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ABSTRACT

Proton precession magnetometer is a scalar magnetometer which is used in the total component measurement of the magnetic field. This paper describes an attempt to develop a proton precession magnetometer for the measurement of diurnal variation of the earth magnetic field in Sri Lanka. The magnetometer constructed consists of a sensor in dual solenoid configuration, containing water as the proton rich material, and an amplifier chain which was designed to suite the magnetic field measurements in Sri Lanka and a polarizing and energy dissipation handling circuit controlled by a Microchip PIC16F877A microcontroller. The proton precession signal which is in the audio range was digitized using a sound card of a personal computer and the frequency of the proton precession signal was determined using fast Fourier transform. 50 hours observations of the diurnal variations of the geomagnetic field, carried out in a location at Wattala, Sri Lanka was used to asses the functionality of the system.

1. INTRODUCTION

Proton precession magnetometer is a scalar magnetometer which is used for the measurement of the total magnetic field of the earth. The measurements of geomagnetic field is important for mineral and petroleum exploration, geological mapping, search for buried or sunken objects, magnetic field mapping, geophysical research, magnetic observatory use, measurement of magnetic properties of rocks or ferromagnetic objects, archaeological prospecting, conductivity mapping, gradiometer surveying, and magnetic modeling[1].

In particular, due to the fact that the geomagnetic equator lies over Sri Lanka, geomagnetic measurements carried out in Sri Lanka are very important for geomagnetic and ionospheric research [2,3]. However, only a few measurements carried out in this region have been reported [2,3,4]. The proton magnetometer described in this paper was developed with a view to fill this gap through the initiation of a geomagnetic research program.

The proton precession magnetometer is based on the precession of protons in a magnetic field [5]. The magnetic dipoles of protons (hydrogen nuclei) contained in a sample of water or a hydrocarbon are temporarily aligned or polarized by application of a magnetic field produced by a current in a coil of wire. When the current is suddenly removed, the spin of the protons causes them to precess about the direction of the earth magnetic field. This precession of protons causes a small signal in the same coil used to polarize them. The frequency of the signal is proportional to the total magnetic field intensity.

2. MAGNETOMETER CONSTRUCTION

Figure 1 shows the basic arrangement of the proton precession magnetometer constructed. The main functional blocks were the sensor, polarizing and energy dissipation handling circuitry and the amplifier chain. The frequency of the detected signal was determined by Fourier analyzing the signal, after digitizing it using the sound card of a computer.

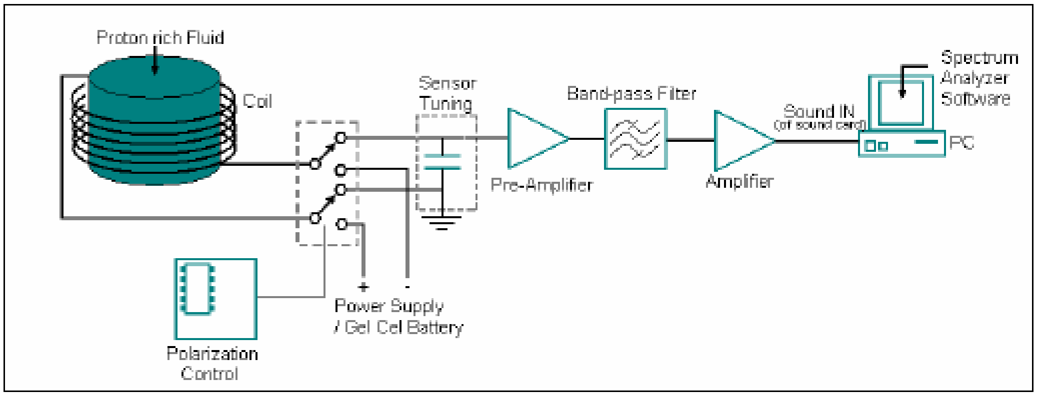

Figure 1: Functional blocks of the proton magnetometer

2.1 Sensor

The heart of the proton precession magnetometer is the sensor which consists of a coil of copper wire wound around a container filled with a proton rich material such as water. From the various configurations available for the sensors [6], dual solenoid configuration was selected due to its property of cancellation of noise generated outside the coil.

In this configuration, two identical single coil sensors are placed side by side for sensing the same magnetic field. The coils are connected in series so that the signals generated inside them are added together. In this arrangement, any noise induced in the two coils due to external sources will be canceled.

Two plastic bottles having a diameter of 5.8 cm and a coil woundable section of 7.8 cm were used as the containers (figure 2). Plastic and glass are suitable substances for the containers as they being non magnetic do not alter the local geomagnetic field. While water, Benzene, Kerosene are suitable as the proton rich samples, double distilled water was used due to its low cost and ease of use. The other reason for the use of water was its absence of reaction with plastic.

The induced rms signal voltage from a practical sensor is in the order of micro volts. To add to this problem is the Johnson noise generated due to the finite resistance of the sensor. Hence, it is important that the sensor has good signal to noise ratio for a given bandwidth Δ of the band pass filter. For a dual solenoid sensor which is constructed with identical containers of radius $\boldsymbol{r_c}$ length $\boldsymbol{b}$ wound with $\boldsymbol{n}$ turns of wire of resistivity ρ in $\boldsymbol{l_s}$ number of layers the induced rms proton precession signal $\boldsymbol{V_{rms}}$ is [7],

$$V_{rms} = \eta_{single} \frac{\chi \omega_L \mu_0 \eta_m n E \pi r_c^2 r_w^2 \sin\alpha}{2\sqrt{2} b \rho (r_c + r_w l_s)} \qquad (1)$$

where χ is the nuclear paramagnetic susceptibility of the proton rich material used, μ_0 is the magnetic permeability of free space, ***E*** is the voltage of the polarizing supply used, ω_L is the Larmor precession angular frequency of the proton precession signal and α is the angle between the local geomagnetic field and the axis of the sensor. η_m (filing factor) is a factor introduced to account for the inequality of the polarizing field through out the entire cross section of the sensor.

$$\eta_m = \exp(-1.4 r_c / b) \qquad (2)$$

We have introduced an additional factor η_{single} to account for the more fringing of the fields at the four ends of the dual solenoid sensor when compared with its singles solenoid counterpart.

$$\eta_{single} = \exp(-1.4 r_c / 2b) \qquad (3)$$

The signal to noise ratio (SNR) of the signal is given by,

$$SNR = \eta_{single} \frac{\chi \omega_L \mu_0 \eta_m \sqrt{n} E \pi r_c^2 r_w^3 \sin\alpha}{2b[(r_c + r_w l_s)\rho]^{3/2} \sqrt{19.2 k T \Delta}} \qquad (4)$$

where ***k*** is the Boltzman constant and ***T*** is the temperature of the sensor fluid.

7.8cm

Figure 2: Partially completed sensor at right and completed sensor at left.

In the sensor design phase, the required gauge of the copper wire, number of turns and the number of layers were determined with the help of the above equations in order to obtain an rms voltage and SNR of close to 1 μV and 100 respectively. In the design phase it was also ensured that the resistance of the sensor was in the vicinity of 10 ohms because a high resistance quickly dissipates the signal via joule heating. The inductance was kept at less than 50 mH as higher inductance means that it takes a longer amount of time to turn off the polarizing field, which leads to greater degradation of the signal. The specifications of the dual solenoid sensor is shown in Table 1.

2.2 Polarizing and Energy dissipation handling circuit

The magnetic dipole moments of the protons cause the protons to precess in the magnetic field inducing a time varying field in the coils. However, precession of all the protons in the proton rich medium is not in phase. So for this to occur, first the proton rich medium is subjected to a strong magnetic field by connecting the coil to a power source. This is referred to as polarization. A 12 V battery was used as the polarizing supply for the magnetometer. After waiting for the alignment of dipoles to take place which is governed by the spin lattices relaxation time, the sensor is disconnected from the power supply. At this point, the signal is picked up by the sensor and it is connected to the amplifier chain to amplify the signal.

Table 1: Sensor Specifications

Parameter	Value
Wire gauge	SWG 23
Coil wound section length	7.8 cm for each container
Diameter of bottle	5.8 cm
Number of Turns	Container 1 – 657 turns / Container 2 – 659 turns
Number of Layers	7 layers each
DC Resistance	Measured - 16.9 Ω
Inductance	Measured - 31.6 mH
Polarizing Current (for 12 V supply)	0.71 A
Maximum current allowed	0.94 A
Filling Factor	0.7562
rms Signal Amplitude	Estimated - 0.54 μV
SNR (for a bandwidth of 250 Hz)	Estimated – 61 dB
Resonant Capacitor (for a precession frequency of 1715 Hz)	272 nF

Typically water has a spin lattice relaxation time between 2 to 3 seconds. So polarization of water for 5 seconds yields a magnetization between 81% and 92%. Longer polarization to achieve 100% polarization is avoided as longer polarization means the data gathering interval becomes longer, resulting in reducing the number of data points gathered. After the polarization, the magnetization of the protons decay in an exponential manner and hence the signal disappears after few seconds. Hence the proton rich material has to be subjected to polarization again. The signal pickup duration was selected as 5 seconds to reduce the strain imposed on the relay in switching back and forth. So this arrangement yields a data point every ten seconds. The switching based on these timing requirements were handled by Microchip PIC16F877A microcontroller based circuit shown in figure 3.

Sensor is connected to *SENSOR CON1* and *SENSOR CON2* inputs. The *RELAY CMD* and *POLARIZE CMD* are the commands applied to the GATE of T_1 and T_2 HEXFET s respectively. Once The *RELAY CMD* and *POLARIZE CMD* are made high the sensor is connected to the polarizing supply via the relay. After 5 seconds of polarization, *POLARIZE CMD* is made low while keeping the *RELAY CMD* high. This forces the energy stored due to sensor inductance to dissipate and this requires 2 ms. After waiting for the specified amount of time *RELAY CMD* is made low and the sensor is connected to amplifier. This allows the signal to be amplified and processed to extract the magnetic field information. After waiting in signal pickup phase for 5 seconds the whole cycle is repeated.

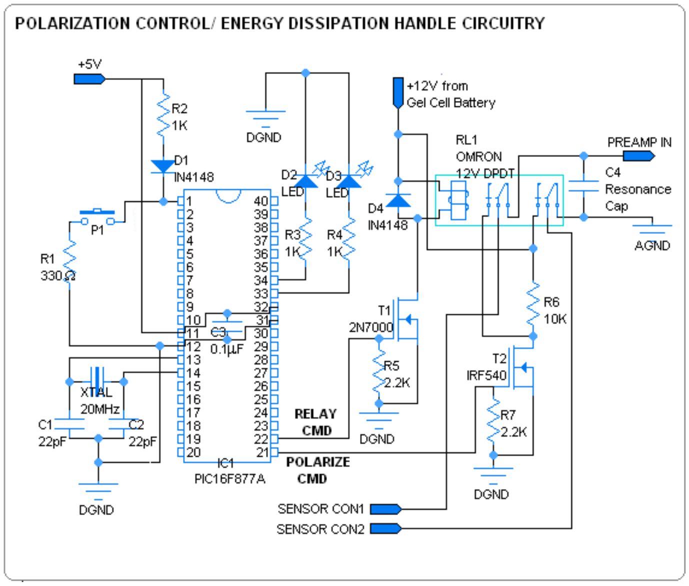

Figure 3: PIC16F877A based polarization and energy dissipation handling circuitry

2.3 Sensor Tuning and Amplification

Prior to connecting the signal to the amplifier, the signal is allowed to resonate hence slightly increasing its gain prior to inputting it to the amplifier chain. According to the predictions based on the International Geomagnetic Reference Field (IGRF) which is a is a mathematical description of the Earth's main magnetic field developed by the International Association of Geomagnetism and Aeronomy [8], the nominal geomagnetic field total component in Colombo region is around 40300 nT which corresponds to a Larmor precession frequency of 1715 Hz. With the expected Larmor precession frequency and the measured inductance, equation 5 was used in the calculation of the value of the resonant capacitor required for a particular sensor. Resonating the sensor has an additional advantage of providing initial band pass filtering. The required capacitance was obtained by connecting several Mylar capacitors in parallel configuration.

$$C_r = \frac{1}{4\pi^2 f_L^2 L} \qquad (5)$$

The amplifier constructed consists of three separate but complementary sections - pre amplifier, band pass filter based on multiple feedback band pass filter and a final gain amplifier, as shown in figure 4. The amplifier chain was based on a low noise amplifier OP77 with a noise voltage rating of 10 nV/(Hz)$^{1/2}$ at 1 kHz. Metal film resistors were primarily used as resistors throughout the amplifier chain to reduce the addition of Johnson noise. The center frequency of the amplifier chain was 1778.3 Hz with a bandwidth of 173 Hz. The largest geomagnetic field variations that can be expected is during magnetic storms and they can be as large as 1000 nT (which correspond to 43 Hz). Therefore a band pass filter having a center frequency of 1715 Hz and a bandwidth of 86 Hz may be the best choice. But the geomagnetic field predicted by the IGRF model is merely a guidance and not an absolute reality as various external sources can further modify the local geomagnetic field. Hence a much larger bandwidth was used for the band pass filter to increase the chances of detecting the proton precession signal.

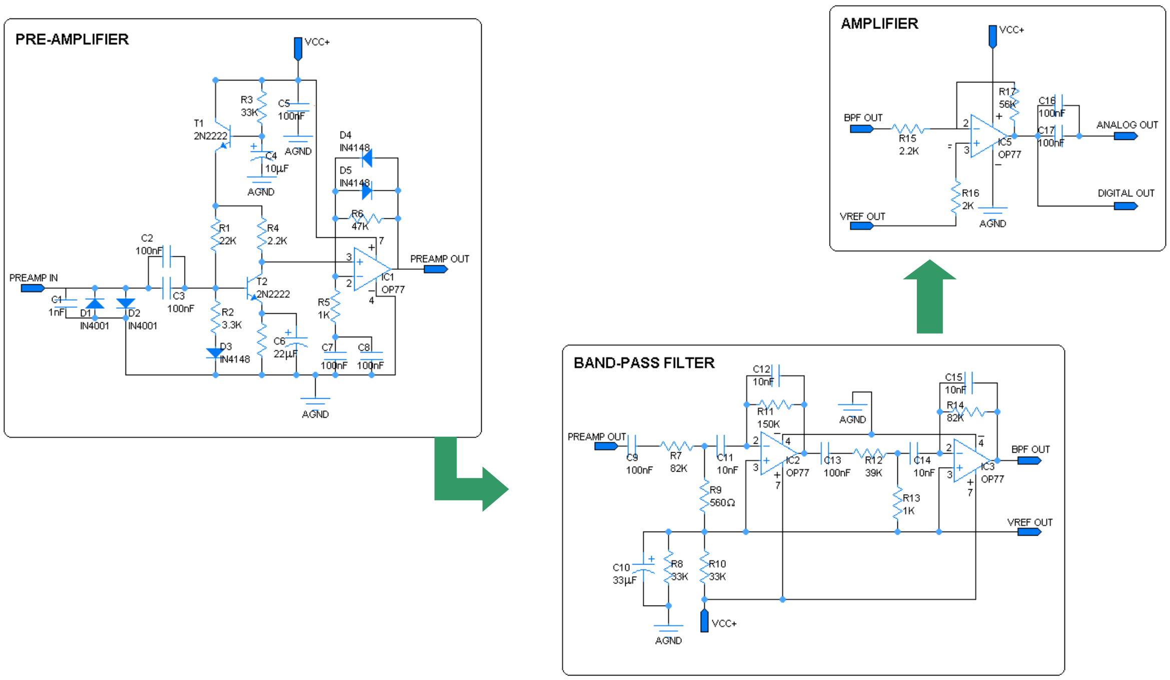

Figure 4: Amplifier chain used in the Proton precession magnetometer

2.4 Signal Analysis

Because the proton precession signal is in the audio range, a sound card of a laptop computer could be used for digitization and the resulting data were analyzed using a software package called Spectrum Lab [9]. The sensor was placed so that it is perpendicular to the local geomagnetic field in order to obtain a signal of maximum rms magnitude (according to equation 1). Sri Lanka has a geomagnetic field declination of – 2.9 degrees which implies that the field vector is almost parallel to the earth surface hence the sensor was placed so that its axis is perpendicular to ground.

The preliminary investigations conducted at a location in Nugegoda revealed a FFT peak corresponding to 1780 Hz (geomagnetic field of 41823 nT). The authenticity of the signal was verified by bringing a screwdriver which has the effect of increasing the gradient along the sensor which result in the disappearance of the signal and the reduction of the signal amplitude when the sensor axis is oriented parallel to ground.

Permanent noise peaks picked up by the sensor were visible as stripes in the waterfall display. The proton precession signal appeared as a dot in the waterfall display due to its decaying due to spin lattice relaxation and this further verifies that the FFT peak observed is indeed the proton precession signal (figure 5). The duration of the proton precession signal was found to be between 0.7 and 0.8 seconds with the help of DSP.

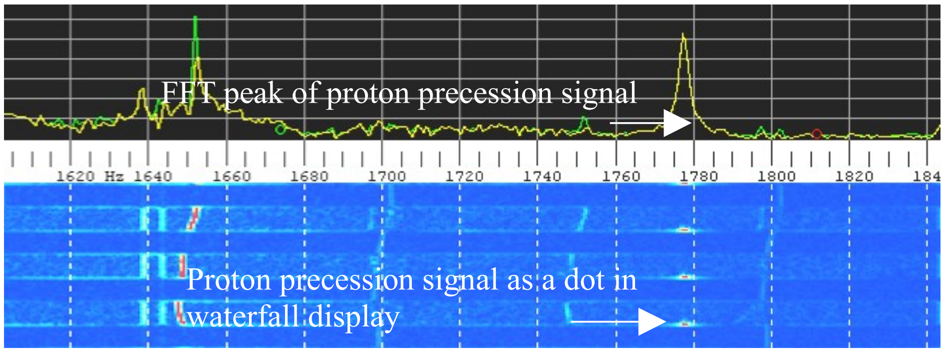

Figure 5: FFT peak associated with proton precession signal.

The geomagnetic field value was determined via the Larmor relation,

$$B_0 = 23.496241 \times f \qquad (6)$$

where B_0 is the geomagnetic field in nT and f is the frequency of the proton precession signal in Hz. The geomagnetic field was calculated by considering frequency of the proton precession signal as the frequency associated with the FFT peak. The accuracy of the result is primarily governed by the resolution which is the ratio of sample rate to the FFT length used. Data was obtained at a location in Wattala using a spectrum setting of 11,025 sample rate and a FFT length of 16,384 which proved to be the optimum setting that could be used in Wattala to ensure that the peak detected was always the FFT peak associated with the proton precession signal and not a permanent external noise peak picked up by the sensor. This setting gives an uncertainty of ± 4 nT for the calculated field values.

The observed geomagnetic field variation observed in Wattala (figure 6) lies between 40,040 nT and 40,220 nT which is consistent with the predicted IGRF model [7]. Based on hourly means, the peaks for day 1 and day 2 were observed at + 89 nT and + 53 nT respectively from the overall mean of 40,096 nT for 50 hours.

3. CONCLUSION

The results described above indicate that the developed proton magnetometer is capable of measuring the earth magnetic field with sufficient precision for the study of diurnal variations. However, for studies of geomagnetic micropulsations, the precision needs to be improved further.

The main difficulty that had be faced in the development of this instrument was the low signal to noise ratio of the precession signal. The approach used in overcoming this difficulty was to digitize the signal and employ digital signal processing techniques, which required the use of a laptop computer. In order to make a more portable instrument, the digital signal processing component will have to be developed in an embedded computer.

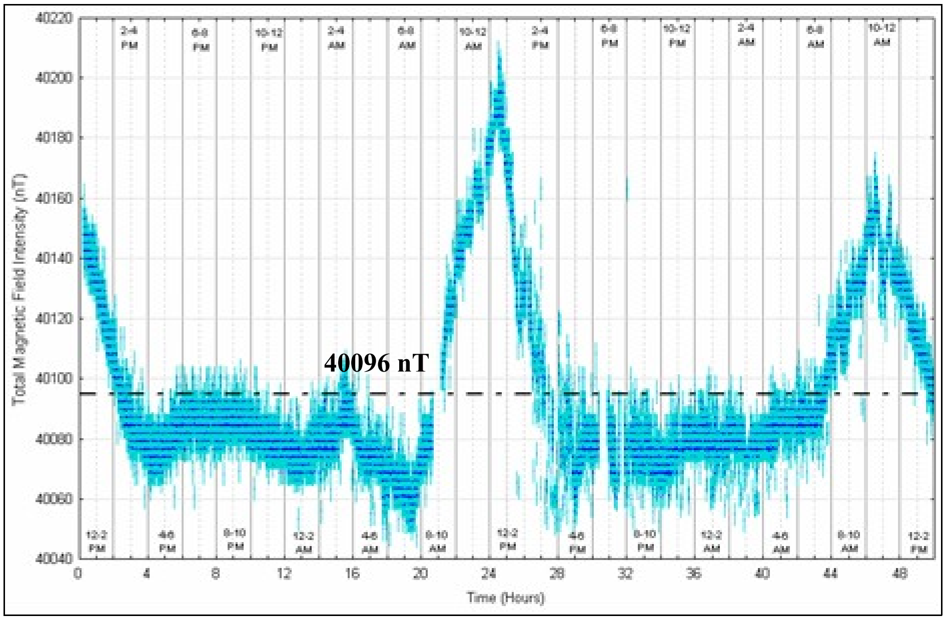

Figure 6: The diurnal variations of the geomagnetic field from 05.30 hours (GMT) on 17.05.2007 to 19.30 hours (GMT) on 19.05.2007 at Wattala. (raw data)

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