Spacecraft Attitude Dynamics

prof. Franco Bernelli

Attitude sensors

Sun sensor

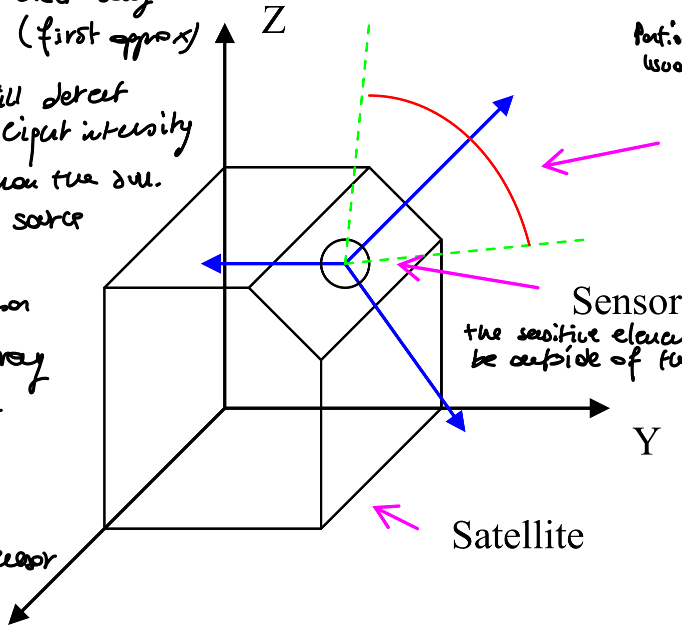
family: - Horizon sensor could detect the border of a celestial body with a big angular dimension such as it is possible to detect the position and the dimension of a celestial body.

- Sun sensor will detect only a point source (first approx)

- Star sensor will detect star with a light intensity much lower than the sun. Star are point source

- magnetic field sensor depend on the accuracy of the model are pretty useful

- Inertial sensor gyroscope, rate sensor
  ↓
  more general



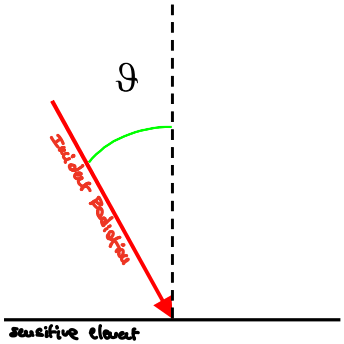
Portion of space seen by the sensor → usually a fixed characteristic FoV < 180°
↑ because there is the S/C on the other end.

the sensitive elements must be outside of the S/C.

Some of the feature of the sun sensor are common between sensor that need to identify celestial body.

- (GPS, GALILEO, GLONASS, BEIDOU) GNSS → allow a receiver to detect it's own position
  ↳ not diffuse, problem with accuracy.

Sun sensor → work on the basis of photoelectric effect



Constant that depends on the surface

$$I = I_0 \cos\vartheta = \alpha S W \cos\vartheta$$

Photo electric effect

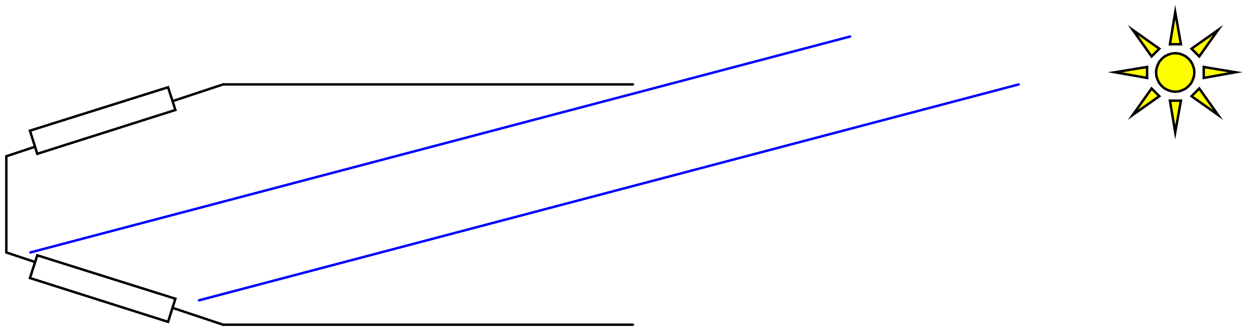
The sensor becomes less and less accurate as the angle ϑ grows → The cosine law is valid for an angle up to ±60° and then it is not accurate enough beyond that. That is still sufficient because they can give us a field of view of 120°.

On the base of this sensor we can design and build different kind of sensor.

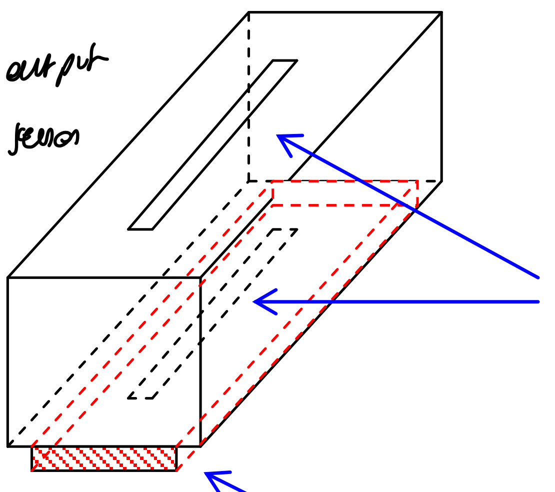
Sun presence sensor and Sun sensor

Have narrow fov and they give the information of the presence of the sun in the narrow field of view.

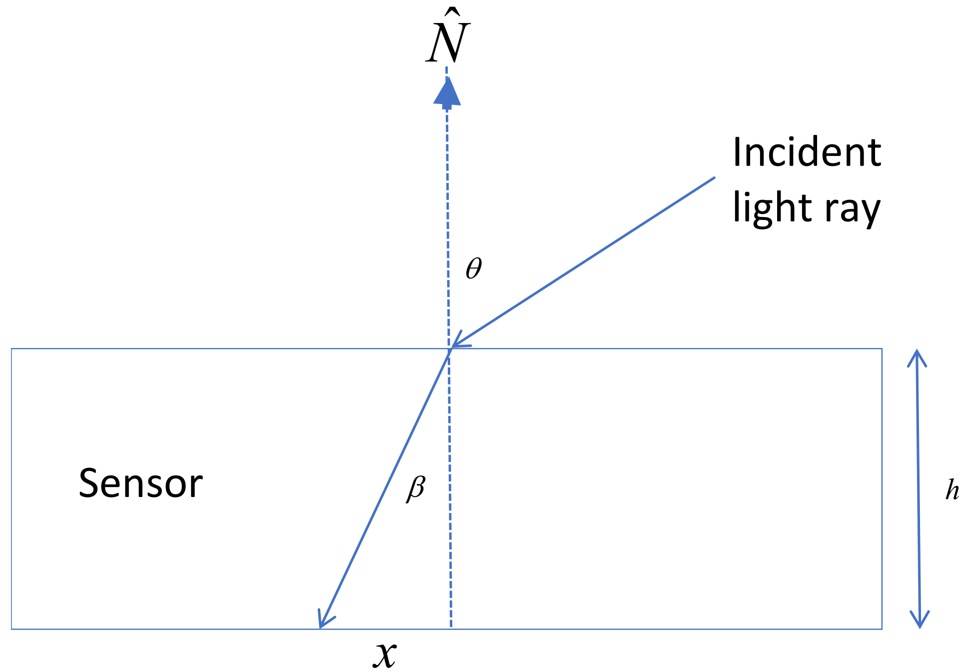
Sun presence sensor



no need to make a precise measurement of the output of the cell → we need to know only if the sensor see the Sun.



Sun sensor



Snell's law

Need to take into account that to interpretate correctly the output of the photocell

direction of the incoming radiation

$$n \sin \beta = \sin \theta$$

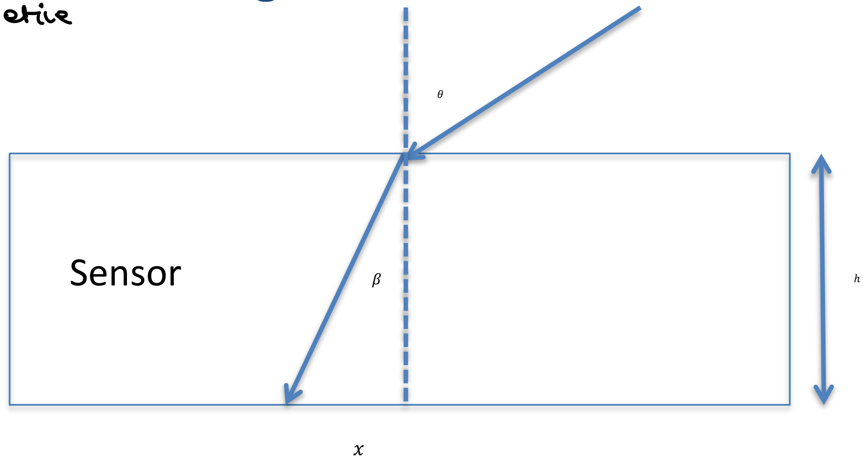
n is the refractive index

known

Sun Sensors for computing the Sun angle

we do not know if θ is positive or negative

$$\widehat{N}_i \cdot \underline{s} = \cos\theta_i$$



$$\begin{bmatrix} \cos\theta_1 \\ \cos\theta_2 \\ \cos\theta_3 \end{bmatrix} = \begin{bmatrix} \widehat{N}_1 \cdot \underline{s} \\ \widehat{N}_2 \cdot \underline{s} \\ \widehat{N}_3 \cdot \underline{s} \end{bmatrix} = \begin{bmatrix} \widehat{N}_1^T \\ \widehat{N}_2^T \\ \widehat{N}_3^T \end{bmatrix} \underline{s}$$

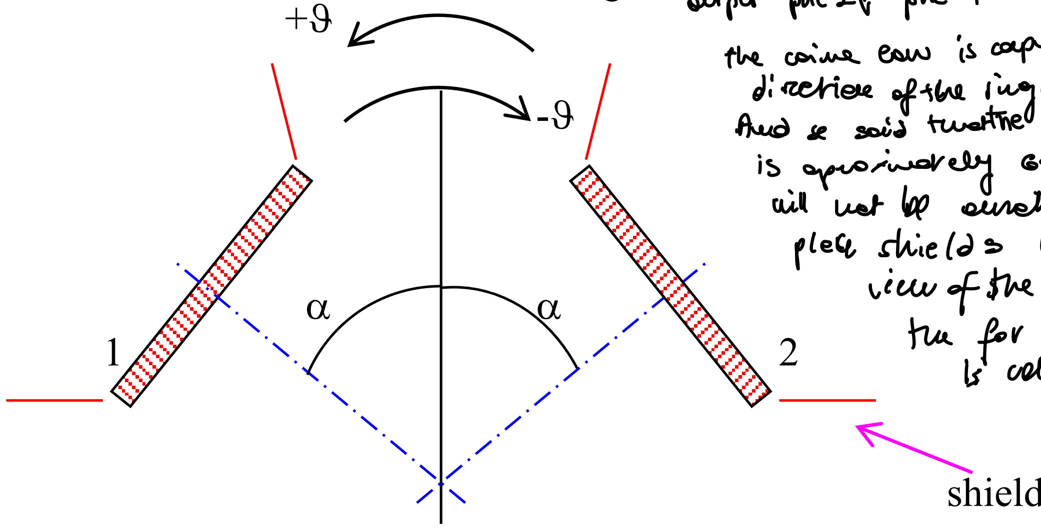
$$\underline{s} = \begin{bmatrix} \widehat{N}_j^T \\ \widehat{N}_k^T \\ \widehat{N}_l^T \end{bmatrix}^{-1} \begin{bmatrix} \cos\sqrt{3}\,x_j/h \\ \cos\sqrt{3}\,x_k/h \\ \cos\sqrt{3}\,x_l/h \end{bmatrix}$$

Analog Sun Sensors

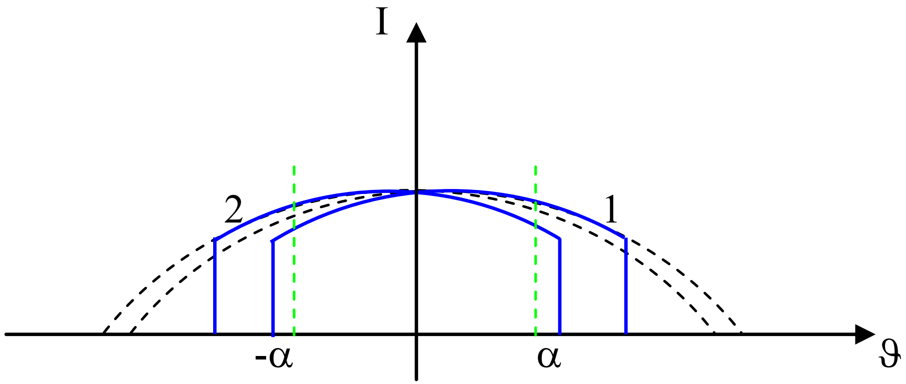
→ if we place two photocell inclined wrt to one another we will see that

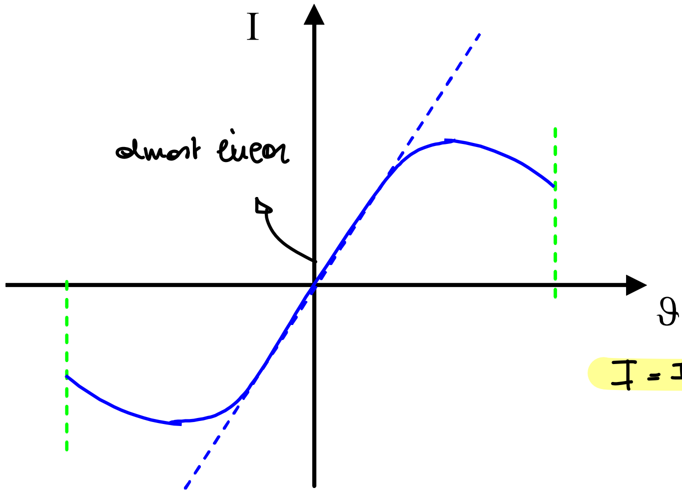
$+\vartheta$ output phc 1 ↑ phc 2 ↓
$-\vartheta$ output phc 1 ↓ phc 2 ↑
} we can identify the angle of the rotation

the cosine law is computed from the normal direction of the single photocell.
And we said that the maximum angle is approximately 60° then the output will not be correct. So it is important to place shields limiting the field of view of the single photocell to the for where the cosine law is valid



Analog Sun Sensors



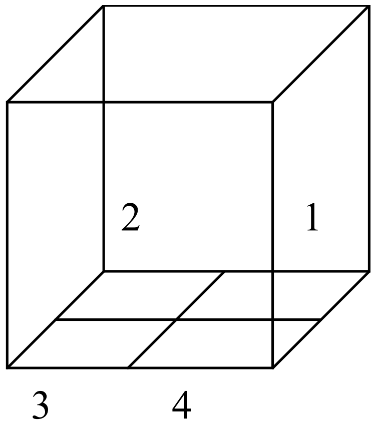


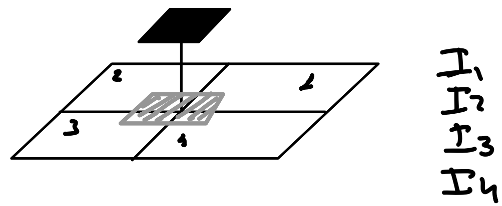
$I = I_1 - I_2$

$$I = cos(\vartheta - \alpha) - cos(\vartheta + \alpha)$$
$$= cos\,\vartheta\, cos\,\alpha + sin\,\vartheta\, sin\,\alpha - cos\,\vartheta\, cos\,\alpha$$
$$+ sin\,\vartheta\, sin\,\alpha = 2\, sin\,\vartheta\, sin\,\alpha = k \cdot sin\,\vartheta$$

Analog Sun Sensors

→ Another type of sensor, using a obstructive element we can calculate the position of the sun.
The sun position depends on the position of the shadow that will reduce the intensity output of the four cells.





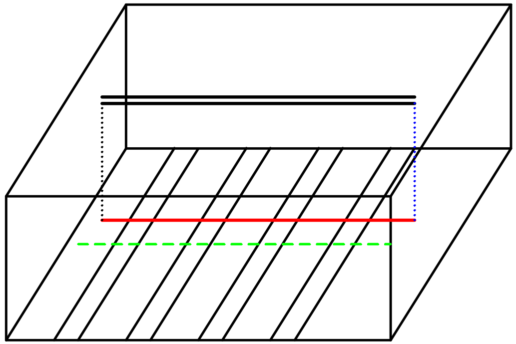
$$I = cA_0 \cdot \underline{i} \cdot \underline{n}A_0 = f(\vartheta, \phi)$$

→ then we will need to calculate the inverse relation starting from the direct function.

$(\theta, \phi) \rightarrow I$ direct

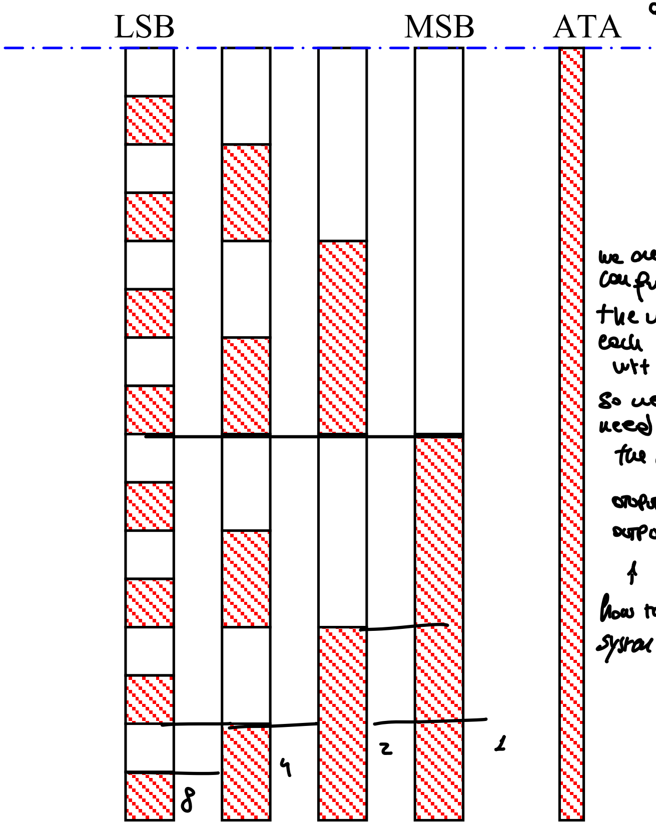
$I \rightarrow \theta, \phi$ inverse.

Digital Sun Sensors



The main drawback of this method is when the sun is in a middle position. between a cover part and not cover part ⇒ transitional state this is a problem because we have uncertainty due to some random noise that it is added

Automatic threshold adjust



we are confronting the value of each bit wrt ATA so we do not need to use the cosine law

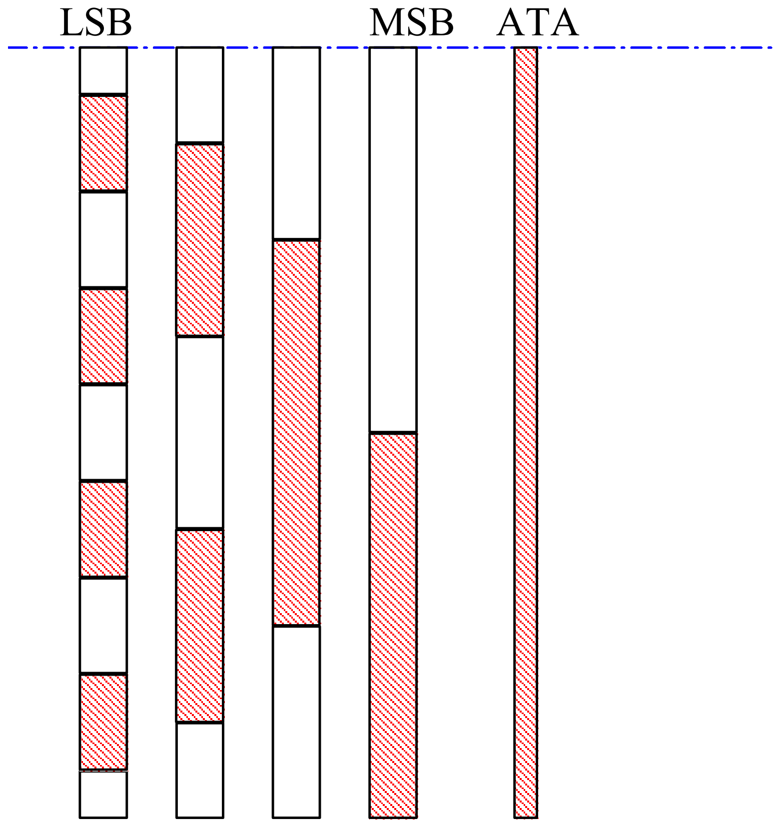
output > ATA = 1
output < ATA = 0

how to build binary system

This cell is half of the previous one

Digital Sun Sensors

⇒ | Automatic threshold adjust does not depends on the cosine law!



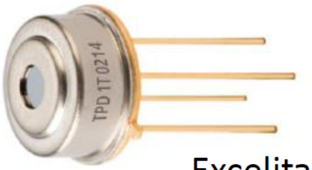
Analog	Binary	Gray
0	0000	0000
1	0001	0001
2	0010	0011
3	0011	0010
4	0100	0110
5	0101	0111
6	0110	0101
7	0111	0100
8	1000	1100

↳ Rule to convert Binary value to a integer

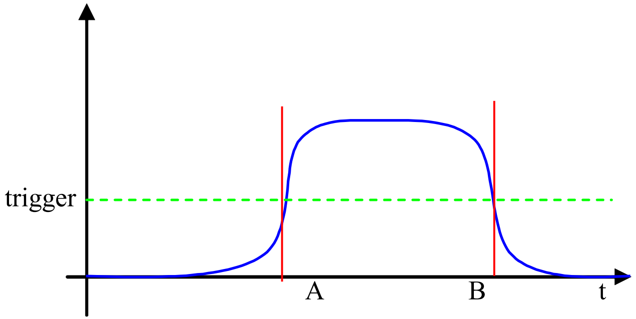
With 7 bits we have 64 degrees FOV, with 8 bits 128 degrees FOV.

Earth horizon sensors – thermopile detector

The earth could correspond to a hole of the celestial sphere → so we need to find the horizon of the sphere to determine it's position.



Excelitas thermopile detector
TPD 1T 0214 G9 / 3850



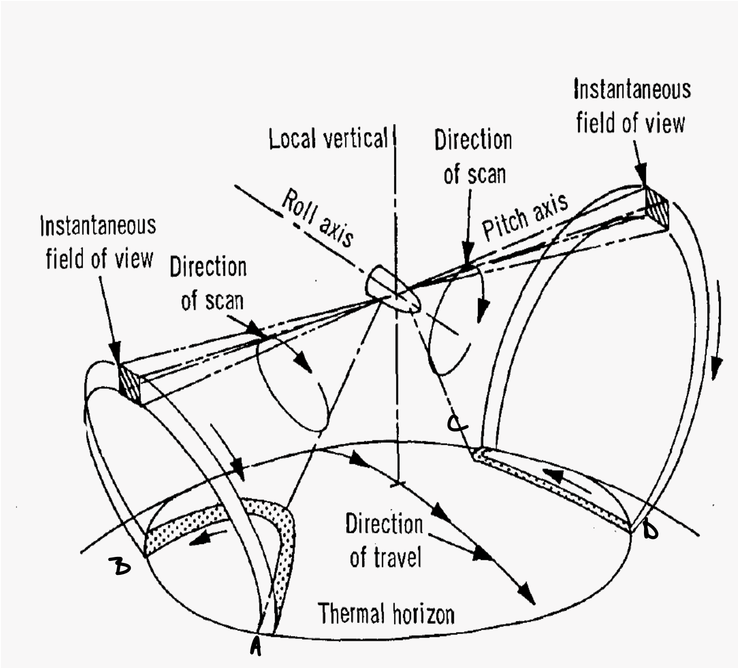
- Thermopiles convert thermal energy into electrical energy → Infrared wave → emitted by the earth even during the day
- Detect Earth's IR spectrum ↳ much higher ratio of $\frac{\text{Emission Sun}}{\text{Emission Earth}}$
- Two types of sensors (i) Scanning sensor FOV 7-10 deg (ii) Fixed pointing to Earth 60-70 deg
- IR sensors still work in an eclipse

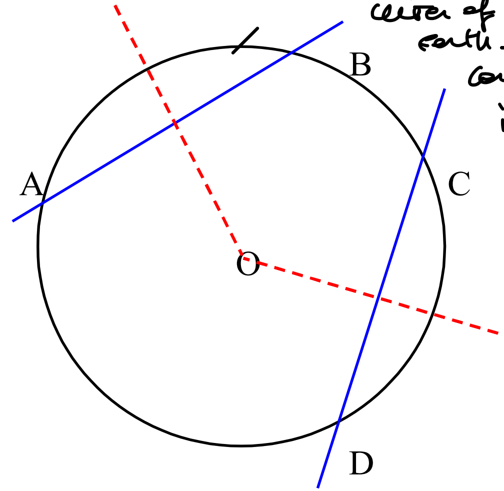
so it is easier to find the edges of a planet.

Scanning EH sensor

There are two types of sensor to detect horizons of celestial body.

Scanning EH sensors have a very narrow field of view → when we are detecting something for the first time or last time we are starting a detecting point. These four points given by two sensor tell us two cords → the normal to the cords is the direction of the middle point center of the earth. With two cord we get an intersection





Horizon Sensors

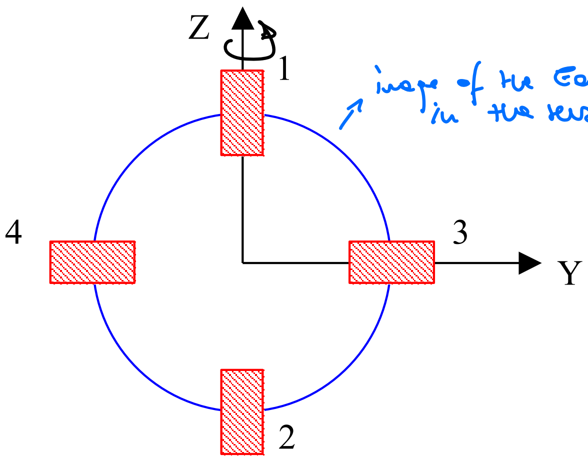
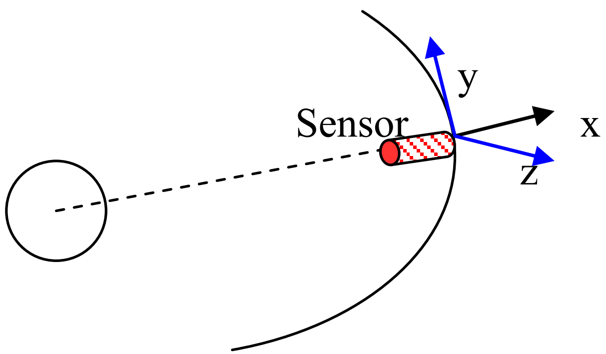


image of the Earth in the sensor frame

4 sensor configuration

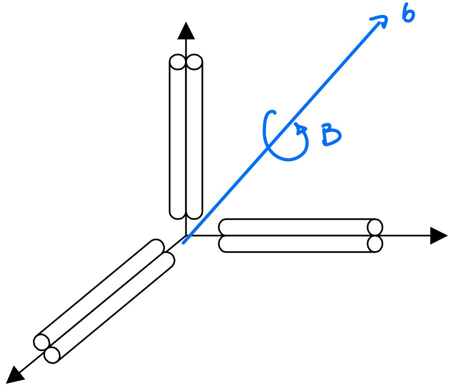
$$(1)-(2)=\Delta z \text{ proportional to } \alpha_y$$

$$(3)-(4)=\Delta y \text{ proportional to } \alpha_z$$



Attitude determination with a magnetometer

Using three pairs of nuclei, as shown below, we can measure the components of the magnetic field along three orthogonal directions, so the B vector.

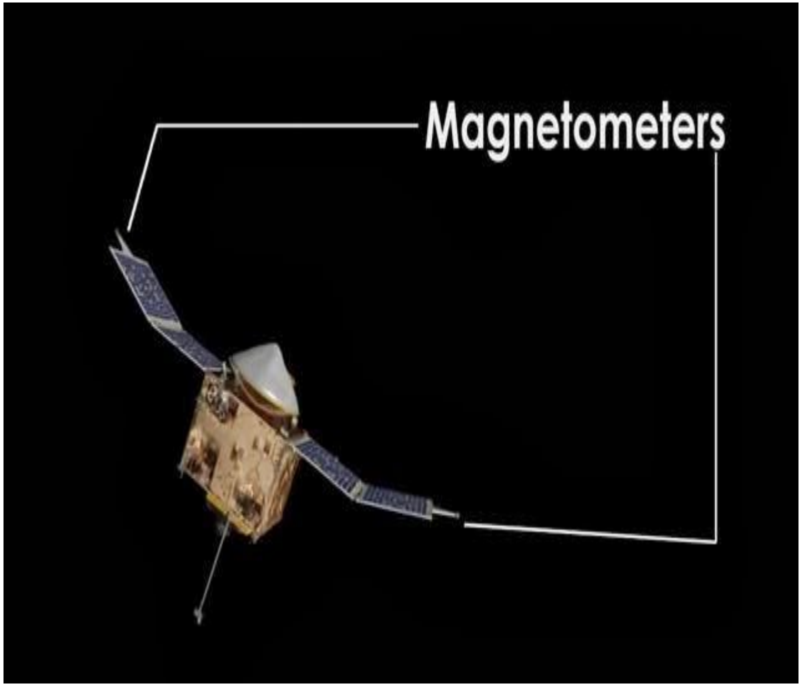


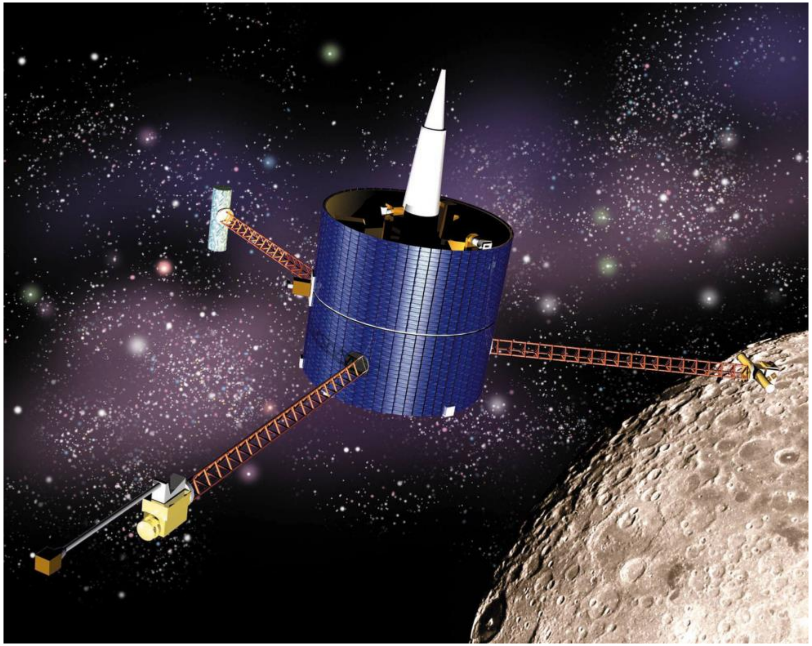
Provides a vector measurement of the local B-field

$$\left\| \underline{b}_B - A_{B/N}\underline{b}_N \right\| = 0$$

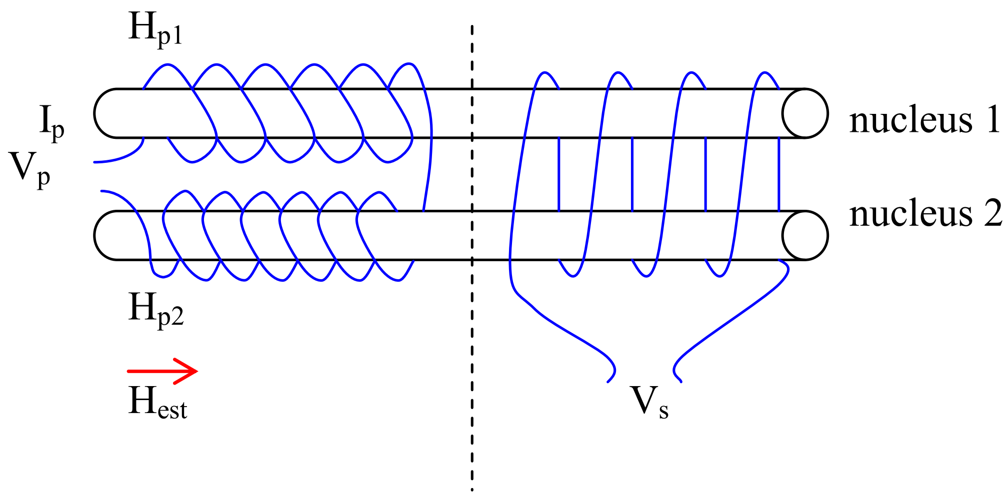
Minimize $$J = \left\| \underline{b}_B - A_{B/N}\underline{b}_N \right\|^2$$

Design magnetometer device from the flux gate concept. If we have a fixed element we can identify the component of the b vector along its axis. With three stationary element we can identify any generic direction and intensity of the b vector in space.


Magnetometers



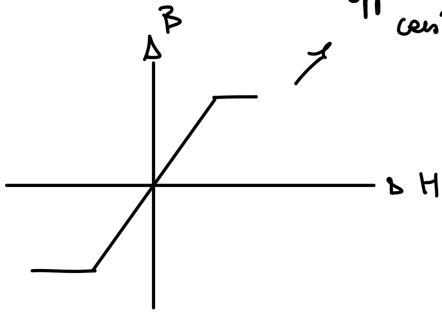
Fluxgate magnetometer



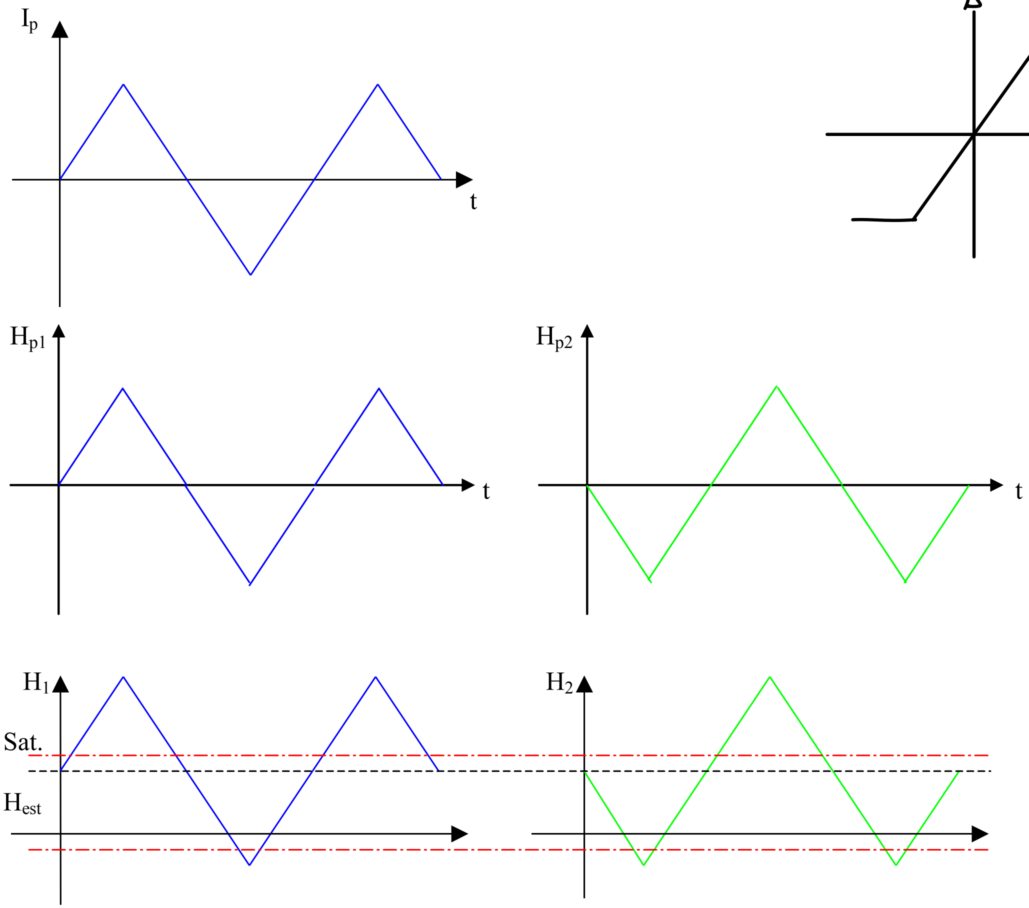
The magnetic field is not proportional to the induction due to the saturation behaviour.

$$\boxed{V_s = -\frac{d\varphi(B_1 + B_2)}{dt}}$$

Fluxgate magnetometer

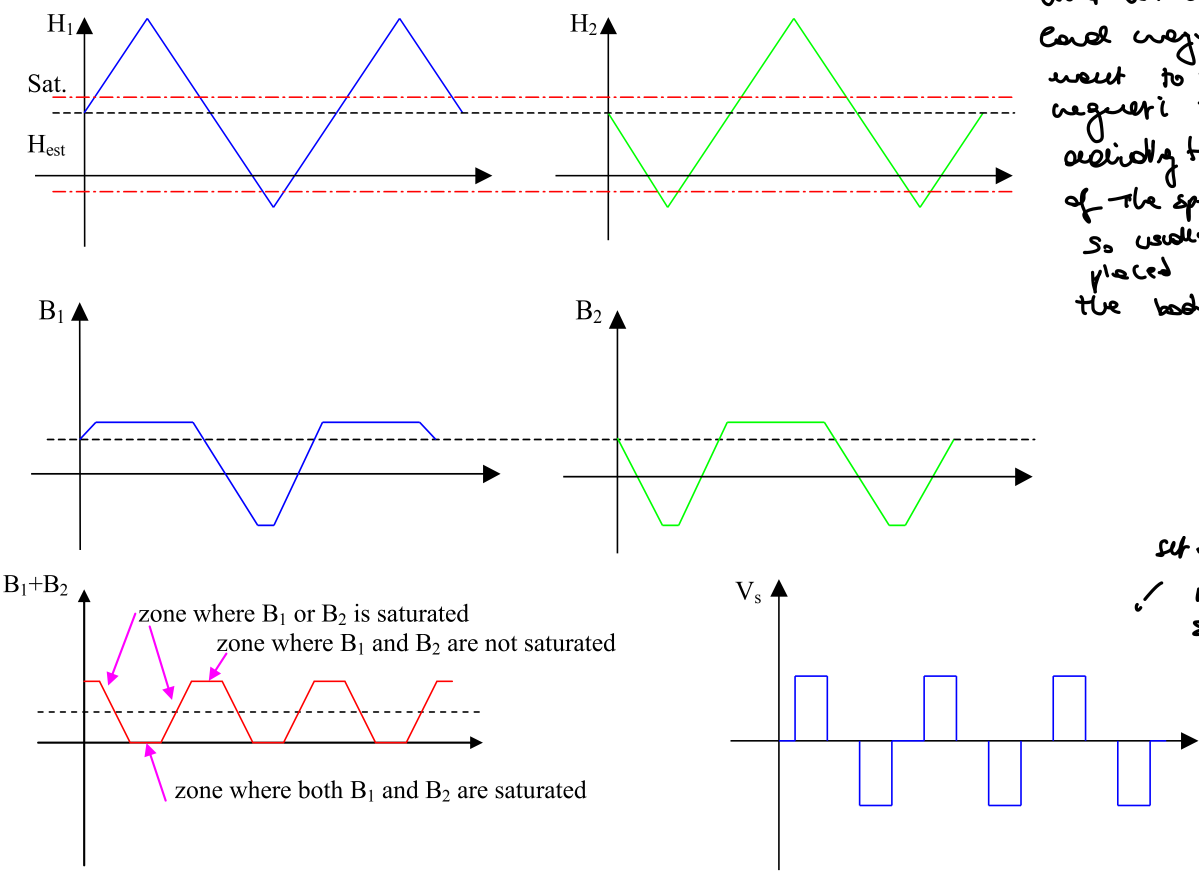


approximation, we are not considering hysteresis phenomena



Fluxgate magnetometer

Magnetic field sensor can be made really small easily.
What we are measuring is the earth magnetic field but we want to measure the magnetic field of the Earth avoiding the magnetic state of the space craft.
So usually the magnetometer are placed as far as possible from the body of the space craft.



set of impulses

we can calculate B from the separation of the impulses.

B↑ low separation

B↓ high separation of impulses