3.5 Magnetometers

- The dip needle
- The fluxgate magnetometer
- The proton precession magnetometer

Magnetometers are instruments used to measure $\mathbf{B}$. They contain either a magnetic dipole which experiences a measurable torque in a magnetic field or a magnetic material whose magnetization (which depends on $\mathbf{B}$) can accurately be determined.

Component magnetometers measure the component of $\mathbf{B}$ in a specified direction.

Total Field magnetometers measure the magnitude of $\mathbf{B}$, $|\mathbf{B}|$.

The dip needle

The first magnetometers consisted of a magnetized needle resting horizontally on a pivot at its mid-point. Such a needle will experience a torque to line the dipole axis up with the Earth’s field just as a compass needle on a vertical axis pivot will align itself with the horizontal component of the field.

In a vertical plane containing $\mathbf{B}$, the torque on a needle of magnetic moment $\mathbf{M}$ is given by:

$$\text{Torque} = \mathbf{M} \times \mathbf{B}$$
In practice the needle is set up with a counterweight, $W$, to balance the torque and then small departures in dip, $\Delta \theta$, are measured as changes in the vertical component occur.

The practical sensitivity of dip needle magnetometers is about 10 nT. Very carefully made versions, operating in temperature-controlled environments, provide excellent long-term field measurements with sensitivities of 1.0 nT.

The fluxgate magnetometer

The fluxgate magnetometer was developed in WW2 for submarine detection. It is a component device and makes use of the fact that changes in the Earth’s field move the operating point up and down on the hysteresis curve of a ferromagnetic core or element. This core links two solenoidal windings, one carrying a DC and an alternating current which produces a field $H$ along the axis, and another which
measures the voltage induced by the changing B (=\mu H) field. If the device is operated such that the DC level of H lies just at the bend in the B-H curve then the core will saturate more in one polarity than in the other and the output voltage, proportional to dB/dt, will be an asymmetric waveform. Small changes in the DC level of H, the changes in that component of the Earth’s field, have relatively large changes in the asymmetric output waveform and these are measured in the detector circuit.

The sensitivity of the fluxgate is about 1.0 nT. The units are small, about an inch long, and three components are usually packaged together.

A fundamental problem with all component magnetometers is their sensitivity to motion in the Earth’s field. Consider a vertical fluxgate magnetometer in the field T with an inclination of 45°.

\[ Z = T \sin \theta \]

If it tilts slightly off vertical by d\theta then
\[ dZ = T \cos \theta \, d\theta. \]

So if \( T = 50,000 \) nT and \( \theta = 45^\circ \) then a d\theta of 0.1°(0.00174 rad) produces a change in the output of 61.5 nT - about 60 times the sensitivity. Usually in a field practical instrument it is not possible to orient the device well enough to utilize its sensitivity.
The proton precession magnetometer

A proton has an angular momentum \( L \) and a magnetic moment \( M \).

The time rate of charge of angular momentum is equal to an impressed torque \( T \). If the body has a magnetic moment the torque is:

\[
T = M \times B
\]

so \( dL/dt = M \times B \)

For the proton there is a fundamental relation between angular momentum and magnetic moment:

\[
M = eL / 2mc
\]

so \( dL/dt = L \times eB / 2mc \)

This is the equation of motion for a vector \( \mathbf{L} \) precessing (rotating) in space about the \( \mathbf{B} \) direction with an angular velocity, \( \omega_L \), given by

\[
\omega_L = -eB / 2mc
\]

The precession frequency is called the Larmour frequency. In a 50,000 nT field \( \omega_L \sim 2100 \text{ Hz} \).
The bottle of water (protons) is subjected to a brief high strength polarizing field which lines up all the protons in the $z$ direction.

When the polarizing field is terminated the protons precess around $B_0$ and produce a $dB/dt$ which is detected by the second multiturn emf sensing coil. The frequency of the detected voltage is proportional to $B$. The coherent precession lasts only a few seconds before random thermal motion take over. This type of device measures the amplitude of $B$ (independent of orientation unless $B$ coincides with $z$ – commercial devices use toroids).

It is insensitive to temperature, and vibration.

Sensitivity: 1.0 nT (0.1 nT with long averaging)
Will not work in high spatial gradients (different $B_0$ in different parts of the container confuse the frequency measuring circuit).

The proton magnetometer measures only the magnitude of the vector field. For anomalies, $\Delta B$, small compared to the Earth’s field it can be seen in the following sketch that the change in the magnitude of the total field, $\Delta T$, is approximately equal to the component of the anomaly vector in the Earth’s field direction. So for most anomalies the changes in $T$ are actually the changes in the component of the anomaly in the inducing field direction. Since almost all surveys are now done with total field (proton) magnetometers the anomalies from models of specific subsurface targets are usually presented in the total field direction.

If $\Delta B \ll T$, $|\Delta T| \sim \Delta B \cos \theta$