be thought of as having three components:

- down in the direction of gravity
- to true North (not magnetic North)
- and an East-West component at right angles to true North

The East - West component causes what is called 'declination', or the compass pointing to "magnetic north" instead of "true North". The true North component is in the horizontal plane, but the down component is much stronger than the North component!. If a compass is not level then it will have a large error because it is starting to read the down component of the Earth's field. That's the reason why conventional compasses should always be kept perfectly level.
The **total value** of the vector resulting from these three components depends on the geographical location with its maximum values around the two Poles and minimum values along the Equator - look at figure 4 on page 9 of the ***ampm-opt.pdf*** document.
The **direction** of this total vector is North-South with an '**inclination'** from the horizontal also depending only on the location on Earth (50° to 70° North in Europe and Northern America but 0° on the Equator) - look at figure 3 on page 8 of the ***ampm-opt.pdf*** document.

If you want to see the nominal value of the earth magnetic field in your region, go first on this link:
How to Get Your Local Field Value.pdf

Other sources of earth magnetic field modeling are the following:
http://geomag.usgs.gov/geomag/geomagAWT.html
http://www.ngdc.noaa.gov/seg/geomag/data.shtml
http://www.ngdc.noaa.gov/seg/geomag/jsp/IGRFGrid.jsp

Some underground or underwater objects or structures with permanent or thermo-remanent magnetism are able to **locally** change these average value and direction. If you bury a permanent magnet and you measure the earth magnetic field over and around it, you will find that the field greatly concentrates in its immediate vicinity. Actually, any ferromagnetic object or matter will produce the same effects as well but with much less magnitude than a magnet.
Magnetometers are all measuring the natural or human-made disturbances of the earth magnetic field. These disturbances are called 'magnetic anomalies'.

Important Note:
There is some confusion in the literature over physical units used in magnetism. SI units are now the preferred units over the older CGS. In the older CGS system (still very much in use in USA), the ***magnetic flux density*** *was expressed in GAUSS (G) while in SI system, it is expressed in Tesla (T) or, more practically, in nanoTesla (nT = 10^{-9}T) with the following relation between the two:*

1 Gauss = 0.0001 Telsa or 1 Gauss = 100,000 nT.

As an approximate reference, the nominal earth magnetic field is on average around 0.5 Gauss or 50,000 nT (while a small modern permanent magnet can easily give 3000 Gauss!!) with its maximum values around the two Poles (70,000 nT) and minimum values along the Equator (25,000 nT).

Actually, the important measurement units in geophysics applications are **Field Gradients** expressed in nT/meter. This is the variation of the absolute or vertical field value measured between two points distant of one meter. Magnetic anomalies are detected by the value of the field gradient they produce when surveying around and above them; higher the gradient, bigger the anomaly. It also means that small anomalies require very sensitive instruments and also a large number of measurements close to each other. There is absolutely no chance to detect an anomaly of 1nT with an instrument whose sensitivity or resolution would be 10nT and an anomaly or object with a dimension of 10cmx10cm will probably be missed with a 5mx5m search grid.

3. What magnetometers are used for and by whom

- The largest **natural** **time-dependent** magnetic anomalies are produced by magnetic storms produced themselves by variations of the solar wind. A magnetic storm is a perturbation of the Earth's magnetic field, caused by solar disturbances, usually lasting for a brief period (several days) and characterized by large deviations from the usual value of at least one component of the field. They can be predicted at FIXED meteorological stations by measuring the trends of the absolute values of the earth magnetic field. The Dst is a geomagnetic index that monitors the worldwide magnetic storm level. It is constructed by averaging the horizontal component of the geomagnetic field from mid-latitude and equatorial magnetograms measured by meteorological stations from all over the world. Negative Dst values indicate a magnetic storm is in progress, the more negative Dst is the more intense the magnetic storm. One of the main practical applications of these measurements is the prediction of near future radio-communication problems as magnetic storms disturb the ionosphere, but some powerful magnetic storms have also disturbed the electrical power grid in some countries. Outside of magnetic storms, there are other **natural time-dependent** slight and slow variations of the magnetic field, they are called **'diurnal' variations** while smaller and quicker variations are called **'micro' variations**. That's the reason why the measurement of the space-dependent TOTAL magnetic field (or one of its vertical or horizontal vector) is not sufficient to make actual field surveys (See later on the chapter on PPM System Configurations)

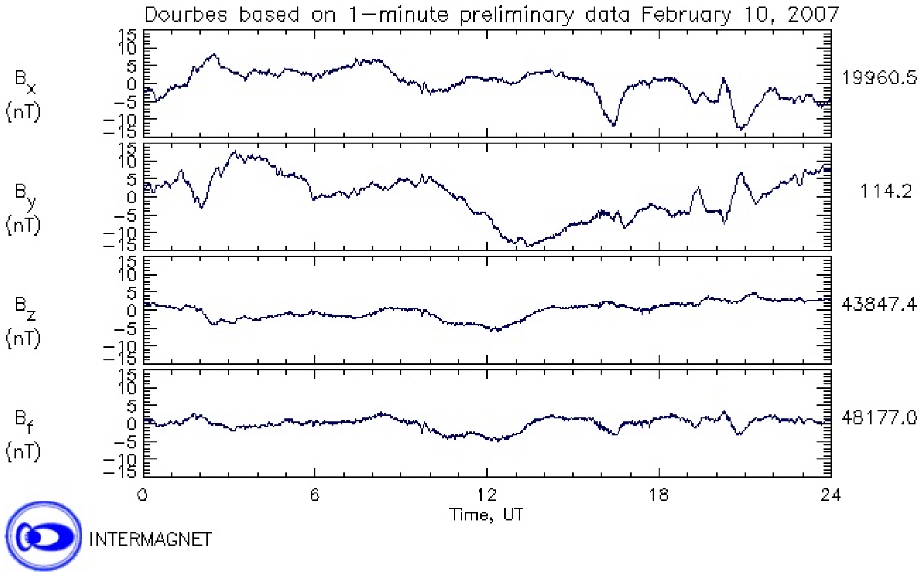
  This is a very good introduction of all these concepts:

  http://geomag.usgs.gov/intro.php

  This is a source of real magnetogram samples:

  http://www.intermagnet.org/apps/dataplot_e.php?plot_type=b_plot

  This is the plots you can get from there from any **Intermagnet** Observatory in the world. These are from the DOURBES node in Belgium.



- **Natural** **space-dependent** magnetic anomalies are caused by the juxtaposition of soils and stones with highly contrasting magnetic properties produced by earlier volcanic activities. These characteristic features are detected by geologists to find specific underground or underwater minerals or metals (even gold since gold deposits are usually accompanied with "black sand"-magnetite deposits) or, in petrology to locate gas or oil pockets kept within porous stones.
- **Artificial (man-made)** magnetic anomalies are generated by:
  - Buried or sunken objects containing a large proportion of ferromagnetic metal (iron or steel)
  - Soil disturbances like filling holes with a soil of different magnetic characteristics than the local ground or unfilled holes like tombs or wells.
  - Burned features like fire pits, baked clay objects, ashes…
  - Permanent magnets buried specially to be easily located later on by geologists or archaeologists.

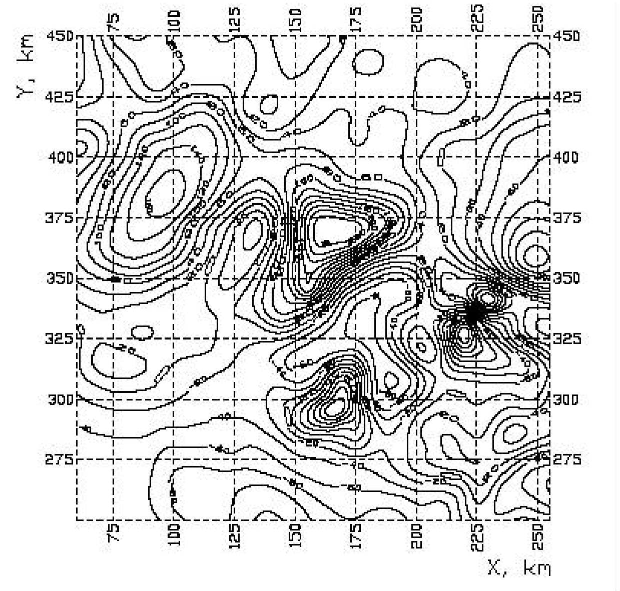
- Currents circulating in the ground generate powerful and fast varying anomalies. These currents are generated by powerful electrical activities like railways or power stations. These anomalies can be felt kilometers away from any railway or power lines.

Thus, magnetometers are useful to:

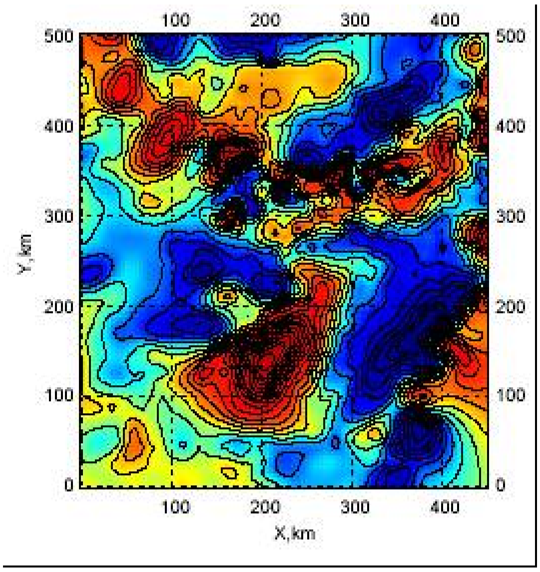
- Public Works to locate pipelines or the steel bars of concrete foundations
- Geologists to locate coal, water, minerals, gold, oil and gas
- Environmentalists to find buried barrels of dangerous or polluted products
- Archaeological Research to locate :
  - old wall foundations,
  - refilled wells
  - tombs
  - old paths
  - Pits
  - Hearths
  - kilns & furnaces
  - Cooking sites
  - Midden deposits
  - Ditched enclosures
  - Trackway
- Military and Humanitarian deminers to locate and destroy UXO (bombs, mines, grenades)
- Sunken Ship Seekers to find cannons, anchors which help to locate the ship remains themselves
- Treasure Hunters looking for iron-made containers (box or case) of precious material
- Relic Hunters looking for old man-made iron objects

*In **summary**, magnetometers are able to detect the presence of Ferro-Magnetic material (Iron, Steel, Cobalt, Nickel, Magnetite,…) because they disturb the value and direction of the earth magnetic field.*
However, magnetometers are COMPLETELY insensible to any other metals, they can not be used as metal detectors even if they are sometimes used as complements in the research of targets.

*Magnetometers also can not easily detect deeply buried (or sunken) small objects except with a highly sophisticated instrument. Look at the figure 46, page 43 of the **ampm-opt.pdf** document, it shows that 1 pound of pure iron (not exactly a small object, equivalent to an ordinary hammer head) could be detected at 3 meters BUT would only generate a field gradient of 1nT. If you only own a mag with a sensitivity of 10 to 25nT (typical of fluxgate and differential mags), then the same mass of iron could only be detected at 1 meter or less IF and only IF your line of survey passes right above it. It is useful to remember that the field produced by a given magnetic moment falls off as the inverse cube of the distance, not the inverse square.*



Y, km
X, km
75 100 125 150 175 200 225 250
275 300 325 350 375 400 425 450



Y,km
X,km
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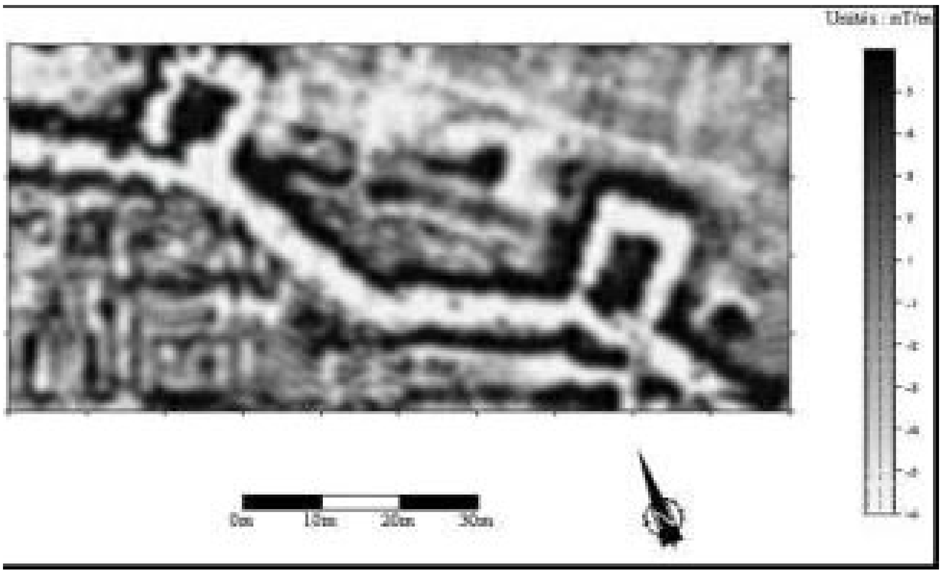
0 100 200 300 400 500



Units : nT/m
0m 10m 20m 30m

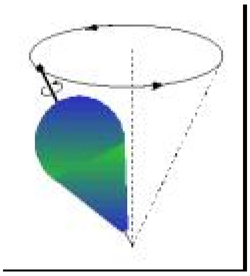
4. Types of magnetometers

There are now a number of types of portable magnetometers based on different physical principles:

- Instruments based on **Magneto resistive** and **Hall effect** sensors are not used to measure the earth magnetic field even if they are sensitive to the value of magnetic fields. They are used in the industry to detect ferromagnetic objects at short distances or to measure higher magnetic fields. We shall not go in more details about them here.
- The **'fluxgate'** sensor has a special magnetic core (high-Mu material) being saturated within the magnetic field to measure a single axis vector of this field. The basic principle is to compare the drive-coil current needed to saturate the core in one direction as opposed to the opposite direction. The difference is due to the external field. Full saturation is not necessary; any non-linearity will do. As the core approaches saturation, the signal picked up in the sense coil will show the non-linearity. Flux-gate magnetometers are widely used in geophysical research to monitor the earth's magnetic field at observatories located throughout the world. At each observatory, three separate flux-gate magnetometers are used; one oriented in each of three orthogonal directions. For amateurs, there are single flux-gate magnetometers commercially available; the most common of these are manufactured in England and which have an output in the form of a frequency-modulated waveform; the output frequency is proportional to the magnitude of the component of the earth's magnetic field which is parallel to the sensor. Amateur magnetometers built using these elements usually are built in the 'Gradiometer' Configuration to measure Vertical Field Gradients. In actual practice, they can detect field gradients of no better than about 100nT.
- The standard **'Proton Precession'** magnetometer is to be discussed in more details in the following chapters. In short, the protons of a proton-rich fluid are magnetized to align in the same direction and stop their normal precession. When they are released, they resume their precession in phase and induce a voltage at a frequency depending upon the ambient magnetic field. This frequency is measured and the corresponding field value is calculated. This type of mag can give sensitivities better than 1 nT with a relatively low sampling rate of 1 measurement every 1 to 3 seconds.
- An **Overhauser** PPM uses a proton-rich fluid mixed with a very small quantity of a special chemical component containing free radicals. A constant magnetic field of RF frequency (around 60MHz) is applied on the fluid. This produces what is called the 'Overhauser effect' providing the same polarization effect from a polarizing field much smaller than in standard PPM and in much less time. The net effect is that Overhauser mags take 4 times less power consumption than normal PPM's and can give up to 100 times better signals and faster sampling rates (more than two measurements per second).
- Cesium is the most widely available **optically pumped alkali vapor** magnetometer. It can give sensitivities better than 0.1 nT with a very fast sampling rate but this technology remains completely out of reach from standard hobbyists for its complexity and the cost of required special material and professional adjustment instruments.

*In summary, the types of mags that can practically be built by hobbyists are essentially the **Fluxgate** and the **PPM**.*

5. Basic physical principles used by a PPM



Normally, proton particles contained in fluids turn around their main axis but this axis also oscillates at a slower precession speed (a spinning top shows this very clearly) whose value uniquely depends on the value of the ambient magnetic field. In a normal status, the precession movement is not synchronized between protons and thus has a canceling effect.

A sensor filled with a proton-rich fluid is placed in a coil at right angles to the ambient magnetic field and a strong current energizes the coil, creating a strong magnetic field - the so-called **polarization field**, which orients all the protons of the fluid in the same direction and stops their precession. When the polarization current is sharply ended, all the protons resume their normal precession but now, IN PHASE and thus, the accumulated action of all these very small magnets induces a VERY SMALL (at the μVolt RMS level) Audio Frequency Sine Wave signal in a signal pick-up coil (which could be the same as the polarization coil). This sine wave signal has a frequency depending ONLY on the TOTAL value of the local magnetic field vector and lasts a few seconds (the relaxation time) during which the precession of the protons still stays in phase. This frequency is called the **'Larmor' frequency**. This voltage is amplified and its frequency precisely measured to determine the ambient field strength.
The exact relationship between ambient magnetic field (B in nT) and Larmor frequency (f) is the following:

```
B = f * 100,000 * 2 * PI / 26751.2 or B = f * 23.4875
f = B * 0,04256
```

For example, for an average ambient field of 50,000nT, f will then be 2.128 KHz

From the above relation, it is quite obvious that a difference of 1 Hz in frequency corresponds to a bit more than 23 nT. If a system should be built with a resolution of 1nT, then the Larmor frequency should be evaluated with at least an accuracy of 1 part in 50,000 or approximately, a precision of 0.01 Hz to have any chance to be successful. Moreover, depending on the proton-rich fluid that has been used in the sensor, the duration of this signal with sufficient RMS amplitude will only be from 1 to 5 seconds as it exponentially decays. Thus, the frequency evaluation must be made as soon as possible after the polarization cut-off to get its maximum amplitude (and maximum SNR). However, this RMS voltage will not exceed a value in the order of 1μV. Its value will mostly depend on the fluid being used, on the polarization current and on the inductance of the signal pick-up coil.
There is a long list of proton-rich fluids that can be used in PPM sensors but, in practice, some liquids are usually rejected because they are potentially dangerous to manipulate. The most usual liquids being used by hobbyists are:

- Simple **distilled or de-mineralized water** (better boiled to remove dissolved oxygen→ longer relaxation time) giving a comfortable relaxation time of 3 seconds but subject to freezing.
- **Methyl, Ethyl Alcohol, Kerosene** (lamp or stove oil), **Diesel Fuel** or **charcoal lighter fluid** with a shorter polarization and relaxation periods of 0.5 second but not subject to freezing
- **Automotive windshield washer fluids**
- **Benzene** with a longer relaxation time of 4 to 5 seconds but rather difficult to find by non-professionals.

You can see here the exponential decay of the magnitude of a typical PPM signal generated after its polarization current has been cut off. Listen to it here.
This is its equivalent frequency spectrum (FFT) with its **high and very narrow peak** showing that it is a pure sine wave with some background noise. Its **Signal-To-Noise Ratio (SNR)** is around 35dB at 2KHz, this is not too good but, if we remove a good amount of this noise from the raw signal (with analogue or digital filtering) , we get this FFT result. As you see, the Signal-To-Noise Ratio (SNR) jumped up to 90dB. Now, listen to it here and hear the difference.
The magnitude of this signal was rather low but with a higher gain amplifier, this is what the digital filtering should give as result.

6. *System configurations of PPM's*

- A **single sensor PPM** measures the total ambient earth magnetic field value and displays and/or logs it in units of nanoTesla. This simple configuration is being used in fixed geomagnetic stations spread all over the world as a network.

- A PPM to be used for field surveys must be built with portable power supply and it must be as light as possible to be easily carried. As already explained, the detection of magnetic anomalies is based on the measurement of field gradients and not of total field values. Thus, using a single sensor PPM would theoretically and simply mean to subtract total field values taken consecutively at survey grid distance to get the required field gradient values. This simple method could indeed be used for surveying small area, provided that the consecutive measurements are made very close to each other in time. Why is that? Remember that the total earth magnetic field value slowly changes during the day (diurnal variations). (Note that anyway, during periods of magnetic storm, it is better to stay at home.)

  If the required precision of the results is not too high (e.g. during a first overview survey of a large area), these variations would not influence the interpretation too much; otherwise, they will disturb the gradient values over the whole length of the survey line.

  One possible solution to this problem is to take two measurements at each crossing point of the survey grid, one high above the ground (e.g. 3 meters high) and the next, immediately after, closer to ground (e.g. 1 meter high). The difference of distance of 2 meters will be sufficient to produce a field gradient if a magnetic anomaly is produced under this point. It is clear that this method is only valid for ground surveys and cannot be applied for underwater search.
  Important Note: *Never make measurements with the sensor(s) lower than 0.5 meter from the ground. The best results would be that your values would be too much influenced by very small ferro-magnetic particles at the surface and the worst would be that your signal would completely disappear.*

- A **'Differential' PPM** uses two sensors mounted on the two extremities of a long staff and connected in series to a single amplifier chain. The signals of the two sensors add together, are amplified and feed headphones. If the area being tested has a constant magnetic field, the precession frequency induced in both sensors is the same and the operator hears a gradually decreasing in amplitude but steady tone which disappears within the relaxation time. In the presence of an anomaly, however, the magnetic field at each sensor is not the same and signals of different frequency are produced. As these signals are added together, they interfere to produce a wavering tone, increasing and decreasing in amplitude until it finally dies out. This is an amplitude beat whose frequency depends on the field gradient between the two sensors; the more beats are heard per unit of time, the stronger is the magnetic anomaly causing them. This configuration is the simplest and lowest cost you can find but, because the measurements are non-quantitative and because the human ears are used as tone amplitude measuring devices, it is also quite crude in sensitivity. You could not expect this configuration to detect any anomalies creating gradients much lower than 25nT. Why is that? Because the imperfect human ears are good at detecting tiny changes of frequencies but are very bad at detecting amplitude changes (That's the main reason why the vertical scale of Audio Spectrum Diagrams is logarithmic = dB).
  This is an example of signal going out of such a configuration. It is the signal sample posted by Phil Barnes on his web site. It gives a beat of around 3 Hz corresponding to a gradient of about 70nT. phil barnes.wav. As you can see on this PCM stream picture, the magnitude of the signal shows some clear beats for about 1 second.
  This FFT curve of the same second of signal duration shows a large and relatively wide peak at around 2KHz.

- The best configuration used by professionals to survey large area with great precision is made of **two complete and identical magnetometers**:
  - One is put on a **local recording base station**, i.e., diurnal station monitor, near but outside the surveyed area. This mag records, with precise time stamps, the total earth field values, including its diurnal variations, during all the duration of the survey.
  - The second one is the **mobile station** making the real measurement on the crossings of the survey grid and recording them with time stamps as well.

  At the end of the survey, the two data stream are merged based on the time stamps and the field values captured at the fixed station are subtracted from the raw measurement values captured at the same time, thus canceling the bad effect of the time-dependent variations of field. The net result is a

3-D map of field values of the surveyed ground relative to the field value of the fixed station. Note that these values are NOT gradients.
To show the difference, take for example a rectangular anomaly crossed by a survey line.

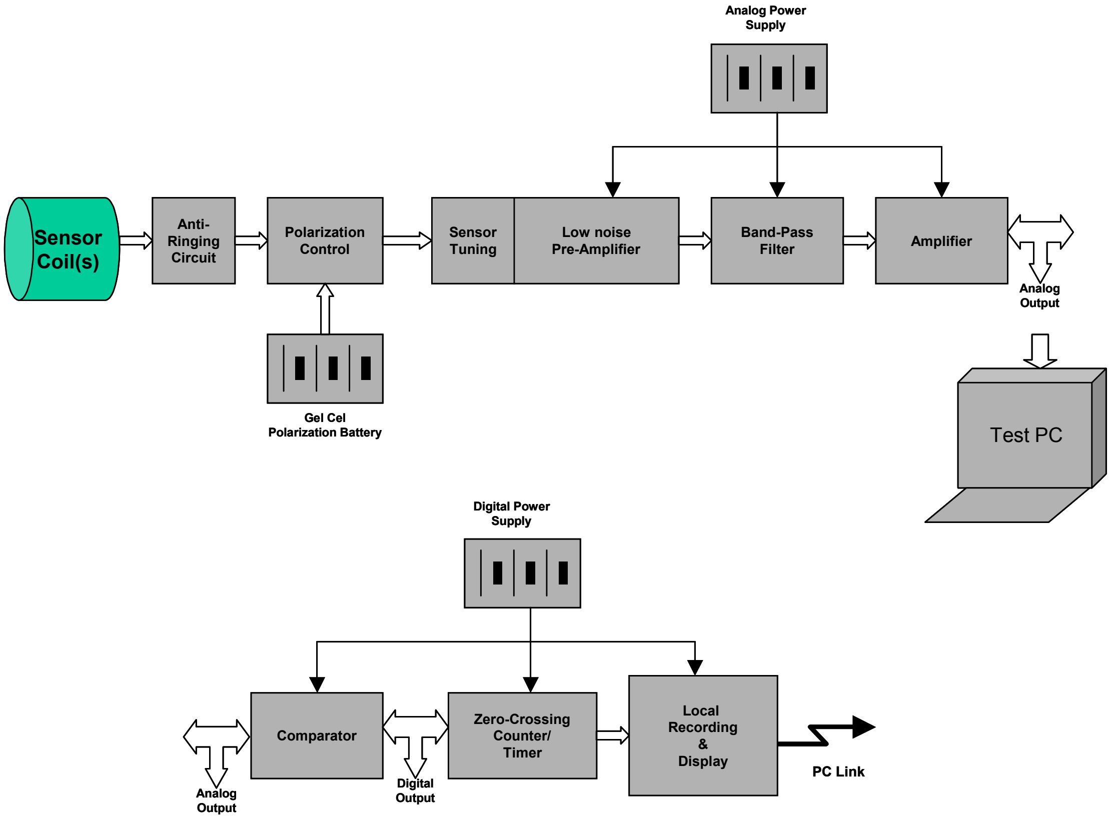
- In this configuration, when crossing over one limit of the anomaly, the values will change of level up or down depending on the kind of anomaly and will stay at this level until the survey operator crosses the other limit of the anomaly.
- In a gradient measurement configuration, you will detect a positive peak of gradient when passing over and another negative peak when leaving the surface. The gradient data displayed as a 3-D map needs more experience to be interpreted than the first. (See more details in the ampm-opt document)

A ‘slightly’ more sophisticated configuration uses a **simplex radio data link** to communicate between the two mags in real time. This avoids the final post-processing and allows verifying the quality level (unexpected level of noise or possible operating errors) of the measurements while they are made.

1. A special gradient measurement configuration is called a ‘**Gradiometer’**. It is also made of **two identical magnetometers** whose sensors are attached to each extremity of a long staff usually held in a vertical position by a survey operator. In this configuration, the polarization and signal pick-up cycles are synchronized on the two mags but the resulting signals coming from the two sensors are kept in separate amplifier chains and frequency evaluation processes. The two total field values are then subtracted to get a net and clean gradient value representing, without any time-dependency, the difference of earth magnetic field as sensed by the two sensors, one closer to ground and the other farther by 1 to 3 meters.

*In summary, all system configurations (except the differential mag which only requires a single amplifier chain) require **two complete and identical magnetometer** systems to be built. However, one of those is enough to start the testing and experimentation of the amplifier, the polarization control and various types of sensors.*

7. *Functional Blocks of a typical PPM*



Basic Proton Magnetometer Modules

2. The **Polarization Control** module switches the polarization battery to feed the sensor(s) with a large DC current, then switches off this current as fast as possible. An adjustable automatic timing mechanism can trigger the switching durations or the program of a micro-controller or a PC can control them.
3. The **Anti-Ringing circuit** absorbs the ringing produced by the large inductance of the sensor coil(s) before the polarization control connects the sensor to the pre-amplifier for the signal pick-up phase.
4. The **Sensor Tuning Capacitors** are put in circuit after the polarization cycle and during the signal pick-up phase**.** They are carefully adjusted to tune the sensor coil at the nominal precession frequency of the local region and thus, act as a supplementary signal amplifier as well as a filter of unwanted frequencies.
5. The **Low-Noise Pre-Amplifier Stage** is a very critical part of the system. It has to increase the µV level signal magnitude up to the mV level without introducing any signal distortion nor any internal noise and preferably, without amplifying too much the external electro-magnetic noise naturally picked-up by the coil of the sensor and the various cables and wires.
6. The center frequency of the **Pass-Band Filter** is adjusted to the nominal precession frequency of the local region and its bandwidth set to a few hundreds of Hz around it.
7. The **Amplifier stage** increases the sine wave signal magnitude to the minimum level required by the following signal processing stages.
8. The **analogue Output** gives a sine wave signal sufficient to be studied in details by PC-based Audio Editing and Spectrum analyzing tools through any integrated audio card.
9. As a first simple solution, the sine wave signal is converted into a clean square wave and its signal level adapted to TTL level by a **Comparator stage.**
   A micro-controller **counts a pre-defined number of zero-crossings** of the square wave signal and very precisely **measures the exact time** it takes. This allows calculating its precise periodicity and thus, its frequency. The frequency is then converted in magnetic field value (expressed in nT units) by a simple multiplication by a constant value.
10. The signal processing method described in 9. is rather simple to implement but it is very sensitive to noise, more specially to spikes. A single missing or extra period changes the result by 1/n with n being the total periods used to make the measurement. For example, if one uses 256 periods, 4% is lost for reach missing or extra period. As a more sophisticated solution giving much more protection

against noise, we have experimented a so-called ‘Phase Shift’ algorithm. The principles of this method will be described later but the tests made up to now show that this method is immune against a low SNR.

11. The current magnetic field value is **shown** in real-time on a local display and appended to a vector of values in local memory.
12. A serial line allows the **downloading** of the vector of measurements to a PC for further study, analysis and plotting.

8. *Sensor Types*

8.1. Single Solenoid Coil

This is the simplest sensor type and the easiest to build by Hobbyists even if it is also the one picking up most of the electromagnetic noise around except if it is shielded inside a large box.
A cylindrical form is selected with a inside diameter fitting a small non-magnetic recipient like a glass or polythene bottle containing a proton-rich fluid.
A relatively thick magnet wire is wound on this form. The wire diameter and the number of turns are not very critical, usually around **1500 to 2000 turns of wire AWG 16 to 22**. The DC resistance should preferably be kept under **10 ohms** to get a DC polarization current of more than **1 Amp from a 12V** gel cell battery. If a higher voltage battery is being used, it is possible to wind the coil with thinner wire. The **Inductance** of the coil should be around **30 to 50 mH**. The **magnetic field** generated in the coil (and on the protons of the fluid) by the polarization should be a minimum of **100 Gauss**.
A Solenoid coil sensor calculator has been written by Jim Koehler and posted by Carl Moreland. It calculates the approximate inductance, resistance and polarization current given the dimensions of the coil, the voltage of the battery and the diameter of the wire. It also evaluates the length of wire to plan. The other calculated parameters of the sensor will be discussed in more details later.

A Solenoid sensor should preferably be positioned **perpendicular** to the local vector of the earth magnetic field. For regions where the inclination of the local field is greater than 45°, the main axis of the sensor should be horizontal while if <45°, it should be held vertical. If the field has a (quasi-) vertical direction, then the horizontal direction of such a sensor is not important but, in equatorial regions, where the earth field is much more horizontal, the sensor should point to the North to get a maximum magnitude of signal.
Note that if a Solenoid coil is positioned in the general direction of the local earth field, the precession signal will be null.

8.1.1. "Fluid inside Coil" Variant

This is the traditional method of polarization, a bottle is inserted inside the coils and its contained fluid is subjected to the powerful field generated by the coil.

8.1.2. "Coil inside Fluid" Variant

This is a more professional version where the coil is wound first around an hollow form and the whole winding is blocked and electrically isolated with epoxy. The final coil is then introduced inside a **bigger container filled with the proton-rich fluid**.
The advantages of such a configuration are:

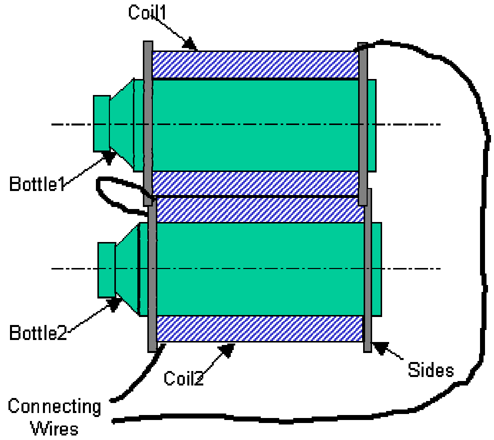
- a better cooling by the fluid itself of the heat generated by the polarization current
- the supplement of protons activated by the polarization field (not only inside the coil but also around it).

Each of the following sensor configurations can also be made in this variant.

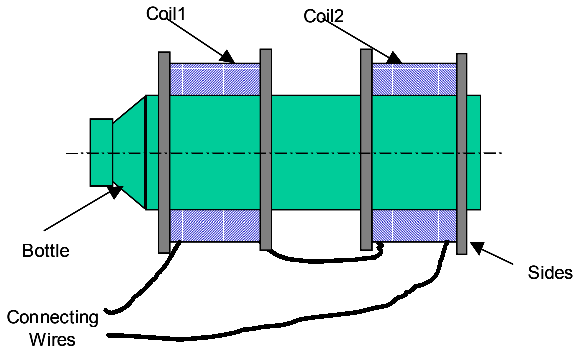
8.2. Double Solenoid Coil

The single Solenoid Coil type of sensor is picking all the electro-magnetic noise around. The very high gain of the amplifier chain of a PPM and its voltage limiting diodes connected to its input makes it a relatively good radio receptor with an antenna made of the sensor coil. A double coil sensor can be built to reduce this noise and produce a **canceling effect on signals coming from the outside of the coil**. There are two possible coil arrangements:

1. Two **identical** single coils sensors are built as described above and kept very close to each other (glued side by side) in order to sense the same magnetic field. They are **connected in series** to add their precession signal voltages and, at the same time, to cancel the effect of noise voltages from outside the coil arrangement.



2. Two separate coils are **wound on the same axis around the same bottle**. There must be a wide gap between the two coils because the two polarization fields cancel each other there. They are **connected in series and in opposition** (wound in the opposite direction) to get the same effect



as in 1. Above.

8.3. Multiple (> 2) Solenoid Coils

This configuration is used by a number of commercial systems. It is made of 3, 4 or 5 coils glued together at regular angles to make a complete circumference. A three-coil system is made of coils glued together and shifted by 120° while a five-coil system is made of coils shifted by 72°.
The purpose of this rotation of the coils is to eliminate the signal dip due to local magnet fields and the angle of the sensor in relation to it. As one coil is null, the others take over. The coils must be wound in the same direction and connected in series.
Three or more separate solenoid coils as pictured also create a self-shielding effect call (phase canceling) or **Hum Bucking**.

8.4. Toroid Coil

A toroid coil has many advantages over the solenoid like its natural **insensibility to external noise and positioning direction**. However, it is more **hard manual work** to wind and it potentially contain less volume of proton-rich fluid.
The same coil sensor calculator can be used to calculate its functional parameters.
Jim Koehler describes the details of construction of such a sensor from the largest ring on the Fisher-Price 'Rock-a-Stack' toy in his paper starting at page 36.
A slightly larger model can also be built from eight 45° PVC tubing bends glued together. This method has the advantage of making much easier the winding of the sensor. Look at the building phases one, two and three. Between the phases two and three, the two halves of the toroid are glued together, the core of the sensor is filled with the fluid and the two still unwound gaps of the toroid are wound.

Corrective note about these two last pictures: The aluminum foil wrapped as pictured around the toroid should NOT be used as shielding. A toroid seems to be naturally protected against external disturbances and thus, does not require any shielding.

A toroid sensor should also be positioned **perpendicular** to the local vector of the earth magnetic field. For regions where the inclination of the local field is greater than 45°, the main axis of the sensor

should be vertical while if <45°, it should be held horizontal. Its horizontal direction of such a sensor is not important.
Note that if a toroid coil is positioned in the general direction of the local earth field, the precession signal will still be **half** the maximum it could be when it is positioned in a perpendicular position.

8.5. Cylindro-Toroid Coil

A cylindro-toroid sensor has the same advantages and limitations as the simple toroid one but it has an added advantage; it is able to contain a larger volume of fluid. This is an example of the still-unwound core of such a sensor.

In summary, the simplest sensor to build is the ***single Solenoid coil*** *and it should probably be the first one to try even if it picks up external electromagnetic noise. When the amplifier chain has been proven to work with this sensor, the other types of sensor can then be built and tested to optimize the whole system. The natural sequence is:*

1. *Single solenoid with internal bottle*
2. *Double solenoid with internal bottles*
3. *Triple solenoid with internal bottles.*
4. *Toroid or cylindro-toroid coil*
5. *Triple solenoid inside a container*

End of Document