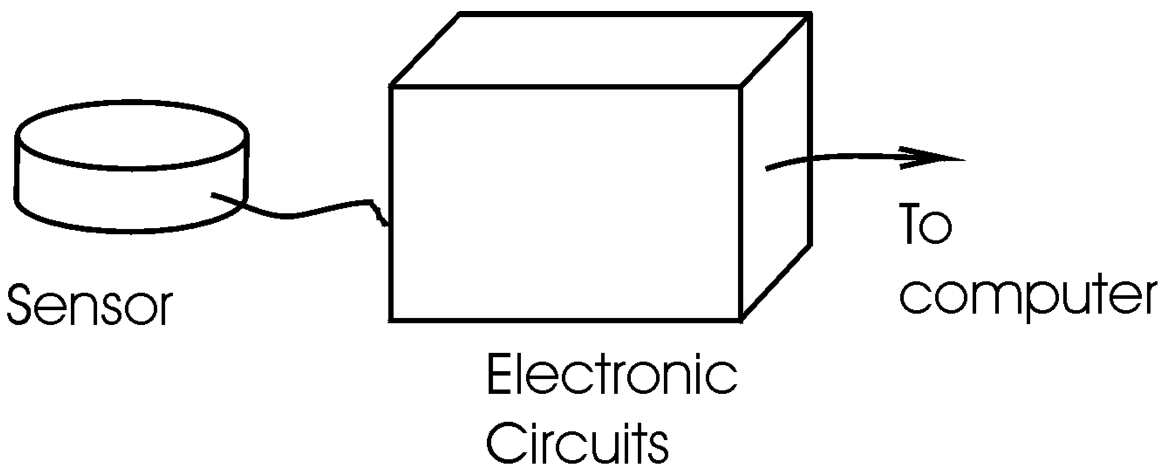
Stand-alone Proton Precession Magnetometer

J.A. Koehler
Comox, BC, Canada

Introduction

This document describes the circuit and construction of a stand-alone, microprocessor controlled proton precession magnetometer. The instrument is capable of a resolution[1] of about 0.1 nT. The instrument is designed to control the polarization of the sensor, make the measurement and then send the measured value of the magnetic field at the location of the sensor via an RS-232 compatible interface to an external terminal or computer.



The circuitry consumes a few mW at +12V although the polarization current for the sensor may be several Amperes during the polarization portion of the measurement cycle. The exact amount of the polarization current depends on the details of the sensor design.

This instrument is suitable for use as a magnetic observatory at some fixed location or for use in single sensor prospecting. As a fixed observatory, the sensor would be located in some place where it is well removed from steel objects and the PPM circuits and computer would be located at and operated from within a building. The sensor would be connected to the rest of the circuit by a long, shielded cable.

For treasure hunting over water, the sensor would be towed behind the boat on a long cable. The circuitry and computer would be located on the boat and the computer would have a program to show the result of each successive measurement of the local magnetic field.

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[1] Assuming the S/N of the sensor is greater than about 50 and the output of the sensor is greater than about 1.0 microVolts.

In both these situations, the computer has to run a program which causes the microprocessor based electronics to make a measurement and then either store or display the results. For treasure hunting, for example, the successive reading would want to be made as rapidly as possible. For a magnetic observatory, it might be desirable to make readings only once per minute or even more seldom.

The design

For a complete discussion of the operating principles and design considerations of a proton-precession magnetometer, please read the document titled "Proton Precession Magnetometers" which is available on my Web site: www.diamondjim.bc.ca . For future reference, I will call this document, 'PPMJAK'.

This stand-alone PPM was built using these design considerations. Indeed, it is basically just one of the 'slave' systems discussed in the later sections of the PPMJAK dealing the design of a gradiometer. A gradiometer requires two identical magnetometers and this stand-alone design is simply one of the two.

A gradiometer may be constructed from two of these stand-alone units by adding a separate controller (the 'master' unit described in the above document) to interact with them.

The complete circuit diagram for this stand-alone PPM is shown in six circuit diagrams:

1. The sensor-relay circuit (the file named 'relay.pdf')
2. The low-noise preamplifier circuit (the file named 'preamp.pdf')
3. An intermediate amplifier (the file name 'Intermediate.pdf')
4. The tuned amplifier circuit (the file named 'Tuned_amp.pdf')
5. The microprocessor circuit (the file named 'Microprocessor.pdf')
6. The interconnection diagram (the file named 'Connection.pdf')

The sensor

The sensor consists of a coil wound around a container holding the active fluid. The design of a sensor was discussed at length in the PPMJAK. There, it was shown that the best design for a sensor uses a toroidal coil rather than a solenoidal one. If you use a solenoidal sensor, you must ensure that the orientation with respect to the local magnetic field is always favourable. This means that the axis of the solenoid should always be within about 60 degrees of perpendicular to the local magnetic field. At 60 degrees, the sensitivity of the solenoidal sensor is reduced to just ½ of its most sensitive orientation (perpendicular to the field). For a toroidal sensor, the orientation does not matter since the sensitivity is never less than ½ that for the most favourable orientation.

For this stand-alone unit, you need a sensor which produces a S/N of better than about 50:1 and which has an output of at least 1.0 microVolt. In general, the larger the sensor and the greater the quantity of hydrogen rich material at its core, the more sensitive it will be. For a magnetic observatory or for a sensor to be towed behind a boat or mounted on a boom in front of a vehicle, large size is not an important restraint and so one can easily construct a sensor which more than meets the minimum requirements. For a hand-held magnetometer to be carried into the field, large size and hence large weight is a disadvantage and it means that you will have to design the sensor more carefully. In any case, the Excel file which is part of the PPMJAK will allow you to design the sensor.

In building the sensor and whatever you plan to use as an enclosure, you must be careful to use only non-magnetic, non-ferrous materials. Nylon hardware is fairly readily available but it is only useful for fasteners which do not require great strength. Brass hardware is often magnetic and so should be used only if you're sure that it isn't – check with a strong magnet. Aluminum is very good (if you can find it!). Stainless steel, often thought to be non-magnetic, may or may not be depending on the alloy (again, check it with a strong magnet). For the enclosure itself, the best materials are the plastics.

If the completed instrument is to be used anywhere where there is a lot of electrical interference, you would be best advised to shield the sensor by enclosing it within a non-magnetic but conducting shield. For a toroidal sensor, this shield can just be household aluminum foil wrapped tightly around the sensor. This does not act like a shorted turn because all the sensor magnetic field is contained within the toroid. If you are using a solenoidal sensor, the shield should be much larger than the solenoid itself – the rule of the thumb is that the shield diameter must be a minimum of twice the outer solenoid diameter – and bigger is better. This is because a significant portion of a solenoid's field is outside the solenoid and so a conductor placed around it nearby acts like a shorted turn.

Low-noise preamplifier module

The design considerations for a low-noise preamplifier are also discussed in the PPMJAK. For this stand-alone PPM, I have decided to use what is probably the very best device available for this purpose: the National Semiconductor LM394 super matched transistor pair. This device consists of two independent NPN bipolar transistors in a single package. The two transistors in the pair are very closely matched but it is not that which makes them desirable in this application. They also provide an **extremely** low noise figure.

Only one transistor of the pair is used in the preamplifier and it is used in a very conventional common-emitter amplifier. The bias current is set to about 70 microAmperes giving a noise figure of about 1.07 at a frequency near 2KHz. National Semiconductor application note, AN222, describes this device and design considerations for low noise audio amplifiers.

The output to this amplifier is shorted to ground in the intermediate amplfier (this doesn't hurt anything) during the polarization phase of the measurement cycle by the 2N7000 FET. The control signal for this, the 'squelch', is supplied by the microprocessor.

The input impedance of this amplifier at this bias current is quite high – several ten's of Kohm. However, the amplifier input should NOT be matched to the sensor output impedance. Instead for best low noise performance,, the sensor should present an impedance of about 5K. This is about the impedance of the sensor when it is used in the 'parallel' configuration (see the PPMJAK).

The sensor is **not** resonated to the desired frequency by a parallel capacitor. Doing so does nothing useful except to reduce any pickup of high frequency noise and restrict the bandwidth of the sensor.

The Q of a toroid or solenoid sensor will typically be about 25 or so. If resonant, this means that the bandwidth of the sensor parallel tuned circuit will be about 80 Hz. This corresponds to a change in magnetic field of about 2000 nT. Therefore, if you tune the circuit to resonate at, say 2100 Hz, corresponding to a magnetic field of 49,000 nT, the sensor will be most sensitive to magnetic fields of between 48,000 and 50,000 nT. This will result in a reduced sensitivity at other locations where the magnetic field is greater than 50,000 nT or less than 48,000 nT

In addition, having a resonant circuit means that the impedance will change very rapidly near the resonant frequency and it may be very difficult to keep the amplifier as a whole from oscillating near this frequency. All in all, **it is best not to resonate the sensor** at the expected frequency of the proton precession at the location where the magnetometer is to be used.

To reduce high frequency noise pickup, it may be necessary to put some small capacitance in parallel with the sensor. Typically, the capacitance needed for resonance is of the order of several hundred nF. Therefore, putting a 1 nF capacitor in parallel with the sensor will reduce the high frequency noise pickup but still not make the circuit resonant. This may be necessary, for example, to reduce the pickup of local radio stations if you use a solenoidal sensor. For toroidal sensors it is not so necessary because of their insensitivity to external noise but, on the other hand, it doesn't hurt either!

Intermediate Amplifier module

The intermediate amplifier circuit is essentially identical to the preamplifier circuit. It provides a broadband voltage gain of about 100, as does the preamplifier so the signal level at the output of this stage is ~10 mV or so. At this level, the amplifier noise added by the following op-amp stages will be negligible.

Tuned amplifier module

In general, there are two approaches to be followed in the tuned amplifier module: either a high-Q, narrow bandwidth circuit or, alternatively, a more broadband approach.

Because you can increase the signal-to-noise ratio by decreasing the bandwidth, there is a temptation to design a narrow band amplifier. This means that you can design the PPM to use a physically small sensor. However, this approach has two significant disadvantages. A narrow bandwidth means that you have to tune the circuit accurately to have its peak gain at frequencies produced by the sensor **at the location** where the PPM is to be used. This means that you must firstly know the magnetic field fairly accurately so you can calculate this frequency and you must also have a fairly accurate audio signal generator to do the alignment.[2] A perhaps more serious disadvantage is that building a high gain, narrow bandwidth amplifier is not simple – it requires careful attention to the layout and by-passing to get an amplifier which does not oscillate.

A broadband amplifier has the advantage that it is suitable for a wider range of magnetic fields – you don't have to design it for any particular location. However, it does require that the intrinsic sensor signal-to-noise ratio be higher than required for a narrow-band amplifier.

I have chosen to implement the broadband approach. The tuned amplifier consists of two stages – a high gain, wide bandwidth first stage followed by a low gain tuned amplifier. I do not have a reference to the origin of the particular tuned amplifier used but it can be found in recent editions of the ARRL "Radio Amateur's Handbook". The amplifier uses two stages of the LM324 quad low-power op-amp. This particular op-amp is suitable for the low voltages used in this circuit and consumes very little power.

The design equations for the resistor and capacitor values of the tuned amplifier require that one know the desired peak frequency for the circuit. I have chosen to design this to be about 2170 Hz which should suitable for most of the US and Canada, Europe and Australia. The ambient magnetic field over this area of the earth varies from about 49,000 nT to about 62,000 nT. For locations where the magnetic field differs from this range (for example, most of South America has a much smaller magnetic field), one should redesign the tuned amplifier but this is easily done.

The modelled frequency response for the low-noise preamplifier, the intermediate amplifier and the two-stage tuned amplifier is shown in the file: amp_res.pdf. As you can see from the graph, the response of this whole system is indeed centred on ~2180 Hz and has a bandwidth of ~ 200 Hz. The overall gain at the centre frequency is ~106 dB which is ~200,000. An input signal of about 0.5 μV therefore would produce an output signal of ~100 mV.

This tuned amplifier response is not very critically dependent on the accuracy of the components because of its large bandwidth. Normal 10% tolerance capacitors and resistors will be good enough. The amplifier is very reproducible and no special layout considerations are necessary.

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[2] Alternatively, for an appropriate design, you can calculate the design components needed for the narrow-band amplifier and then build it using high precision resistances and capacitances. 2% capacitors and 1% resistors are readily available.

Microprocessor module

The microprocessor module uses a comparator to turn the sinusoidal output of the preceding stages into a square wave at the logic levels of 0 and +5 V. It requires a signal of at least about 5 mV rms to trigger properly. The comparator used, the LM2903, is a very low power comparator and the circuit shown has some hysteresis to reduce the possibility of oscillation for very low signal input levels.

The output of the comparator goes to the microprocessor that does all the work. The program in the microprocessor controls the relay in the polarization phase of the measurement cycle and then measures the frequency of the signal from the sensor with great accuracy. The measurement accuracy is about one part in 1.7 million so that, assuming the sensor provides a sufficiently high S/N ratio, the measurement of B is accurate to at least 0.1 nT.

In the PPMJAK, the polarization cycle was discussed in some detail. There it was noted that there should be some delay between the activation of the relay and the turning on of the polarization current. There should also be a similar delay at the end of the polarization cycle to isolate the preamplifier circuitry from the voltage pulse produced when the sensor polarization field collapses. The delay period chosen was 50 mS. This is plenty for almost any relay – the particular relays shown in the circuit (Omron G2R-24-DC12) open and close in about 7 mS. Also, the amplifier circuitry should be 'squelched' during the polarization phase of the cycle. The microprocessor does this all.

On being turned on, the microprocessor starts one measurement cycle. The value of the measured magnetic field, in nT, is stored internally in the microprocessor's memory. The value is sent out to the serial RS-232 port in response to the character, 'v', being received through that same port (9600 baud). Another measurement can be initiated by either momentarily shorting the RESET input of the microprocessor to ground (with, for example, an external push-button switch) or, alternatively, by sending the character, 'm', to the serial port. When the microprocessor has finished a measurement, it sends the character, 'r', to the serial port to indicate that it has a measured value stored within its memory. Either upper or lower case letters may be used for these commands to the microprocessor. To summarize:

Your action	Microprocessor's response
'm' or 'M'	It starts a measurement, It sends an 'r' when finished
'v' or 'V'	It sends out the measured value
Push-button pressed	same as if it received an 'm' or 'M'

The unit is intended to be controlled by an external computer or terminal. The push-button switch should be added only if you want to also allow manual initiation of the measurement cycle.

Relay module

The relay used is an Omron G2R-24-DC12 (available from Digikey). The coil requires 12V to activate and the contacts are rated for 5A. My sensors have a resistance of about 7 Ohms so the current through them will be about 1.7 A during the polarization cycle. Since the polarization current is not turned on till after the relay contacts have closed and is turned off before they open again, there will be no arcing of the contacts so the relay lifetime should be good.

The 10K resistor across the sensor during the polarization cycle is used to dissipate the 'ringing' in the sensor after the polarization current is turned off.

Putting it all together

The diagram showing the interconnections between the various parts of the complete circuit is given in the file: Connections.pdf. The push-button switch is optional if you are using a computer to control the device.

For use in marine or mobile treasure hunting, you would probably want to have a computer continuously interrogating the stand-alone PPM and storing the measured values on disk for future reference. If you wanted to make a horizontal gradiometer using two sensors separated by a boom and two copies of the electronic circuitry, you could use a computer with two serial ports: serial ports are inexpensive. The computer could then control the two magnetometers and measure (and store for future reference) the difference between them. Gradiometers are not sensitive to changes in the local magnetic field causes by ionospheric currents.

The programmed microprocessor for this project may be ordered from the author for $25 plus $3 PP. You will also receive a parts list and a list of distributors for some of the more difficult to get components. Please state how long you want the polarization portion (in seconds) of the measurement cycle to last. The address is:

From November to April:

J.A. Koehler
3290 N. Koehler Rd.
Florence, AZ, 85232

From April to November:

J.A. Koehler

RR2, Site 292, C56
Courtenay, BC, V9N-5M9
Canada

All year Email: koehler@mars.ark.com

Construction hints

A. The sensor and desired polarization times

I have been deliberately vague about the construction of the sensor because so there are so many possibilities. Let me give some examples.

Suppose you want to construct the stand-alone magnetometer to use in marine treasure hunting. In this application, the sensor will be towed behind a boat at the end of a long cable and you will want to make successive measurements as rapidly as possible because you are looking for changes in B as you drag the sensor over a wreck. Here you can make the sensor quite large – several kg of the hydrogen rich liquid. You might, for example, make a toroidal sensor with more than a litre of hydrogen-rich liquid and with a calculated output signal of more than 10 μV. Using water, it takes ~2 to 3 seconds to get the liquid to within 1/e (~1/3) of the maximum polarization – this is called the 'spin-lattice relaxation' time. But, because the signal is so large, **you don't need to get the maximum polarization** and so can make this part of the cycle much shorter – perhaps just a second or so long. The measurement part of the cycle takes about ½ second so measurements could then be made every ~1.5 seconds or so. Alternatively, with this large a sensor, you could use kerosene as the sensing liquid. It produces a weaker signal than water but has a much shorter spin-lattice relaxation time and only needs to be polarized for about a ½ second. This means that measurements can be made about one per second.

For a magnetic observatory, you don't usually have any constraints on size and you may only want to make one measurement every minute or so. However, you may be unable to use water as the hydrogen-rich liquid because it would freeze outdoors. If you do use kerosene as the liquid, because its spin-lattice relaxation time is so short, there is no point in polarizing for more than about a second.

For a hand-held prospecting device, you normally want to make the sensor as small as possible because weight is so important. Here, you would normally use water as the liquid because it gives you the greatest sensitivity and you would want to be sure that you have achieved maximum polarization. For these reasons, you would want the polarization phase to take at least five seconds and, hence, could not make observations more frequently than one every six seconds or so. If you are walking from one location to another, this is going to be fast enough.

B. Circuit construction

The ultimate best solution is to lay out and produce proper pc-boards. The end results are then very easy to make and are very reproducible. However, laying out and producing pc-boards is a very expensive proposition because of the set-up charges. Most boards go through at least two iterations before getting to the final stages. If anyone is interested in undertaking this as a project, I'd be glad to help in every way possible – but I'm not willing to do it myself.

I often use a method of construction which is very simple, electronically very good, but which takes more space and looks somewhat messy. That is to use a piece of double sided pc-board and to grind 'pads' for component mounting with a Dremel tool or similar. The components are then sort of 'surface-mounted' from pad to pad. The conductor surface is used as the electrical ground and is connected to the conductor on the bottom of the pc-board which then acts as a ground plane. The bottom surface also acts as a nice shield and finished boards may be stacked on top of one another.

An example of this form of construction is shown in the picture: construction.jpg. This board is, in fact, an early version of the tuned amplifier used in this PPM. IC's like the microprocessor, the op-amp, the comparator and the oscillator should be mounted in sockets. Smaller IC's like the DS1233 or the LM394 can be soldered directly to the pads like all the other components.

You have to spend some time in planning and laying out the board beforehand but the final product is mechanically robust and electronically good. The circuits used here can be laid out on three small boards which are large enough to make for easy assembly – there's plenty of room to easily accommodate all the parts. The boards can then be stacked on top of one another separated by aluminum spacers using nylon bolts.

For the prototype circuit, I built the system on four boards as described above. The preamplifier was on one board, the intermediate amplifier on a second board and the tuned amplifier and the comparator were built on a third board. These were all done using the 'Dremel technique'. The microprocessor circuit was built on a separate board using wire-wrap. Each board was about 6.5x9cm (about 2.5"x3.5").

What if I don't have (or don't want to use) a computer to control the thing?

I designed the stand-alone PPM to interface to a computer because I actually use two of these units as the two slaves in a gradiometer (see PPMJAK). The master controller is the 'computer' which controls the two slaves.

To make a completely self-contained magnetometer which doesn't require an external computer, it is possible to do one of two things:

1. add a small microprocessor based computer to control the PPM and to display the results, or,
2. use some of the uncommitted pins on the PPM microprocessor to display the results on an LCD display unit. There are enough pins available.

The first alternative is the simplest but most expensive. I already have the design of a small microprocessor board (pc-board design already done!) using another 90S2313 microprocessor, an RS-232 interface and a LCD display. It would be a very simple matter to program this unit to interface with the stand-alone PPM and to continually display the measured values and the difference between the measured value and it preceding value. I estimate the cost of building one of these units to be less than $50 – the most expensive item is the LCD display. If there was enough demand, I would be willing to undertake the development of this board (i.e., program the microprocessor). Contact me if you're interested.

The second alternative requires more programming of the existing 90S2313 microprocessor and is somewhat more complicated. It is actually not much less expensive than the first alternative because the major cost is the LCD display. If anyone is interested in pursuing this alternative, I'd be glad to give what assistance I can.

Making a gradiometer

A gradiometer requires two sensors and two copies of the circuit. All the active components used in this circuit are double. That is, the LM394 has two identical transistors in the package – enough for two low-noise preamplifiers. The same goes for the intermediate amplifier. The LM324 low power op-amp has four op-amps in the package – enough for two tuned amplifiers. The LM2903 comparator has two comparators in the package – enough for two circuits. The MAX202 TTL/RS-232 converter has four circuits in it – two transmitters and two receivers – enough to make two RS-232 interfaces.

Therefore, one can essentially make the gradiometer by just adding the passive components needed to duplicate the circuit. For a gradiometer, only a single 10 MHz oscillator is required – it should drive both microprocessors in parallel; and, only a single DS1233 microprocessor RESET supervisor is used – both microprocessor RESET- lines are tied together.

I have built a prototype gradiometer in which I use another microprocessor, a 90S8515, to act as the computer getting the signal from the two 'slaves'. The general features of such a system are described in the PPMJAK. I expect to make available the details of the circuit and programmed 90S8515's at a later date.