Attitude & Orbit Control Systems:

orientation

Links to other subsystems:

- Payload → pointing requirements drive AOCS design
- Orbit
- Config. → influenced by FoV requirements and specific orientation of satellite
- Structures → for large, light-weight structures w ↓ fundamental freqs., the flexibility needs to be taken into account
- Propulsion → controlled by AOCS

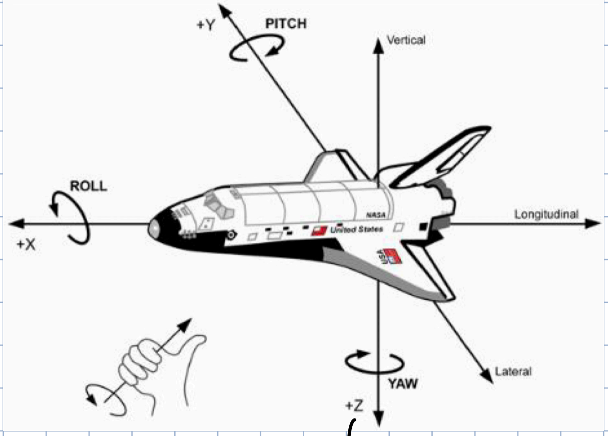
Attitude Control: orientation in space

To control attitude, spacecraft must have ability to:

→ determine current attitude

→ determine differences between current & desired attitude

→ apply torques to change attitude



z points to Earth's centre ('nadir')

Attitude Control used for:

- Detumbling
- Earth pointing
- Sun pointing
- Tracking
- Safe mode

used when something goes wrong:

→ point solar panels at sun

→ point antennas at earth

→ everything else off

Orbit Control used for:

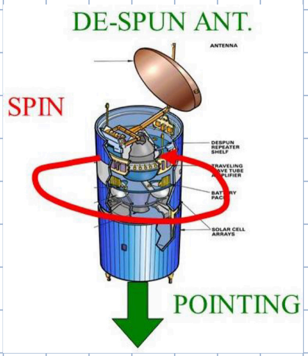
- Launch vehicle trajectory
- Orbit injection
- Single impulse manoeuvres
- Hohmann transfer
- Interplanetary flight
- Orbital rendezvous

Orbital control covered already:

→ changes at perigee made at apogee

Spacecraft Stabilisation :

- Spin stabilisation → use spin to give gyroscopic stability in inertial space

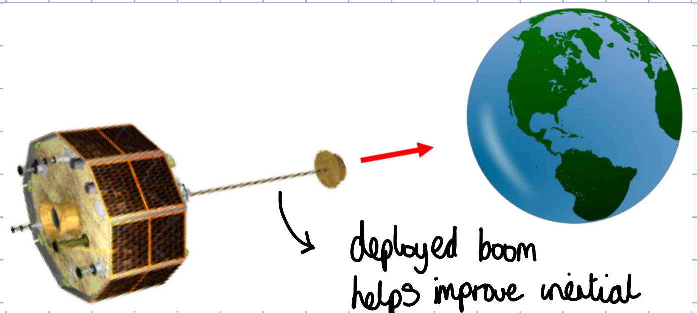


Takes adv. of resistance of spinning body to disturbance torques.
Thrusters used to remove procession
Control of moments of inertia required.

Pros : low cost, long life, provides scan motion

Cons : poor manoeuvrability, pointing is challenge, one axis fixed, low power.

- Gravity gradient → 'long satellites' tend to point towards earth as closer portion feels slightly greater gravitational force



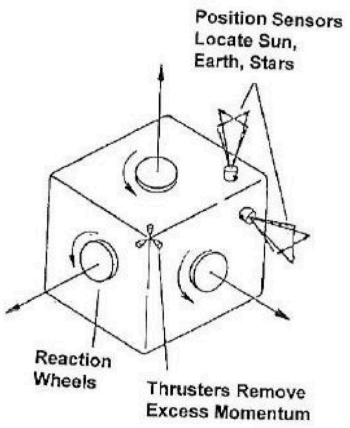
deployed boom
helps improve inertial
properties

Takes adv. of spacecraft to align its long axis w. gravity vector
Gravity torques must be > disturbance torques (usually < 1000km)
Momentum wheel often used to provide yaw stability

Pros : Simple, low cost, long life, nadir pointing

Cons : low accuracy, poor manoeuvrability, poor yaw stability

- Three - axis control → active control



Most commonly used now

Spacecraft treated as aircraft → seperate control / actuation per principle axis

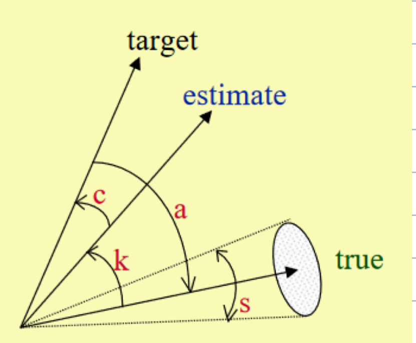
Asymmetry or momentum wheels = cross - coupling between axes

Conceptually simple but requires more actuators

Pros : larger flexibility during operation

Cons : more complex and costly

Pointing Control :



Target - desired pointing direction
True - actual pointing direction (mean)
Estimate - estimate of true (instantaneous)

a - pointing accuracy (long-term) = attitude error
s - Stability (peak - peak) motion = attitude jitter
k - knowledge error
c - control error

We need to know what pointing accuracy required and then what knowledge of the accuracy (usually 10% of pointing accuracy)

Pertubations :

- So far we've considered point masses

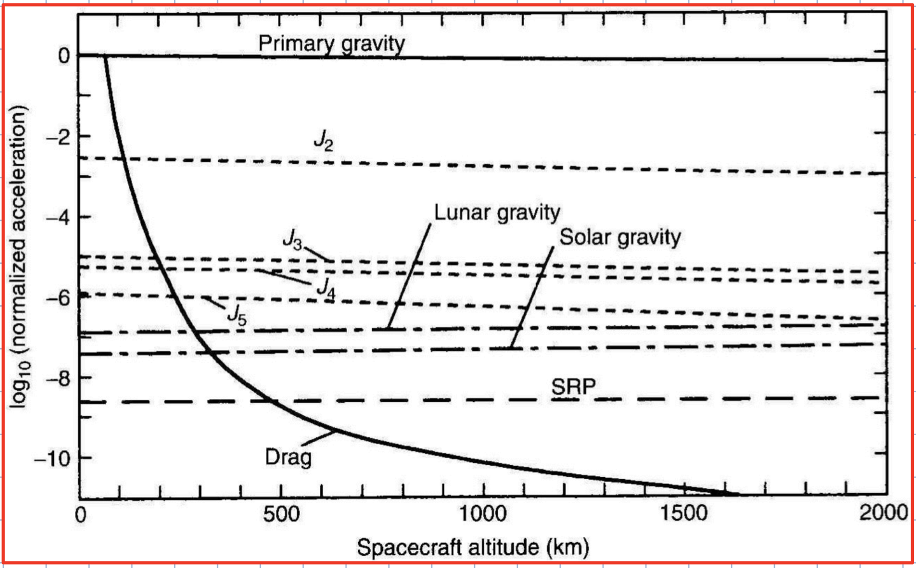
  ↳ in reality nothing is ever in orbit around a point-mass without any other pertubations

- The two-body problem is usually the dominant orbital dynamic. Everything else is reguarded as a small pertubation.

$$\ddot{r} = -\frac{\mu}{r^3} r + a_p$$

The spacecraft in orbit is subject to small forces & torques arising from:

1. Non-sphericity of Earth (or other attracting body)
2. The moon & sun and other bodies
3. Gravity gradient
4. Interaction with magnetic field
5. Aerodynamic drag of residual atmosphere
6. Solar radiation pressure
7. Satellite centre of mass
8. Operation of mechanisms



J2-5 : effects due to non-sphericity of earth

Magnetic Torque : especially concerning for polar LEO satellites

$$\boxed{T = DB}$$

T → torque (Nm)

D → Spacecraft electric field strength (Am^2)

↳ from electric circuit currents

B → local magnetic strength (Tesla)

↳ at poles : $B = \frac{2M}{R^3}$

at equator : $B = \frac{M}{r^3}$

Drag :

$$\boxed{F_{drag} = \frac{1}{2}\rho V^2 C_D A}$$

A → impacted area

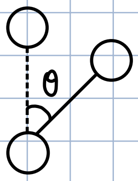
C_D ↳ usually 2.2 for spacecraft

Gravity Gradient Torque :

$$\boxed{T = \frac{3\mu}{2r^3}\left|I_z - I_y\right| . \sin 2\theta}$$

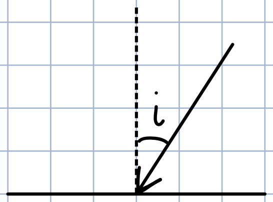
max torque at 45°

→ reduces w. altitude



Solar Radiation Pressure :

$$\boxed{T_{srp} = F\left(\overset{\text{centre of pressure (m)}}{c_{ps}} - \overset{\text{centre of gravity (m)}}{c_g}\right)}$$



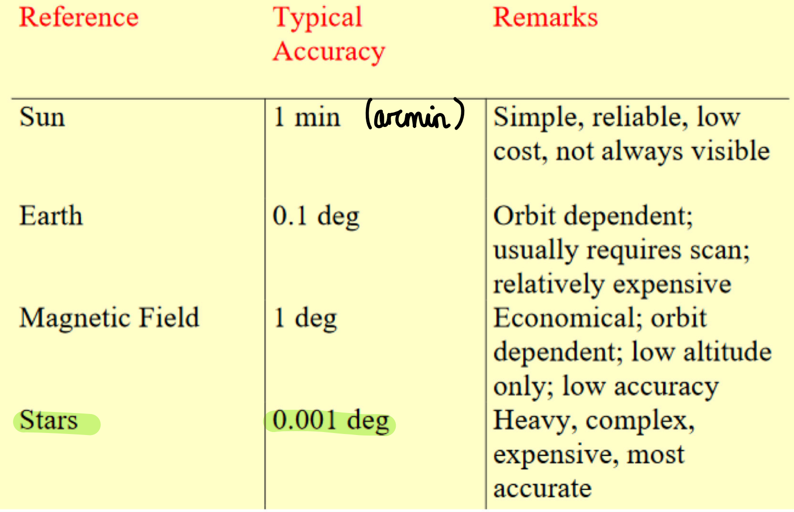
$$\boxed{F = \frac{\overset{\text{solar flux at Earth (1370 W/m}^2\text{)}}{G_s}}{\underset{\text{Speed of light}}{c}} \underset{\text{area exposed to radiation}}{A_s}\left(1 + \underset{\text{reflectance factor (usually} \sim 0.6\text{)}}{q}\right)\cos \overset{\text{incidence angle}}{i}}$$

Attitude Determination :

Sensors : attitude determination requires 2 sensors, e.g : $\xrightarrow{\text{for 3D}}$

1. Magnetometers - measure magnitude & direction of magnetic field
2. Sun sensors - measure position of sun
3. Earth sensors - " earth
4. Star trackers - compare image of sky to stored map
5. Gyroscopes - measure rotation of spacecraft without external references

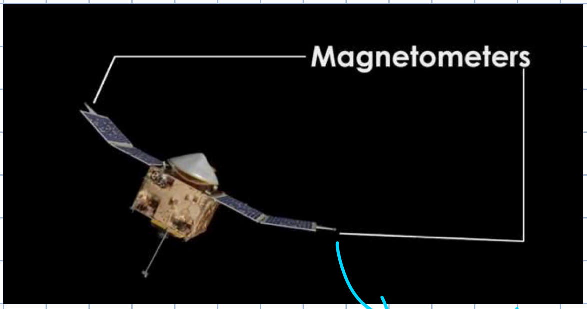
Sensor Performance :



Reference	Typical Accuracy	Remarks
Sun	1 min (arcmin)	Simple, reliable, low cost, not always visible
Earth	0.1 deg	Orbit dependent; usually requires scan; relatively expensive
Magnetic Field	1 deg	Economical; orbit dependent; low altitude only; low accuracy
Stars	0.001 deg	Heavy, complex, expensive, most accurate

$\text{arcmin} = \frac{1}{60}$ of a degree

Magnetometers:

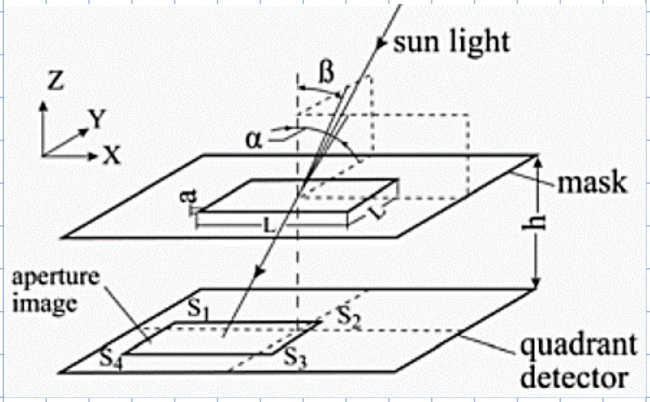


mounted on boom to avoid electric field

Measures B_x, B_y, B_z of ambient magnetic field

→ compares measured to modelled B

Sun Sensor:

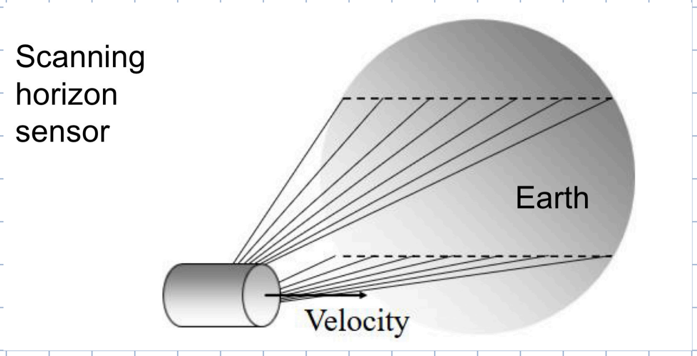


Outputs digital data on angular position of sun azimuth (α) & elevation (β).

Light falls through slit onto photodetectors
→ voltage induced

Orienting 2 sensors perp. = full determination of position

Earth Horizon Sensor:

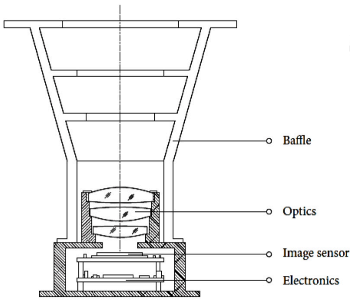


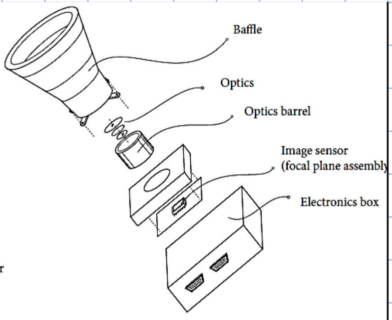
Only provides 2 axis knowledge.

Scans 2 beams across earth: difference in time and spacecraft relative angles and beginning & end give 2 axis knowledge.

Poor in yaw.

Star Tracker:





~ camera that takes pics of stars and compares to catalogue of stars

Pros: highly accurate and reliable

Cons: high mass, volume, power, can be blinded by sun & moon

Gyroscopes :

- Spinning masses, can detect spacecraft motion
- W. no torque, gyros point in same direction.
- W. torque, they precess in predictable direction and amount
  - precession = rotation with constant angular v. in a direction 90° from applied torque
- Must spin at high speed

Attitude Determination :

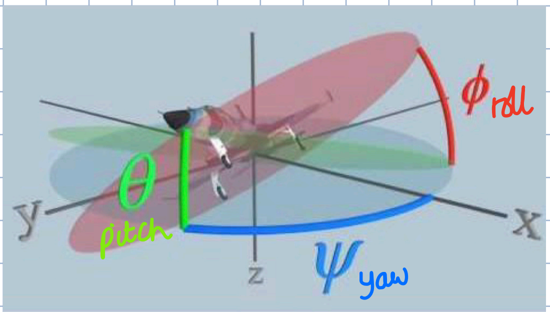
Collect sensor data → State vector estimation: analyse data for best fit → Express attitude as vectors → Correct attitude w. actuators

State vector estimation:
- Batch estimators
- Recursive least squares
- Kalman filter

Express attitude as vectors:
- Euler angles
- Direction cosine
- Quaternions

Rotation Representations :

- **Euler Angles**



- Easy to understand
- Have singularities
- Not easy to implement on computer
- Sequence is critical

R_1, R_2 & R_3 are rotation matrices each corresponding to 1 of 3 Euler angles.

Total $R = R_1 * R_2 * R_3$

- **Direction Cosine Matrix**

Product of Euler rotations

$$\begin{bmatrix} X_b' \\ Y_b' \\ Z_b' \end{bmatrix} = R_1 \begin{bmatrix} X_b \\ Y_b \\ Z_b \end{bmatrix} \text{ where } R_1 = \begin{bmatrix} cos\psi & sin\psi & 0 \\ -sin\psi & cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

so total R = R_3*R_2*R_1 =

$$\begin{bmatrix} \cos\theta\, cos\psi & \cos\theta\, sin\psi & -sin\theta \\ -\cos\phi\, sin\,\psi + \sin\phi\,\sin\theta\, cos\psi & \cos\phi\, cos\psi + sin\phi sin\theta sin\psi & \sin\phi\, cos\theta \\ \sin\phi\, sin\psi + \cos\,\phi\,\sin\theta\, cos\psi & -\sin\phi\, cos\psi + cos\phi sin\theta\, sin\psi & \cos\phi\, cos\,\theta \end{bmatrix}$$

- Quaternion
  - → no singularities
  - → no trig functions
  - → 4 dimensions : 3D vector + angle of rotation

Actuators:

Reaction & Momentum Wheels

↑ or ↓ rpm changes attitude

1 for each axis

Reaction: flywheel which can be rotated in one direction or the other

attitude changed with change from a nominal rotation rate of zero

Momentum: flywheels which rotate at a fixed, nominal non-zero rate

Works as $T = \frac{d\vec{H}}{dt}$

Pros :	Cons :
- Electric (no fuel consumed)	- Only rotation around CoM
- Power efficient	- Mechanism → undesirable
- Don't rely on mag. field	- Saturation → max rpm exceeded (max momentum stored) ∴ any $\frac{dH}{dt}$ = deceleration → requires thruster to reverse

Control Moment Gyros :

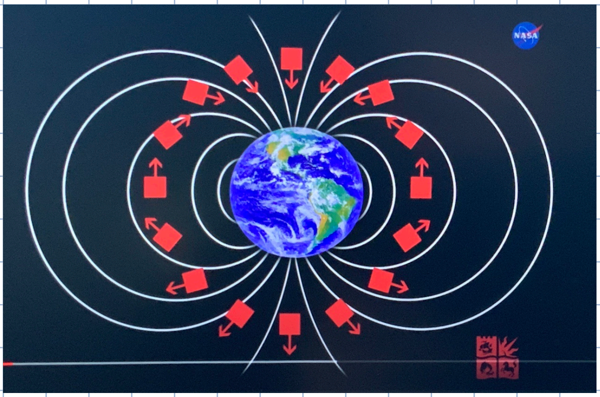
- Like reaction wheels + axial control → 4 degrees of freedom

→ can be used for control of large spacecraft.

Magnetorquers : (or torque rods)

- long helical coils w. solid metal core.
- use current to generate magnetic field → interacts w. ambient magnetic field and alligns

→ used for detumbling or desaturating reaction wheels



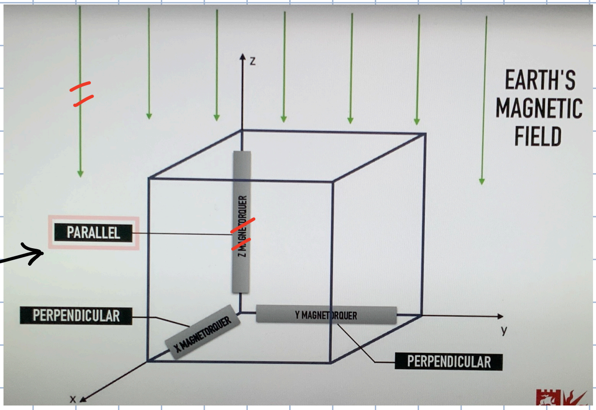
Pros :

- Low power
- No propellant
- Inexpensive
- Lightweight
- No mechanism

Cons :

- low torque
- Depends on strength of field
  - ↳ good for LEO

Parallel torque rod is not useful, only perp



Thrusters / Reaction Control System :

- Provide control torques
- Usually use same devices as those that control translation
  - ↳ operated in equal & opposite pairs → torque but no net force
- Redundancy usually required → complex, expensive
- Also used for orbit control

AOCS :