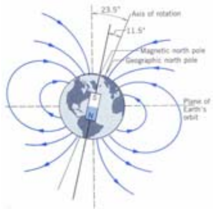
Magnetometers

FYS3610

Earth magnetic field

- Earth magnetic field larges at the poles (~ 60 000 nT) and smallest as the equator (~ 30 000 nT).
- The earth's magntic field strength is proportional to $1/r^3$ (until the influence from the solar wind gets noticeable).



Magnetometers

- Search coil magnetometer.
- Fluxgate magnetometer
- Proton magnetometer
- Hall effect sensor
- Magnetoresistive sensors
- SQUIDs

Search coil magnetomer

- Based on **Faraday's law of magnetic induction**, which state that an emf V is induced in a conducting coil placed in a time varying magnetic flux Φ.

$$V = -N\frac{d\phi}{dt} = -N\frac{d(\mu_0\mu_r \cdot A \cdot B_p)}{dt} = -NA\mu_0\mu_r \cdot \frac{dB_p}{dt}$$

(A coil of N turns wound on a material with a relative magnetic permeability μ_r and cross-section area A is placed in a variable magnetic flux density B which has a component B_p along the axis of the coil).

Search coil magnetometer

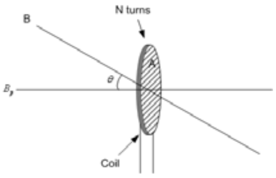
- Assume the coil is placed in a spacecraft, and the angel between the earth's magnetic field B and the component B_p perpendicular on the coil is θ. Assume the magnetic field has an simpel harmonic variation with time:

$$\Downarrow$$

$$B_p = B\cos\theta \cdot \sin(\omega t)$$

$$\Downarrow$$

$$V = -AN\mu_0\mu_r \cdot B\omega \cdot \cos\theta \cdot \cos(\omega t)$$



Search coil magnetometer - properties

- The signal strength is proportional to the frequency of the magnetic field.
- This type of magnetometers requires a changing magnetic flux relative to the coil; **can't measure a static B-field !**
- Signal strength proportional with the cores $\mu_r \rightarrow$ the size of the sensor coil can be redused by using a core with high μ_r
- Direction sensitive.
- Suitable fore measuring high-frequency fluctuations.

Search coil magnetometer

The measured magnetic field has three components:

- signal because of movement of the sensor in a stationary field (change the angel θ).
- Time variations in the magnetic field (what we are interested in)
- ”Time variations” caused by spatial variations in the field (instrument placed on a moving spacecraft → not measuring at the same point i space at different times t).

This three contributions are generally not possible to separate directely, but the interesting component can be separated e.g. by using a band pass filter (as long as the other signals doesn’t have frequency components in the same range).

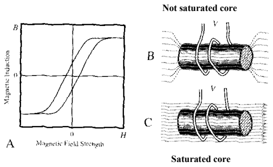
Search coil magnetomer

- One is usaually interested in B rather than dB/dt, so an analog integrator is usually used to obtain a signal proportional to the magnetic field B.

Flux-gate magnetometer

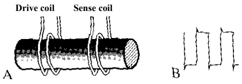
Principle:

An external magnetic field H applied to a ferromagnetic core, induce a magnetic flux B in the core; **B = μH** (μ is the permeability of the material). For high H values the material saturates, and the magntic flux B can not be further increased. **When the core is not saturated, the flux lines in the vicinity are drawn into the core. When the core is saturated, the magnetic flux lines are no more affected by the core**



Flux-gate magnetometer

- Two coils are wounded on a feritte core, a **driver coil** and a **sense coil**.
- The driver coil drives the core into and out of saturation, by applying an **exitation current** through the coil.
- Whenever magnetic flux lines are drawn out of the core, they induce a positive current spike in the sense coil. When they are drawn inside the core, they generate a negative current in the sense coil. (**Lenz law**).
- The induced signal in the sense coil is proportional to dB/dt



Flux-gate magnetometer

- The excitation current in the driver coil will induce a corresponding current in the sense coil, with the shown arrangement of the two coils. And this signal will be superimposed on pulses induced by the external magnetic field.
- To awoid this, the driver coil must be placed orthogonal with respect to the sense coil.

Flux-gate magnetometer - properties

- Suitable for measurement of static and slow varying fields.
- Time resolution of the instrument tied to the frequency of the magnetic field (excitation current) generated by the driving coil.
- Direction sensitive.

Proton-magnetometer

- A proton in a magnetic field has a energy of:

$$E_{mag} = \mu \cdot B = g_n \cdot \beta_n \cdot I \cdot B$$

where μ is the protons magnetic moment, B is the magnetic flux density (which we want to measure), I is the **angular momentum** of the proton and g_n is a konstant ($g_n = 5.586$ for a proton).

- I can have two values; +1/2 and and -1/2. **This means that the protons in a magnetic field will be divide in two groups with different energy states (Zeeman effect).**

Proton-magnetometer

- With radiowaves it is possible to induce transitions between the two states, as long as the radiowave energy is exactly equal to the energy difference between the two states. This **resonance condition** is given by:

$$\Delta E_{mag} = hf = g_n \cdot \beta_n \cdot B$$

Operation of the instrument:

- The radiowave is turned on, so that almost every proton have a transition to the highest energy state.
- The radiowave is turned of → the protons return to the lowest energy state, and electromagnetic radiation is irradiated.

Proton-magnetometer

- The magnetic flux density B is proportional to the frequency of the radiation :

$$B = \frac{h}{g_n \cdot \beta_n} \cdot f = C \cdot f$$

($C = 2.3488 \cdot 10^{-8}$ T/Hz)

- Measures the total magnetic field !

Hall sensor

- A current (I) is passed through a conductor / semiconductor, located in the magnetic field (B). The current carriers (electrons / holes) experience a **Lorentz force** due to their motion, and deviate them perpendicular to I and B. The resulting charge build-up on the faces of the conductor gives rise to an additional electric field that cancel the magnetic force. This additional field is sensed by electrodes on the semiconductor faces (measures the voltage difference between the faces of the conductor).

Magnetoresistive sensors

- Use the property that some materials change their resistivity in the presence of an external magnetic field (caused by the Lorentz force).
- Most conductors have a positive magnetoresistivity; i.e. their resistance increase in the presence of a magnetic field
- (Usually connected in a Wheatstone bridge)

SQUID

- SQUID = **S**uperconducting **q**uantum **i**nterference **d**evice.
- **Most sensitive magnetometer** (Sensitivity of around 1fT/Hz$^{1/2}$; about 10^3 to 10^6 more sensitive than other high sensitivity magnetometers).
- Formed from superconducting rings and Josephson junctions.
- Can use high-temperature superconductors (cooling down to 77 K).
- Best sensitivity been optained with low-temperature semiconductors (cooling down to 4 K).

SQUID

- Cooling downt to such low temperatures means a large and very complex system !

Magnetometers in a rocket / spacecraft.

- Magnetic materials within the spacecraft will be sensed by the magnetometer (static B-field)

  → avoid magnetic materials in the spacecraft.

- Time varying currents in the cable harness (signal lines) create AC-magnetic fields, which are picked up by the magnetometer

  → mount the magnetometer on the end of a boom, which are deployed away from the sapcecraft.

  → use twisted pairs and coaxial cables in the cable harness, to reduce the magnetic interference from the rocket.

Magnetometers in a rocket / spacecraft.

- With 3 magnetometer units, one can measure the magnetic field in all 3 directions.