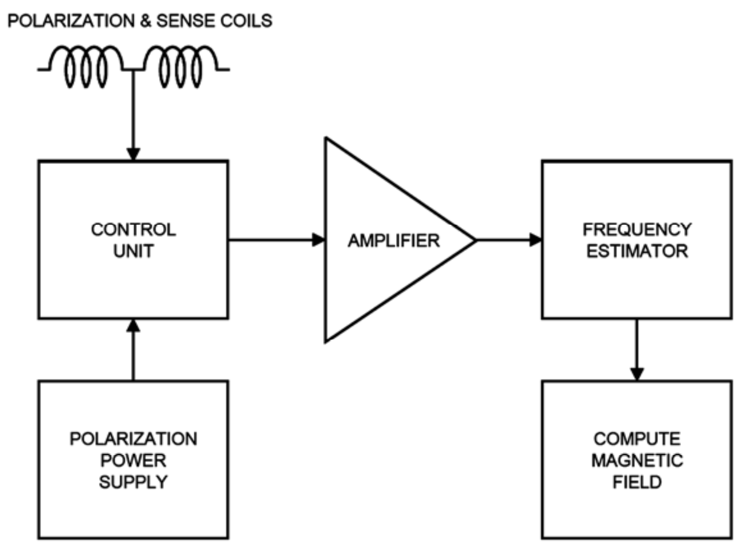
Build an Earth's Field Magnetic Observatory!

PART II, A Brief Survey of Amateur Proton Magnetometers

Last article we discussed fluxgate and proton magnetometers in general, the Earth's magnetic field in my backyard, and online references for Space Weather. In this article, we will do a quick survey of several amateur proton magnetometer projects that I have become aware of over the years. Before the survey of other projects, we begin with a discussion of a basic proton magnetometer architecture. Later, we can use this basic block diagram as a reference point for comparing the various designs discussed in our survey. The polarization and sense coils are shown here in symbolic block diagram form.[1]



Block diagram of a typical Proton Magnetometer

Conventional proton magnetometers apply a voltage to a polarization coil to cause a DC current to flow through the coil which creates a magnetizing current to align the protons in the working fluid. A sense coil (which may or may not be the same coil as used for polarization) is then used to observe a precession signal generated by the precessing protons as they return as a group to their original non-aligned random spins.

The polarization field, a relatively large DC magnetic field, is usually provided for a short time and on a periodic basis and is used to align the spins of protons within a working fluid. The polarizing field is developed by passing the

DC current through a coil (usually a solenoid coil) which has some tens, to hundreds of turns, of copper wire.

Each measurement cycle, the DC current which creates the polarizing field is turned on for about one to three seconds. When a steady current is caused to flow in a coil, energy is stored, just as a voltage represents an amount of stored energy in a capacitor. Proton magnetometers need to discharge this stored energy stored relatively quickly in order to cause a well pronounced proton precession signal. Just as shorting the contacts of a charged electrolytic capacitor causes a spark, so can quickly discharging a coil (opening the circuit) using a switch or relay contacts.

The sample volume of the working fluid is generally defined by the volume of a plastic bottle which holds the working fluid. The polarizing field should be on the order of 100 Gauss and should be relatively uniform across the volume of the plastic bottle. For example, winding the polarization coil neatly, as opposed to scatter winding the coil, can improve the uniformity of the polarization field within the solenoid.

All conventional proton magnetometers also have one or more coils to receive the precession signal after the polarization current has been turned off, and to convey it to a high gain amplifier. The receiving coil can be the same as the polarization coil, or there can be separate coils to perform the two functions (polarization and receiving). Generally there are two (or more) receive coils to cancel out as best as possible any signal pick-up from the environment unrelated to the precession signal.

There are many varied approaches for making proton magnetometer coils including solenoid coil pairs, toroidal coils and triple noise cancelling coils. The most common configuration by far, however is the “two-coil” configuration. Two common two-coil configurations are the folded solenoid and the counter-wound pair. The folded solenoid uses two identically wound coils connected so as to cancel signals in the environment. The counter-wound pair, also wired for cancellation of environmental signals at the sensor assembly, is literally counter-wound (e.g. one coil is wound clockwise and the other is wound counter-clockwise). Note that “turning over” one coil of a pair of same-direction wound coils results in a folded solenoid configuration, and does not give a counter-wound coil pair.

The received precession signal can be less than several microvolts, so the high gain amplifier typically has an electronic gain of between about a half million and two million.

Following the amplifier, a frequency estimation function block determines the frequency of the proton precession signal. This is no small feat, since the precession signal is an exponentially decaying noisy sine wave having a peak amplitude of less than a few microvolts and a duration of generally less than three seconds. The frequency measuring block is usually either a frequency counter circuit implemented in hardware, or more likely today, a software frequency estimator. The precession frequency multiplied by a physical constant called the Larmor constant, determines the magnetic field. Amateur proton magnetometer efforts have ranged in frequency resolution from about 1 Hz to 0.001 Hz for our backyard observatory project using the FDM (filter Diagonalization method) as the frequency estimator.

Now, turning to our brief survey of past of past amateur proton magnetometer projects, we begin with what I believe to be the grandfather of all such projects, the C. L. Stong Scientific American Magazine, “The Amateur Scientist” column on Nicholas Wadsworth's proton magnetometer[2]. Nicholas Wadsworth designed and built a proton gradiometer for his brother, R. M. Wadsworth, a plant ecologist.[3] His brother buried small magnets at points of interest in fields and used them as markers that would not be disturbed, so that he could observe the spread or retreat of certain species over a period of several years.[4] Nicholas Wadsworth built what was probably the first amateur proton magnetometer to find the buried magnets. He used an ultra-high gain transistor amplifier[5] and a tuned pot core with 1,170 turns as his narrow band filter. He cleverly used two magnetometer bottles to make a “gradiometer”, his unit operated by generating a “beat” tone between the precession signals from each bottle. Wadsworth reported his nominal precession frequency was about 2,025 cycles, which corresponds by the Larmor constant to about 47,576 nT. He reported being able to detect a change of about $3x10^{-5}$ Oersted (~3 nT).[6] A 1 Hz change to 2,026 Hz corresponds by Larmor to about 47,600 nT or a delta of 23 nT.

As a gradiometer, Wadsworth’s instrument could not be used to measure the Earth’s magnetic field, since both coils measured the geomagnetic field equally, thus cancelling it out.

Wadsworth used three micro-switches linked to a plunger, to apply and remove the polarizing current for both coils.[7] The reported polarization field was about 30 Oersteds, which is about 30 Gauss. 30 Gauss is significantly less than the recommended 100 Gauss, however he used a relatively long 3 second polarization time which increased the number of aligned proton spins in his distilled water sample. The Wadsworth switch is very cleverly wired and his schematic diagram is well worth a carful going over with colored pencils.[8]

Decades later, James Koehler wrote and published online several versions of a treatise[9] on amateur proton magnetometer building. Many of us have read his writings over the years while attempting to build a working prototype. One of his many proton magnetometer designs[10] uses the "phase slip" method to determine the frequency of the precession signal. The coils are identically wound coils, what I refer to as the folded-solenoid arrangement. In recent years, he has also designed several all solid state switching schemes for charging the sensor coils, discharging them, and then switching the coils to the high gain amplifier for detecting the precession signal.

Another proton magnetometer project[11] by Dan Fountain uses a digital counting scheme to measure the precession frequency by counting zero-crossings of the amplified precession signal. He reports some difficulty in finalizing his design, a work in progress. His website says that his project is based on an earlier amateur project of which I am not familiar, by Phil Barnes.

Stefan and Richard Hollos designed a proton magnetometer for use as a teaching experiment. The Hollos design uses small sensing coils within a separate polarizing coil wound from a heavier wire. Their frequency estimator is based on a high resolution Fourier Transform[12]. They published a paperback book[13] in the form of a construction article along with an introduction to the physics of proton magnetometers.

More recently, an international team organized by Willy Bayot, and which included James Koehler, designed and produced a very sophisticated proton magnetometer[14] for use in archeological studies. Many of their project notes include schematic diagrams. My understanding is that the project's software is based on James Koehler's application of the phase slip method. Willy Bayot also wrote an informative guide[15] for amateur proton magnetometer projects. Their magnetometer project includes mapping, GPS coordinates, and a submersible version for underwater studies. There is much active discussion regarding proton magnetometers for treasure hunting and archeological applications at the Geotech online forum[16].

Next article, we will discuss the FDM proton precession magnetometer block diagram. By contrast to Wadsworth's 1 to 2 Hz, our FDM proton magnetometer project can resolve to about .001 Hz for observing very small changes in Earth's magnetic field. Following the introduction to the FDM proton magnetometer, we will describe a FDM proton precession magnetometer sensor stand and tell how to wind the coils a backyard geomagnetic observatory.

[1] As will be seen later in our discussions, there are a great variety of polarization and sensor coil configurations. No literal wiring should be inferred from this first block diagram view.
[2] C.L. Stong, The Amateur Scientist, Building a Sensitive Magnetometer, Feb. 1968. *See also*: Journal of Scientific Instrumentation, Vol. 44, pg. 552, 1967.
[3] Private communications with Nicholas J. Wadsworth, July, 2012. Note that his first name was misspelled by editor C. L. Stong in the original Scientific American publication. I retain the misspelling (Nicholas) in our writings so that readers researching the original publication can more easily find our notes.
[4] R. M. Wadsworth, An Invisible Marker for Experimental Plots, Journal of Ecology, Vol. 58, No. 2, pages 555-557, July, 1970, http://www.jstor.org/stable/i313509 .
[5] "The design used germanium transistors as when I started silicon was still an inferior material", Nicholas Wadsworth (July, 2012). Also, note that there was insufficient space in the Amateur Scientist column, "to go for instance into the design of low noise input stages or the problems of feedback over high gain amplifiers, which can both be troublesome if you do not take care. As an example I did not specifically say that the interstage coupling capacitors were chosen to provide a top-cut starting just above the working frequency and the emitter resistor bypass capacitors were chosen to provide a low frequency cut starting just below".
[6] $B=\mu_0*H$ and $\mu_0\sim1$ in air, therefore 10^{-3} Oersted (H) ~ 100 nT (B) in air.
[7] "The switch consists of the contact assemblies of three micro-switches. The assemblies are mounted so that one plunger actuates all three assemblies. When the plunger is released, the battery circuit is broken and then the coils are reconnected to the amplifier", pg. 125, second paragraph from the bottom, Amateur Scientist column, see fn. 2.
[8] *In our September 2009 Journal notes*, I had questioned the effectiveness of the zener diode discharge scheme of the proton magnetometer (two bottle gradiometer) project. It appeared to me that when the switch changed state, the zener diode was never actually in a discharge circuit. Recently, I learned that Wadsworth had also published a 1967 note on experimental technique and apparatus, A proton free-precession magnetometer for locating buried magnets, Journal of Scientific Instrumentation, Vol. 44, 1967. The 1967 note is not so much a construction article, however it solves the zener diode mystery! In the note, he explains, "One plunger operates all three switches and connects the coils to the dry battery". Then, "when the plunger is released, the switch nearest the battery breaks contact first and the others, which operate a millisecond or two later when the magnetizing current has decayed, connect the coils to a low-loss tuning capacitor and to the amplifier which has a noise factor of about 3 dB and a bandwidth limited to 25 Hz by a single tuned circuit".
http://www.gellerlabs.com/PMAG/Wadsworth/JSciInst1967switch.jpg . So Wadsworth had a "mechanical" time line in 1967! For those less experienced in powered coil discharge, here is a more detailed view http://www.gellerlabs.com/PMAG/Wadsworth/Wadsworth%20Cycles.jpg . For convenience I reversed the battery polarity to match the Amateur Scientist schematic diagram (it may be a different battery symbol in the Rev. Sci. note, where the short line represents battery +). In step 1, the battery voltage is applied to the two series connected coils to establish the polarization current. In step 2, the switch nearest the battery breaks contact first. As is well known, when a "charged" coil discharges, the polarity of the voltage across the coil terminals reverses, however the direction of the current remains the same. At the first moment of coil discharge, the coil current has not yet changed. The second drawing shows the zener diode now conducting the coil discharge current. In step 3, by "a millisecond or two later", the coil has been discharged, and the coils are now coupled to the amplifier. In other words, for those of us who over the years who used three pole double throw buttons or three pole double throw relays, we completely missed the intermediate zener controlled coil discharge step, resulting in contact arcing!
[9] Proton Precession Magnetometers, Rev 2, http://members.shaw.ca/jark/PPM.html .
[10] James Koehler, Proton Precession Magnetometer, Circuit Cellar Magazine, May 2007.

[11] I have seen references to the Phil Barnes project, but do not have a link for it.
[12] "C Program Magnifies Spectrum When An FFT Can't Hack It", Stefan Hollos and Richard Hollos, Electronic Design, Aug 18, 2003, http://electronicdesign.com/article/embedded-software/c-program-magnifies-spectrum-when-an-fft-can-t-hac.aspx .
[13] Stefan and Richard Hollos, Signals from the Subatomic World: How to Build a Proton Precession Magnetometer, Abrazol Publishing, May 2008, ISBN 1887187006.
[14] The PPM-MARKIV Project, http://users.skynet.be/fa352591/index.htm .
[15] http://perso.infonie.be/j.g.delannoy/BAT/IntroductiontoMagnetometerTechnology1-2.pdf .
[16] Geotech, Technology for treasure hunting, the Magnetometers forum, http://www.geotech1.com/forums/forumdisplay.php?f=9 .