

Geomagnetic observatory

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FDM Proton Precession Magnetometer

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This article describes a proton precession magnetometer (PPM) for monitoring the Earth's magnetic field. The project PPM has sub nano Tesla resolution. To put nano Tesla sensitivity in perspective, changes of 1 nanotesla (nT) can be caused by a safety pin at less than 3 feet, a car at 125 feet, a bus at 250 feet, and a train at just over a half mile $(\sim 1 \text{ km})^2$. These numbers are only rough approximations, because the influence of any particular object depends largely on the ferrous metal content of the object.

By measuring very small changes in the Earth's magnetic field, one can also observe the diurnal variation of the geomagnetic field, typically on the order of tens of nano Tesla. Larger changes in the geomagnetic field are often related to solar activity. The Sun can send out massive amounts of charged particles as a Coronal Mass Ejection (CME). As shown in the SOHO (ESA & NASA) illustration of figure 1, when an Earth-directed CME impacts our planet, there can be large swings in the geomagnetic field, sometimes rising to the level of a geomagnetic storm. Such geomagnetic disturbances can include very large swings in the geomagnetic field. The magnitude and shape of waveforms of the total field ("F" scalar) can vary widely over geographic location on the Earth.



Figure 1: A Coronal Mass Ejection (CME) [Courtesy SOHO (ESA & NASA)]

Geomagnetic storms will occur with increasing frequency as we approach the peak in the 11 year solar cycle. Most geomagnetic events, including minor storms, go relatively unnoticed. As the severity of a geomagnetic storm increases, the Aurora Borealis (the "northern lights") show in the night sky, and can become visible at lower latitudes with stronger storms.

Radio propagation can also be affected, for example long distance high frequency communications can be completely disrupted. More severe geomagnetic storms can cause geomagnetically induced currents (GIC) in the power grid. GICs can become large enough to literally burn out high voltage distribution transformers and take down an entire power grid as happened in Quebec Province, Canada in 1989.

The most severe geomagnetic storm in recorded geomagnetic history was the Carrington event of 1859. It is believed that a Carrington type event today could damage many, if not most of the power grids in North America and Europe. Since the remanufacture of hundreds of high voltage distribution transformers is a long term prospect, many people could be without power for weeks or months. While a Carrington type event is believed to be uncommon, the frequency of such high impact events is unknown. As such, if you plan to be able to record a Carrington event with our project PPM, you had better plan to run it on a battery with a solar charger!³

Now, turning back to our PPM, a PPM measures the magnitude of an ambient magnetic field based on the quantum mechanical phenomena of proton spin precession. The beauty of the PPM is that once the frequency of a precession signal is accurately measured, the magnetic field is known. Even though this technology dates back to the 1950's, small lab or home built versions of a PPM can still be a challenging project. However with some electronics construction experience a DIY PPM project is very do-able⁴.

A PPM needs to operate in a relatively uniform magnetic field. The Earth's magnetic field, outdoors away from structures and ferrous metals, typically has uniformity in space of better than 10⁻⁵. The spatial magnetic gradient need not be perfectly homogeneous. For example, my outdoor observatory sensor operates fine at about 33 feet from a parked vehicle. However, the gradients in almost all buildings and homes are too severe. Without complex shimming with gradient coils, a PPM sensor will not work indoors.

Varian-Packard method

Varian-Packard method

Most geophysics and amateur PPMs use the Varian-Packard method⁵. The PPM operates between two magnetic fields, $B_{\rm M} \sim 100$ Gauss (0.01 Tesla), and the Earth's total magnetic field, $B_{\rm E} \sim 0.5$ Gauss (50 µT)⁶. The $B_{\rm M}$ field is typically provided by momentarily powering a polarizing coil, such as a solenoid coil, the "powered coil". The $B_{\rm M}$ field is most effective when oriented perpendicular to $B_{\rm E}$.

By well known quantum mechanical phenomena, the basis of all nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI), the polarization field B_M can be used to align a percentage of the proton spins. In a NMR working fluid, the percentage of the proton population which become spin aligned depends on the magnitude of B_M , the time duration of B_M , and the Tau 1 time constant for the NMR working fluid in use. After a polarization time (t_p), an active switch is turned off and the powered coil current begins to fall. The rate of fall of the current (di/dt) is proportional to the voltage across the powered coil terminals⁷. The field B_M collapses as the powered coil current falls towards zero.

By controlling the terminal voltage, the powered coil is discharged relatively quickly and in a controlled manner from about 1.5 Amps to 0 A. The crucial portion of the field collapse occurs over

tens of μ s from a few Gauss through the Earth's field B_E of about 0.5 Gauss, after which, the proton spins precess in a way analogous to a spinning top. The precession signal falls off exponentially as the proton spins return to an equilibrium minimum energy state in B_E^8 . As the spins fall out of the alignment previously caused by B_M , the protons precess at exactly the Larmor frequency fcorresponding to B_E at that moment of time. The Larmor frequency is directly proportional to B_E by a constant⁹. Given a measured frequency of the precession signal, the following equation is used to calculate the magnetic field:

$$F = \frac{2\pi f}{\gamma_p}$$

As per the IAGA10, $\gamma_{p} = 2.675\ 153\ 362\cdot 10^{8}\ T^{-1}s^{-1}$

The powered coil is now part of a receive coil noise-rejecting coil pair which picks up the tiny exponentially decaying electromagnetic signal radiated by the proton precession.

Because we study the proton precession signal both in the frequency domain and in the time domain, the project can also be used to explore some of the basic concepts of Earth's field nuclear magnetic resonance (EFNMR). In the time domain, the peak magnitude of the precession signal is proportional to the time duration of B_M and the NMR fluid Tau1:

$$V_{PrecessionSignalPK} \propto \left[1 - e^{-\binom{t_p}{Tau 1}}\right]$$

Therefore, all other conditions somewhat stable (e.g. fluid temperature) the PPM can be used to measure Tau 1 by varying a fixed polarization time and recording the resultant precession signal amplitude. Also, in a uniform field $B_{\rm E}$, the NMR Tau 2 decay constant can be directly measured from the envelope of the exponentially decaying precession signal¹¹.

Figure 2 shows a block diagram and figure 3 a picture of the indoor hardware of our PPM project. The PPM includes three hardware modules, the switch control module (SWCTRL), a narrow band low noise amplifier (NBLNA), and a relatively low cost National Instruments USB 6008 (or USB 6009) digitizer with digital I/O lines. A stand-alone compiled LabVIEW program runs the application and a frequency estimator executable calculates the Larmor frequency to 6+ digits resolution for each digitized precession waveform. The sense coils are mounted three to four feet above the ground serve as the PPM sensor coils (figure 4). The outdoor sensor coils are coupled to indoor electronics via a shielded twisted pair cable¹².



Figure 2 : A block diagram of the indoor hardware of the PPM project.



Figure 3 : A picture of the indoor hardware of the PPM project.



Figure 4: The sense coils are mounted three to four feet above the ground serve as the PPM sensor coils

SWCTRL module

SWCTRL module

Figure 5 (schematic diagram) and figure 6 (photograph) show the SWCTRL module. The SWCTRL module configures the sense coils in one of two states, as a single coil with the working NMR fluid bottle within, for the polarization cycle, or as a center-tapped counter-wound coil pair to cancel ambient noise while coupling the tiny exponentially decaying precession signal to the electronics indoors.



Figure 5: A schematic diagram of the SWCTRL module



Figure 6: A photograph of the SWCTRL module

The SWCTRL board uses a telecom relay to configure the coils. The galvanic isolation and ultra-low capacitance between relay contacts is highly desirable for decoupling the polarization circuits and the amplifier¹³. Active "on-off" control of the polarization current by program control for time t_p is accomplished with a MOSFET. The relay is operated first, via a first USB 6008 digital I/O line. The relay is "de-energized" to configure the powered coil for a polarization cycle. After the relay is stable, also by program control via a second USB 6008 digital I/O line, the MOSFET switch is turned on to provide the polarization magnetic field B_M for time t_p . After time t_p , the MOSFET is switched off. At this point, coil *di/dt* is controlled by establishing a desired V using an ultra-fast turn-on TVS diode across the MOSFET (figure 7 photo, 8 powered coil discharge waveform). The TVS voltage is selected to be slightly below V_{DSS} , so the MOSFET does not operate in its reverse avalanche mode. Any energy remaining in the coil following the controlled discharge by TVS diode is dissipated by the secondary dump resistor.



Figure 7: Photo of the TVS diode



Figure 8: The powered coil discharge waveform

Following the controlled collapse of B_M , the relay is once again energized¹⁴. When the relay is energized, the contacts are wired to connect both of the sense coils in series as a center-tapped pair. The center-tapped pair is connected in parallel with the resonating capacitor bank and also coupled to the NBLNA balanced input. Using an LCR meter, such as an Agilent U1733C, the sense coils are balanced for inductance so that as wired, the coil pair rejects most EMI/RFI signals picked up from the environment. The precession signal appears across the terminals of the powered coil having the NMR working fluid bottle within.

As shown in figure 9 (schematic diagram) and figure 10 (photograph), the first stage of the NBLNA is a passive common-mode filter designed to attenuate RF signals which might create undesired inband interference signals such as by rectification.



Figure 9: The schematic diagram of the NBLNA



Figure 10: A photograph of the NBLNA

The tiny exponentially decaying (~2 kHz) precession signal is then AC coupled through a pair of film

capacitors and bias resistors to an Analog Devices SSM2019 balanced input integrated audio amplifier. The NBLNA distributes the relatively high gain (~100,000 to 1 million, typically used at about 250,000) among several Linear Technology LT1097 OpAmp stages including an adjustable multiple feedback bandpass filter set to a nominal local Larmor frequency (varies with geographic location)¹⁵.

An LT1357 drives an output audio transformer which converts the single ended output to a balanced output for the USB 6008 digitizer differential input. The transformer also provides a galvanic ground break between the NBLNA and the USB 6008 to help suppress possible ground loops. With its relatively high gain, low noise input, and FET front end, the NBLNA can be tested using the Johnson noise generated by a standard ¹/₄ Watt metal film resistor¹⁶.

As noted above, the amplitude of the precession signal is proportional to the magnitude of B_M , the time duration of B_M and the NMR fluid Tau 1. The USB 6008 is operated on the +/- 1V scale. To make good use of the USB 6008 +/- 1V input scale over a wide range of fluid temperatures (the NMR fluid is outdoors at a sensor stand), in one polarization time controller mode, the precession signal amplitude is held relatively constant. A peak envelope (PEV) servo in software automatically varies the time duration of B_M by controlling the polarization time t_p , to maintain the desired precession signal amplitude.

We use 4 ounces (125 mL) of Prestone De-Icer windshield washer fluid as our all season NMR fluid, because winter temperatures here in upstate, NY can fall to -30 F (figure 11 shows a photograph of the sensor stand covered for winter). The Rain-X orange windshield washer fluid works as well. In fact at most above freezing temperatures, the project PPM works just fine with 4 ounces of just about anything liquid, from tap water to orange juice and wine vinegar.



Figure 11: A photograph of the sensor stand covered for winter

It's not all that surprising that no special fluid is required, since neither MRI of the human body nor NMR spectroscopy require volatile fluids of fuels to work. In fact, some early experiments in Earth's field MRI imaging were done with apples, oranges, and egg-plants¹⁷. With the strong dependence of Tau 2 on fluid temperature, we are able to display an approximate fluid temperature from a Tau 2 moving average by the equation:

$$T_{fluid} = \frac{1}{c_2} \times \ln\left(\frac{Tau \ 2}{c_1}\right)$$

Larmour frequency

Larmor frequency

A frequency estimator converts the digitized precession waveform (also called the free induction decay (FID) signal) to the Larmor frequency. The frequency estimator used for this project is the

filter diagonalization method (FDM), which was provided by Professor Vladimir A. Mandelshtam. In about 1995, Professor Mandelshtam first adapted a new FDM solution to the problem of Harmonic Inversion and spectral analysis for uses such as NMR spectroscopy¹⁸.

The precession signal at the terminals of the powered coil, even as resonant with the resonating capacitor bank, is a noisy exponentially decaying signal, with a peak amplitude of less than 10 microvolts and a usable amplitude lasting only about a second or less. Remarkably, a modern frequency estimator such as FDM can return a fundamental Larmor frequency of 6+ digits of resolution from a single digitized precession waveform. Carl Olsen is experimenting with other suitable .exe "plug-in" frequency estimator modules which perform the phase slip method [Koehler] and the Goertzel high resolution FFT [Hollos]¹⁹.

As adapted for this project, each measurement cycle, FDM.exe returns the fundamental (highest amplitude) Larmor frequency, the amplitude of the fundamental frequency, a figure of merit, and a narrow band (typically 300 Hz) signal to noise ratio. If these parameters exceed preset user thresholds, an "auto-retry" system automatically retakes a measurement until the auto-retry conditions have been met.

Passing vehicles cause a gradient in both time and space across the powered coil and generally cause a less desirable figure of merit value. For sense coils in yards within a 100 ft or so of roadways, the auto-retry system helps to reject measurements distorted by passing vehicles. For the geomagnetic observatory application we typically plot and record data at about once per minute. The auto-retry cycle is set to about 10 seconds, time enough to let most offending vehicles pass from sensor view. Because nearby lightning transmits significant electromagnetic energy at about 2 kHz, the auto-retry system also rejects a number of distorted waveforms during severe thunderstorms.

Figure 12 shows a plot of total field (the geomagnetic "F" scalar) of a typical diurnal cycle in Colorado Springs, CO, courtesy of Carl Olsen. Figure 13 shows a plot of total field during the geomagnetic storm of March 9, 2012.



Figure 12: Shown is a plot of the total field of a typical diurnal cycle in Colorado Springs, CO (Courtesy of Carl Olsen)



Figure 13: The figure shows a plot of the total field during the geomagnetic storm of March 9, 2012 in upstate NY

Figure 14 shows a verification run done by Mark Haun during the storm of January 25, 2012. Mark compared the recorded data from his FDMPPM to that from the relatively nearby Natural Resources Canada geomagnetic observatory at Victoria. Mark's interest in the geomagnetic field has been in part related to identifying times when there might be good sighting of the Aurora Borealis so often associated with magnetic storms. Using optical filters and a photomultiplier tube on a tower, Mark also records the 558 nm sky brightness peak²⁰. During the March 9, 2012 G3 storm, Mark reported that the brightness peaks appeared to correlate well with times of highest rates of field change (dB/dt), as recorded with his FDMPPM.



Figure 14: A verification run done by Mark Haun during the storm of January 25, 2012

Detailed construction information including journal notes, documentation, articles, and references are available at our website (reference 1). A Windows 7 machine and a couple of free downloads from National Instruments are all that is needed to run our complied observatory LabVIEW code (latest front panel shown in figure 15).



Figure 15: The latest front panel view with the result of some free downloads from National Instruments running the author's compiled observatory LabVIEW code

For those with access to a LabVIEW development system, we also offer the vi source code. FDM.exe will be made available with data I/O details; however the FDM FORTRAN source code will not be distributed, since it is not owned by us. We will also post several post-processing routines, including an Excel graph which shows the performance of the polarization time controller (the PEV servo) over time (figure 16 shows a sample chart for several days of FDMPPM data, ending about March 31, 2012).



Figure 16: We see a sample chart here of several days of FDMPPM data, ending on March 31, 2012

We also offer kits of parts for the SWCTRL and NBLNA modules. Carl Olsen offers tested and built FDMPPMs²¹. Feel free to contact me with questions. There are far too many related references, including government space weather observations and predictions, to list here. Many such resources can be found on our links and references page²².

About the author



Joe Geller designs engineering and physics related instruments. He also was an engineer at Brookhaven National Laboratory. He has a bachelor's degree in electrical engineering from the School of Engineering and Applied Science at Columbia University.

References

1 GELLER (company name); very detailed project notes and documents can be found at our website: www.gellerlabs.com, joegeller@gellerlabs.com.

2 J Jankowski and C Sucksdorff, Guide for Magnetic Measurements and Observatory Practice, 1996, pgs. 38, 49, Table 3.1.

3 T. Ferris, Solar Storms, National Geographic Magazine, June 2012; J. Kappenman, A Perfect Storm of Planetary Proportions, IEEE Spectrum, February, 2012, P. Riley, On the probability of occurrence of extreme space weather events, AGU, Space Weather, Vol. 10, 2012.

4 I first read Nicholas Wadsworth's Amateur Scientist project, Building a Sensitive Magnetometer, in Scientific American magazine, in 1968. C.L. Stong, The Amateur Scientist, Building a Sensitive Magnetometer, Feb. 1968, See also, Journal of Scientific Instrumentation, Vol. 44, pg. 552, 1967; Later, I was further inspired by the many projects and writings of Professor Koehler, including his

treatise on amateur Proton Precession Magnetometer (PPM) building. James Koehler, Proton Precession Magnetometers, <u>http://members.shaw.ca/jark/</u>

5 A. Abragam, *The Principles of Nuclear Magnetism, pgs.* 64-65 (Oxford Press, 1961), discussing Packard M., Varian R., Free Nuclear Induction in the Earth's magnetic field, Phys.Rev. 93, 941 (1954), also discussed in the Koehler treatise.

6 The magnitude of the "total field" vector is the "F scalar". The horizontal component, as for example, is "seen" by a compass, is of lower magnitude by the cosine of the local inclination or "dip" angle.

7 Vcoil=L(di/dt)+iR, however since the resistance of the coil and cable (R) is relatively low, the iR component can be ignored for rough calculation.

8 Some more sophisticated EFNMR applications include EFNMR spectroscopy, Appelt, et. al., Chemical analysis by ultrahigh-resolution nuclear magnetic resonance in the Earth's magnetic field, Nature Physics, Vol. 2, Feb. 2006, and use more complex pulse patterns beyond the our very simple application of the Varian Packard method in a wide variety of EFNMR apparatus ranging from spin echo measurements to EFNMR magnetic resonance imaging (MRI) with the addition of gradient coils, See for example, Mohorič, et. al., NMR in the Earth's magnetic field, Progress in Nuclear Resonance Spectroscopy 54, pgs. 166-182, 2009, see pgs. 175-176, and fig. 9.

9 Joe Geller, PART IX, The Gyromagnetic Constant and the Larmor Equation <u>http://www.gellerlabs.com/PMAG%20Articles.htm</u>.

10 IAGA: In 2010, the International Council for Science, Committee on Data for Science and Technology adopted a new value for the gyromagnetic constant. *See:* <u>http://www.iugg.org/IAGA/iaga_pages/pubs_prods/value.htm</u>.

11 G. Planinšič, J. Stepišnik, M. Kos, Relaxation time measurement and imaging in the Earth's magnetic field, J. of Mag. Res. A 110, 170-4 (1994); for our simple approximation of peak precession signal amplitude, we use only the first term of Planinšič's equation 1

12 Suitable cables include twisted shielded cables with #22 AWG wire pairs, and shielded CAT 5 cables with paralleled pairs equivalent to #22 wire.

13 All solid state solutions exist, however generally all solid state switching comes with the added complexity of additional active drivers, and optical isolation to make up for the lost galvanic isolation and low capacitance of a simple relay.

14 Our small telecom relay includes a rare earth magnet which helps speed contact movement. We found that our precession signal amplitude has less measurement-to-measurement amplitude variation when closing the relay before digitization.

15 Find your nominal total local field at the NOAA National Geophysical Data Center:

http://www.ngdc.noaa.gov/geomag-web/#igrfwmm

16 "Use resistor noise to characterize a low-noise amplifier", Measure gain or noise with an AC voltmeter, Joe Geller, edited by Martin Rowe and Fran Granville, EDN, June 23, 2011 http://www.edn.com/design/components-and-packaging/4368142/Use-resistor-noise-to-characterize-a -low-noise-amplifier.

17 J. Stepišnik, et. al., Magnetic resonance imaging in the earth's magnetic field, Second European Congress of NMR in Medicine and Biology, Berlin 1988, Abstract Book, P-127; G. Planinsic, et. al., Relaxation-Time Measurement (reference 11).

18 Vladimir A. Mandelshtam, Howard S. Taylor, Harmonic inversion of time signals and its applications, Journal of Chemical Physics (1997), Volume 107, Issue 17, 1997, Pages 6756-6769, *See also*, Mandelshtam, et. al., Application of the filter diagonalization method to one- and two-dimensional NMR spectra, Journal of Magnetic Resonance, Vol. 133, Iss. 2, pgs. 304-312, 1998, and Mandelshtam, et. al., Harmonic inversion of time signals and its applications, Journal of Chemical Physics, Vol. 107, Iss. 17, pgs. 6756-6769, 1997; Professor Johnson's "harminv" is a version of FDM for LINUX, there is also some good explanatory material on the MIT harminv page which contrasts FDM with more traditional FFT methods <u>http://ab-initio.mit.edu/wiki/index.php/Harminv</u>.

19 J. Koehler, Proton Precession Magnetometer, Circuit Cellar, May 2007; Richard Hollos, Stefan Hollos, C Program Magnifies Spectrum When An FFT Can't Hack It, Electronic Design, http://www.exstrom.com/journal/sigproc/specmag.pdf.

20 Walla Walla aurora monitor, <u>http://www.keteu.org/~haunma/aurora/data.php</u>.

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22 References and Links, http://www.gellerlabs.com/PMAG%20References.htm