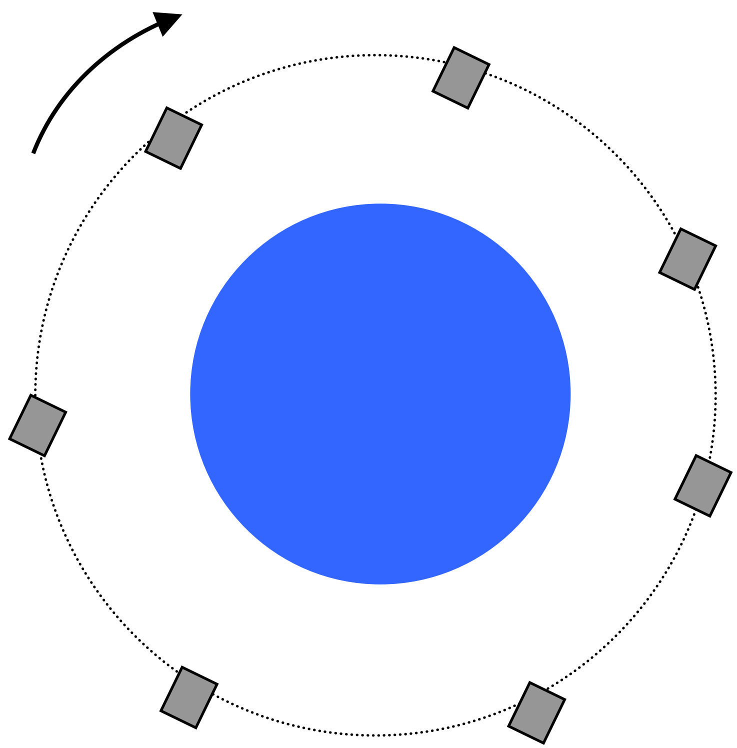
SESA2024
Astronautics

Chapter 6:
Attitude Control

Contents

Attitude Control Introduction

Basic motion: Consider a body in orbit (with no disturbances)…



(No changes)

Attitude Control Introduction

Primary Purposes of the Attitude Control System (ACS) are:

– To achieve the pointing requirements of the **payload**, in terms of directions, accuracy, stability, etc.

e.g. Earth pointing (comms payload, remote sensing payload, ...)

Diverse directions (astronomical observatory, ...)

– To achieve the pointing requirements for **"house-keeping"**, in all phases of the mission

e.g. Power raising ⇨ Sun pointing

Communications ⇨ Earth pointing

Thermal dissipation ⇨ Deep space

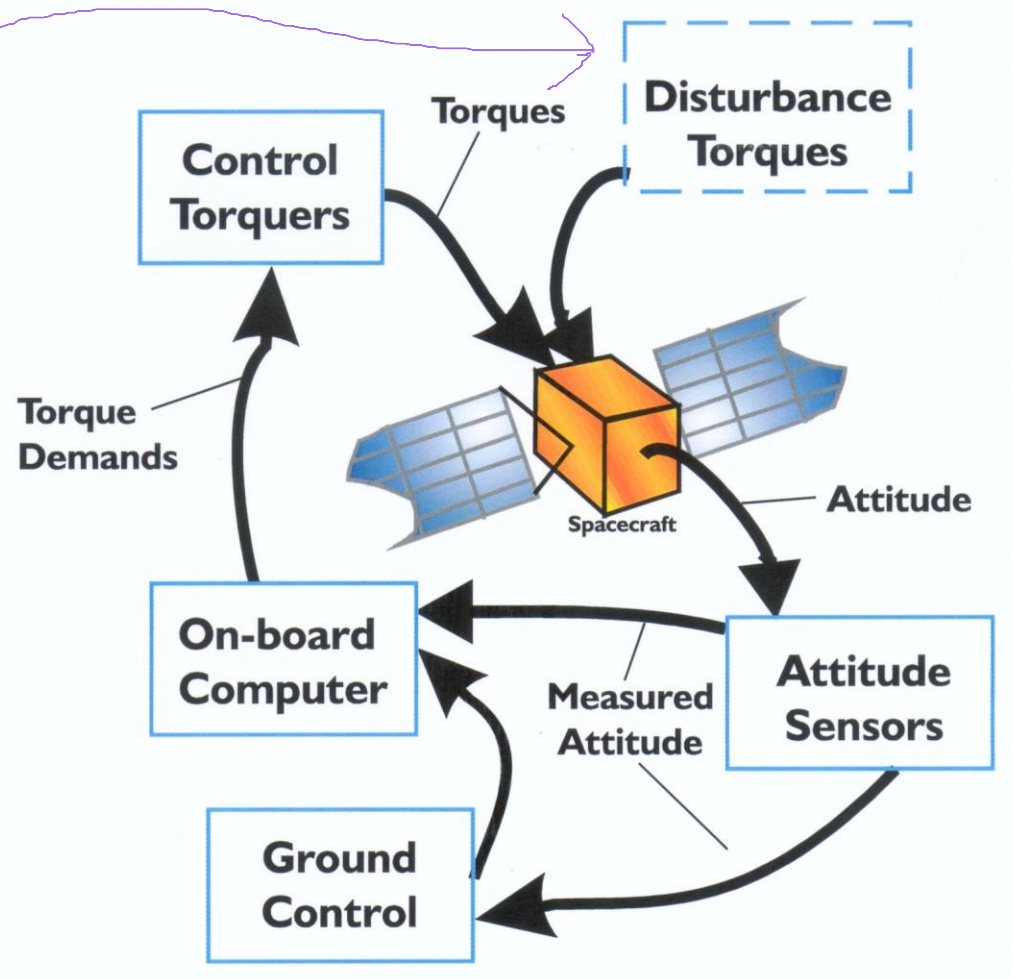
Thrust vector direction for rocket engine firing

– To ***'manage the overall (angular) momentum'*** of the spacecraft to achieve its pointing mission.

Attitude Control Introduction

Typical ACS operation showing flow of information:

In situations where a satalite passes through thin parts of the atmosphere the large thin areas (such a solar panels) can have a non uniform tiny rotational force applied, which adds up over the cuarse of many orbits.



So… we need to consider the rotational motion of spacecraft about its Centre of Mass (CM), and torques about the CM.

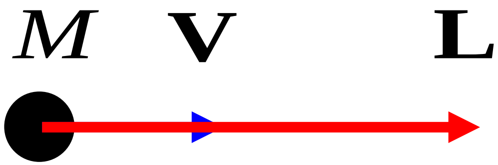
Rotational Dynamics

Linear Momentum

a 'stepping-stone' to translational/orbit dynamics

$$\mathbf{L} = M\mathbf{V}$$

vector scalar vector



Newton's second law:

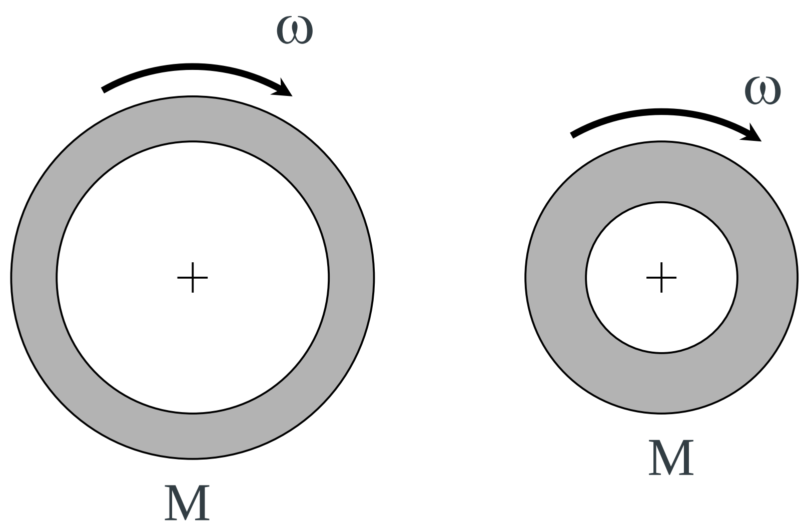
$$\frac{d}{dt}(\mathbf{L}) = \frac{d}{dt}(M\mathbf{V}) = \sum \mathbf{F}_{ext}$$

Free Motion:

- No Force, $\Sigma\,\mathbf{F}_{\text{ext}} = \mathbf{0}$ ⇨ Momentum **L** is constant

Rotational Dynamics

Angular Momentum – *Inertia, one dimension*



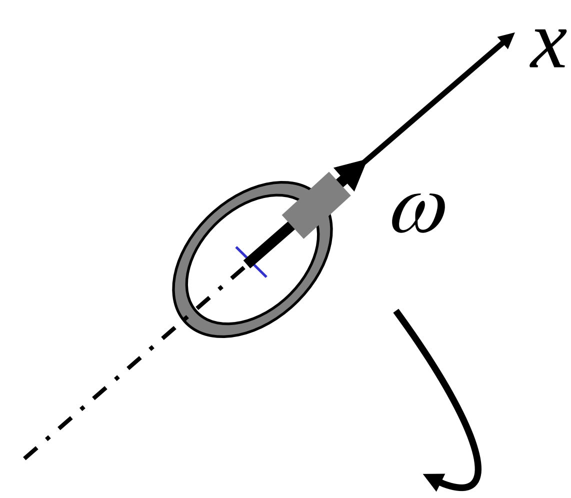
Is the angular momentum the same?

Rotational Dynamics

Angular Momentum – *Inertia, rotational vectors*

For this one dimensional motion:

$$\underset{\text{vector}}{\mathbf{H}} = \underset{\text{scalar}}{I_{xx}}\,\underset{\text{vector}}{\boldsymbol{\omega}}$$



Newton's second law:

$$\frac{d}{dt}(\mathbf{H}) = \frac{d}{dt}(I_{xx}\boldsymbol{\omega}) = \sum \mathbf{T}_{ext}$$

Free Motion:

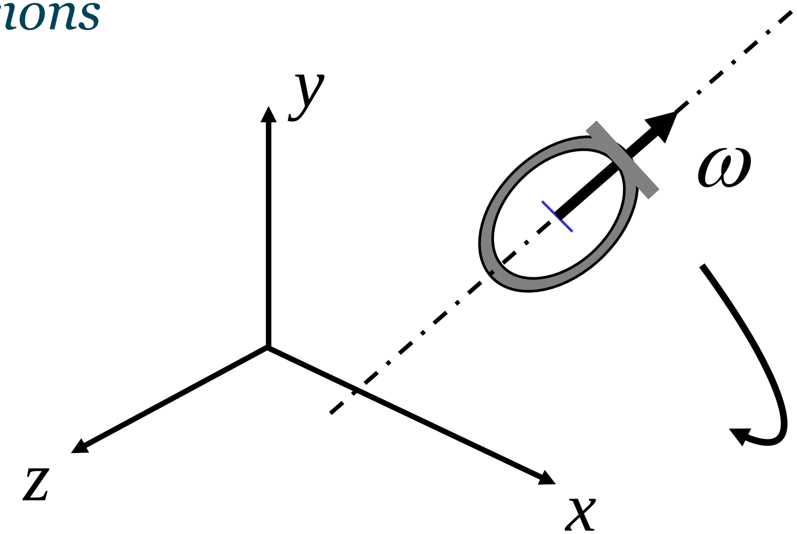
No torque, $\sum \mathbf{T}_{ext} = 0$ ⇨ Momentum **H** is constant

Rotational Dynamics

Angular Momentum – *In three dimensions*

In three dimensions:

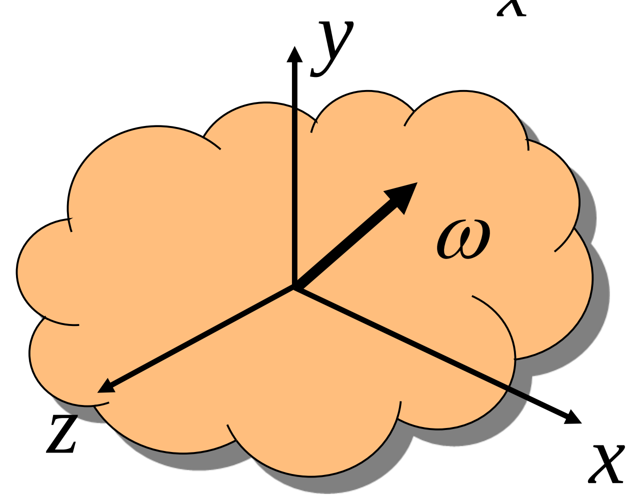
$$\boldsymbol{\omega} = \begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix}$$



Angular momentum:

$$\mathbf{H} = \mathbf{I}\boldsymbol{\omega}$$

vector matrix vector

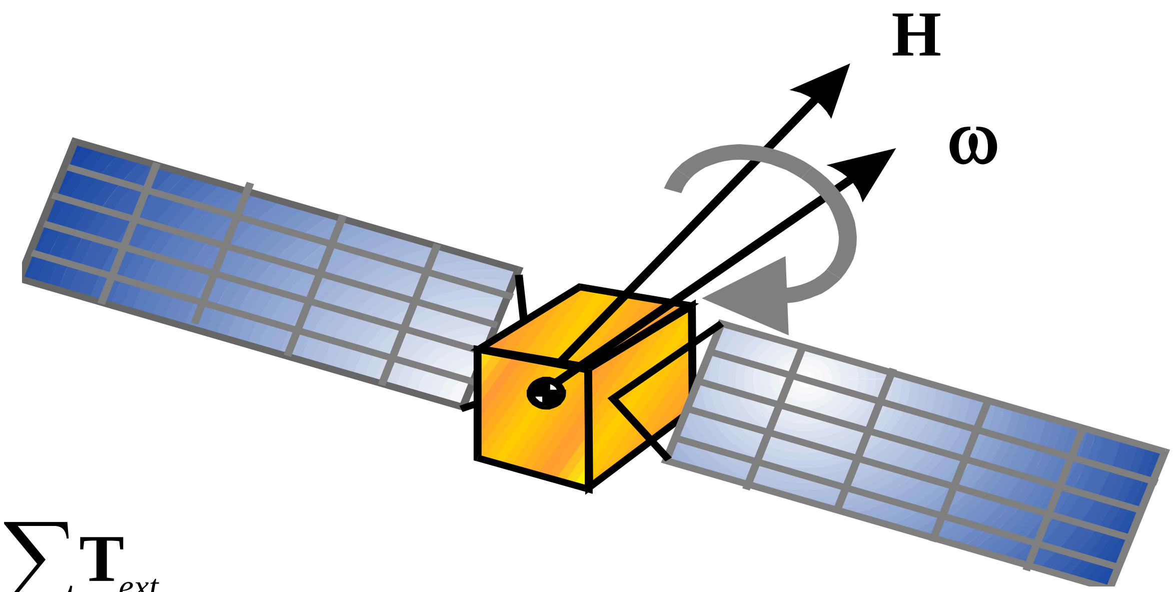


Rotational Dynamics

Angular Momentum – *in three dimensions*

$$\mathbf{H} = [\mathbf{I}]\,\boldsymbol{\omega}$$

vector matrix vector



Newton's second law:

$$\frac{d}{dt}(\mathbf{H}) = \frac{d}{dt}(\mathbf{I}\boldsymbol{\omega}) = \sum \mathbf{T}_{ext}$$

Free Motion:

- No torque, $\Sigma\, \mathbf{T}_{ext} = \mathbf{0}$ ⇨ Momentum **H** is constant

Rotational Dynamics

Angular Momentum – *the inertia matrix*

Angular momentum of a rigid body such as the main structure of a Spacecraft is given by: $\mathbf{H} = [\mathbf{I}]\,\boldsymbol{\omega}$

Angular Velocity

Inertia Matrix referred to Centre of Mass

$$[\mathbf{I}] = \begin{pmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{pmatrix}$$

I_{xx}, I_{yy}, I_{zz} are Moments of Inertia

I_{xy}, I_{yz}, I_{zx} are Products of Inertia

Products of inertia are a measure of unbalance, and cause 'cross-coupling'

Rotational Dynamics

Angular Momentum

$$\mathbf{H} = [\mathbf{I}]\,\boldsymbol{\omega}$$

$$\mathbf{H} = \begin{pmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{pmatrix} \begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix}$$

So the components of the angular momentum vector are:

$$\mathbf{H} = \begin{pmatrix} \left(I_{xx}\omega_x - I_{xy}\omega_y - I_{xz}\omega_z\right) \\ \left(I_{yy}\omega_y - I_{yz}\omega_z - I_{xy}\omega_x\right) \\ \left(I_{zz}\omega_z - I_{xz}\omega_x - I_{yz}\omega_y\right) \end{pmatrix}$$

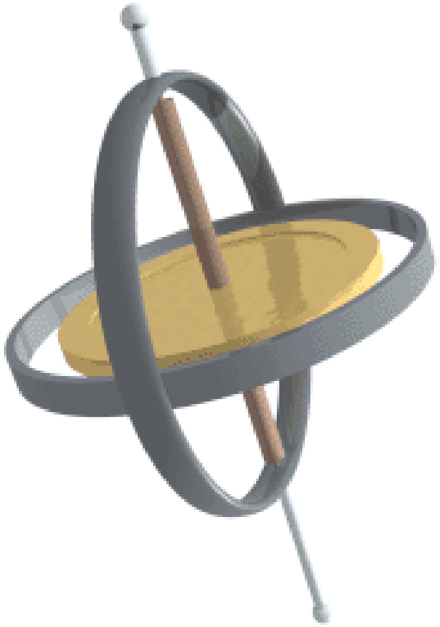
Rotational Dynamics

The Inertia Matrix

[I] is an important quantity when sizing up the control system inputs for any vehicle.

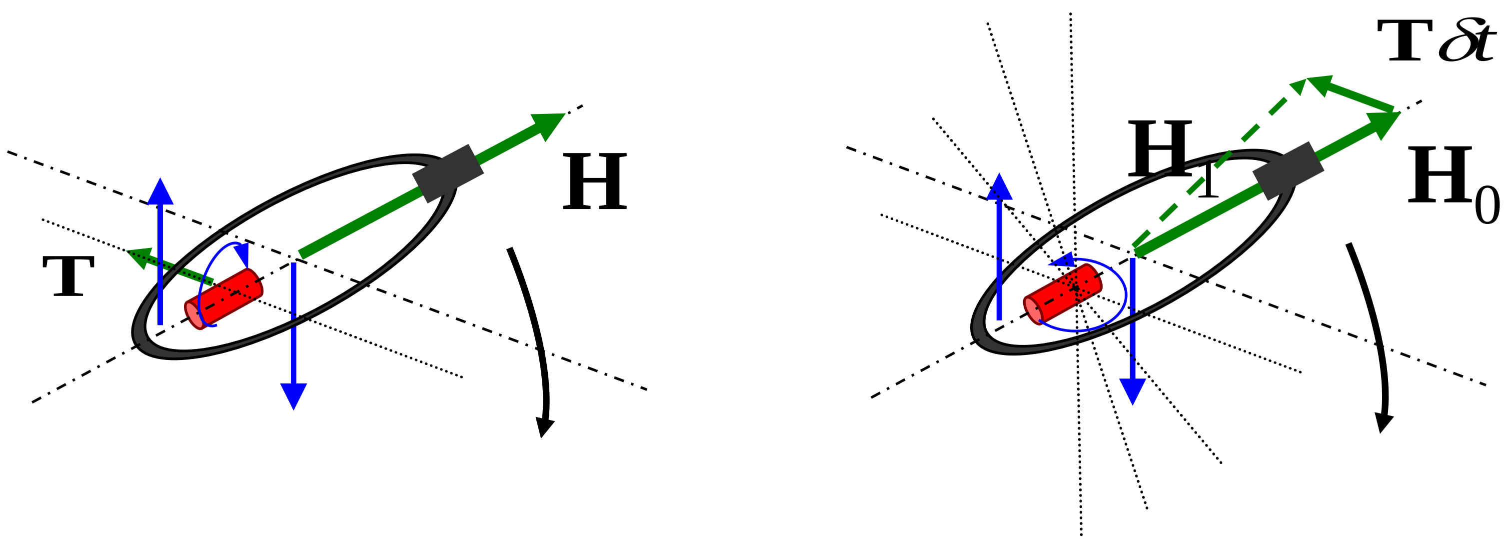
Rotational Dynamics

Rotational Motion – Gyroscopic precession



Rotational Dynamics

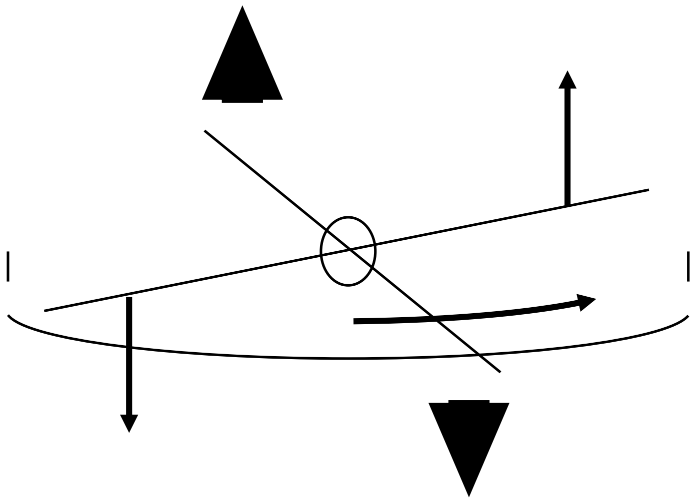
Rotational Motion – Gyroscopic precession

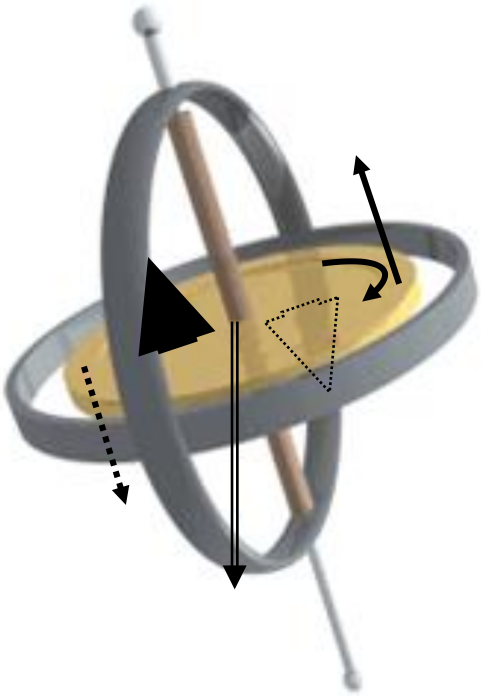


The rotational displacement occurs 90 degrees later in the direction of rotation.

Rotational Dynamics

Rotational Motion



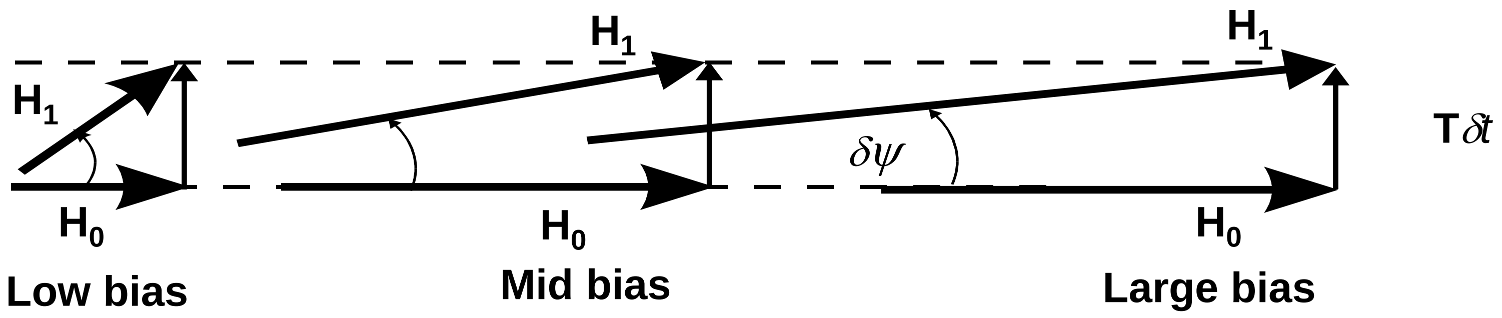


Rotational Dynamics

Rotational Motion – momentum bias

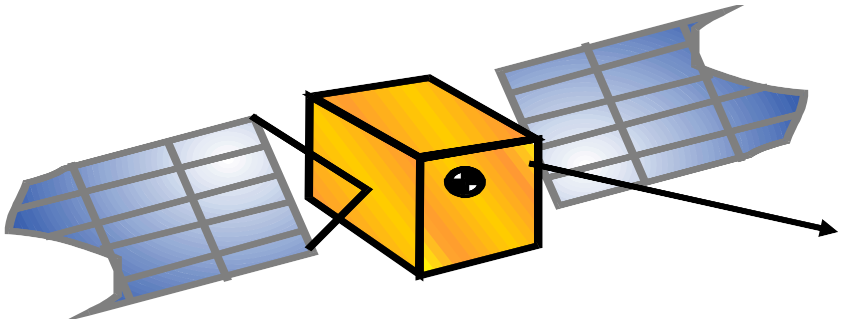
Momentum reduces sensitivity to torque – gyroscopic rigidity

During δt, the momentum changes direction $\delta\psi$ from $\mathbf{H_0}$ to $\mathbf{H_1}$



Momentum 'Management'

- The ACS must 'manage' the momentum **H** of the spacecraft, using control torquers to do so.



- This can be achieved using the principles of:

  Conservation of momentum - using internal torquers to store/transfer momentum, Gimballing

  $(\Sigma\, \mathbf{T}_{ext} = \mathbf{0} \;\Rightarrow$ Momentum **H** is constant$)$

  Newton's second law - using external torquers to apply a torque to the satellite

  $(\Sigma\, \mathbf{T}_{ext} \neq \mathbf{0} \;\Rightarrow$ Momentum **H** changes in magnitude/direction$)$

Momentum ‘Management’

Notes:

1) Momentum build-up

External disturbance torques (e.g. aerodynamic disturbances, etc) will cause a progressive build-up of angular momentum

2) Only external torques affect the total angular momentum of the system…

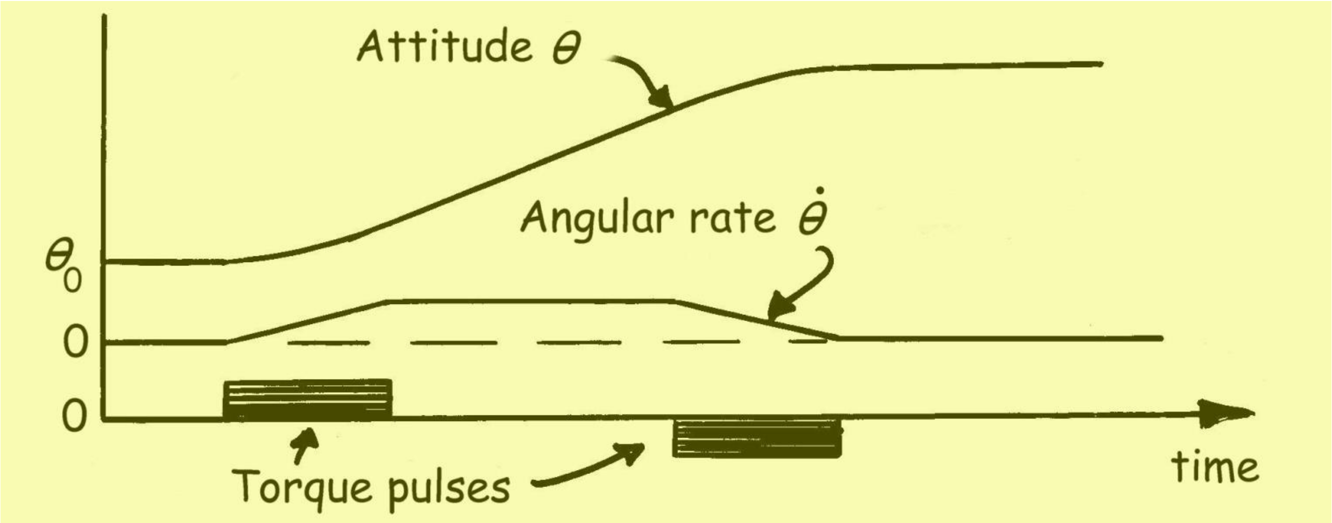
… therefore spacecraft must carry external torquers (e.g. thrusters, magnetorquers, etc) if angular momentum is to be controlled.

Momentum Bias is a method commonly used to provide inherent stability.

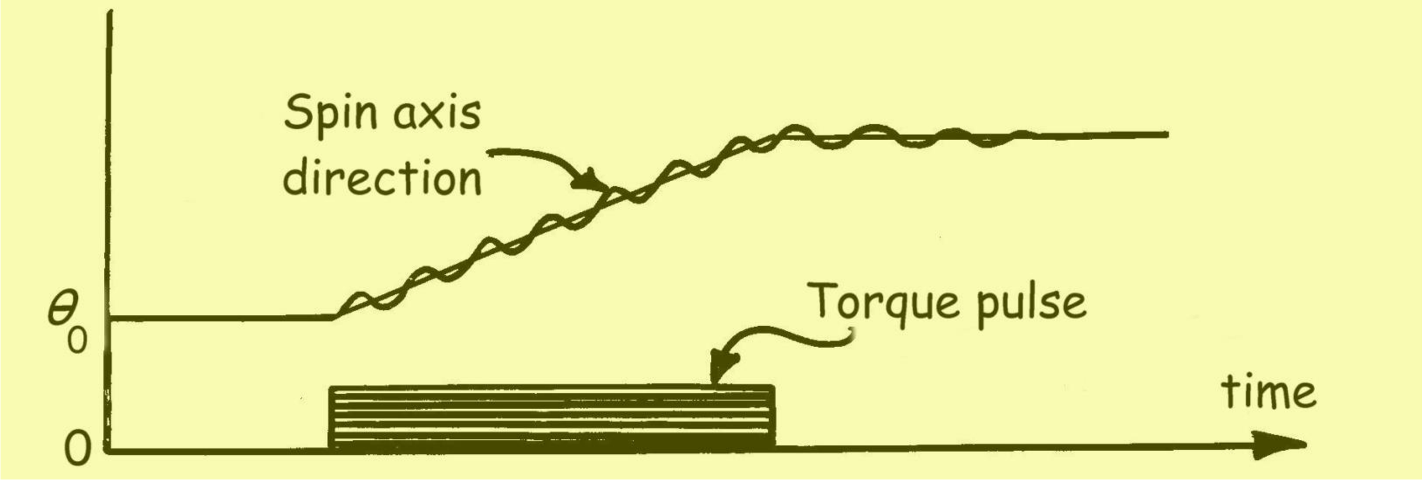
But
- to use momentum bias, it is desirable that one body axis of the spacecraft remains invariantly pointing (usually perpendicular to the orbit plane)
- bias also introduces an oscillatory nutation mode
- a system with bias will have different torque responses

Momentum ‘Management’

Torque response without bias



Torque response with bias



A constant torque can precess the bias direction at rate: $\dot{\theta} = T/H_0\,, \quad H_0 = H_{bias}$

Spacecraft Categories

Spacecraft

- No bias
  - **3-axis stabilised (zero bias)**
    - Examples: Magellan, Spot 5, Hubble ST, JWST, Comsats (many)
- With bias
  - **Hybrid**
    - Examples: Navstar GPS (2R), Comsats (many)
  - **Dual-spinner**
    - Examples: Giotto, Intelsat 2-4,6, Galileo (Jupiter)
  - **Spinner**
    - Examples: Intelsat 1, Meteosat SG, Cluster, Small sats

Spacecraft Categories

Spacecraft

No bias

3-axis stabilised (zero bias)

Examples

Magellan
Spot 5
Hubble ST
JWST
Comsats (many)

With bias

Hybrid

Examples

Navstar GPS (2R)
Comsats (many)

Dual-spinner

Examples

Giotto
Intelsat 2-4,6
Galileo (Jupiter)

Spinner

Examples

Intelsat 1
Meteosat SG
Cluster
Small sats

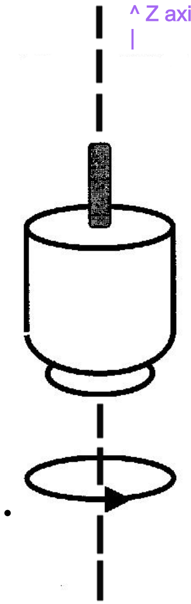
Spacecraft Categories – Spinner

Equation makerers use of intertia matix

Pure Spin Stabilisation

$$\mathbf{H} = [I]\boldsymbol{\omega}$$

- whole spacecraft body spins at a rate of typically 10 to 60 rpm.



Ideal inertia matrix:

[I_xx , 0 , 0]
[0 , I_xx , 0]
[0 , 0 , I_zz]

I_z to be large,
0's to ensure long term stability.
I_zz > I_xx
These conditions lead to increased stability.

Major System Consequences

Becomes hard to balance these VVVV

- power
- thermal
- communications
- limited mounting space for non-scanning payloads!

Choice of Spin Axis

The spin axis can only have a constant direction if it is a principal Axis.

For long-term stability it must be the axis of maximum inertia.

It may be the axis of least inertia for spin motion of limited duration.

Equal inertias about axes at right angles to the spin axis are needed for constant precession in response to a torque

Nutation

This is the weird shakey motion

Spinning introduces an oscillatory 'nutation' mode which must be damped out –

- passive dampers
- active damping via control torquers

Location of masses in structure becomes really important to maintain balanced inertial matrix, limiting what can be done structurally

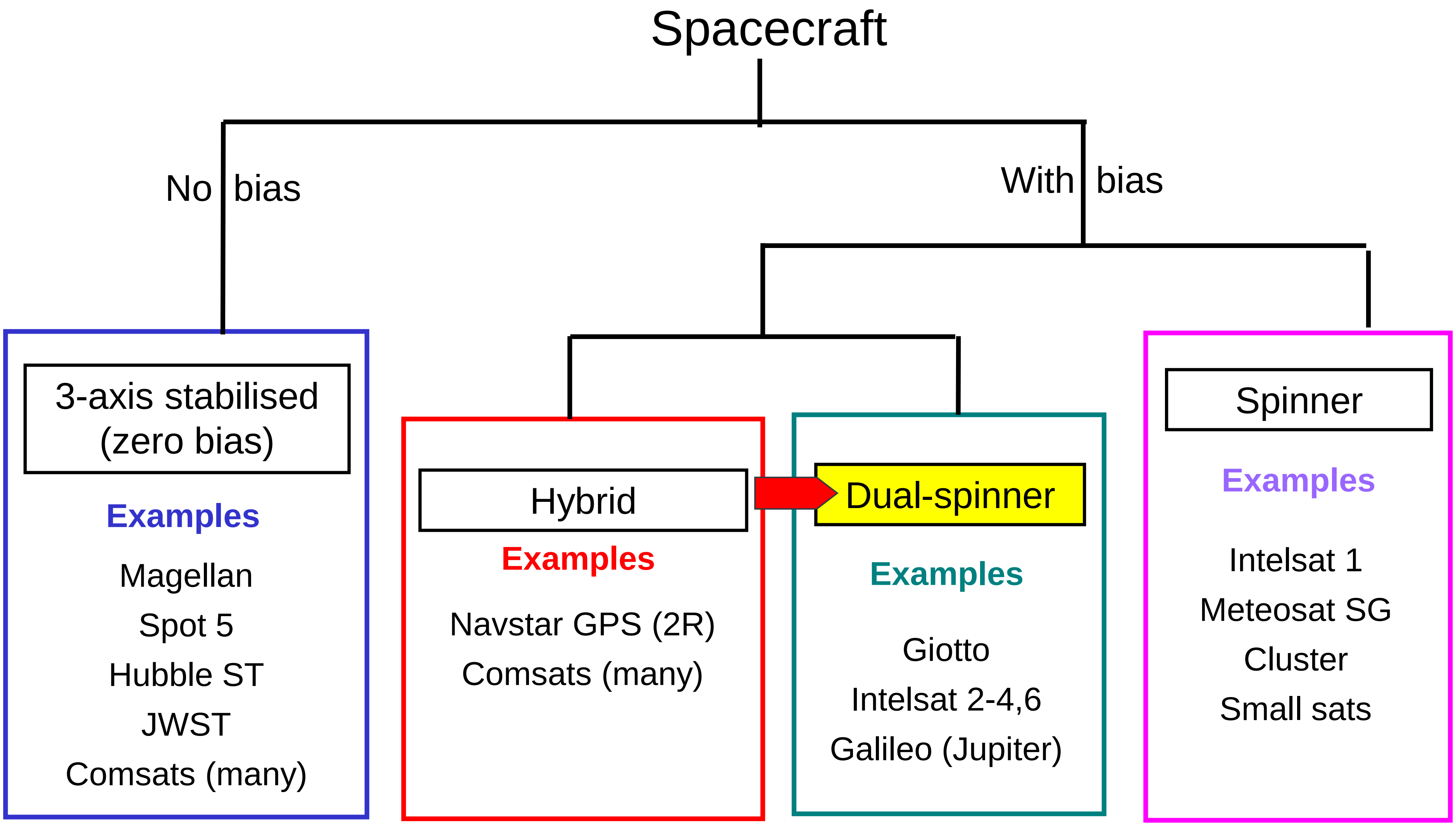
Spacecraft Categories - Spinner

Examples

Cluster

Meteosat SG

Spacecraft Categories

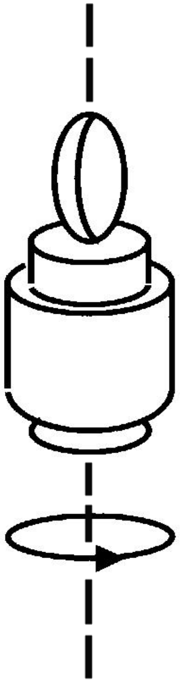


Spacecraft Categories – Dual Spin

Part of the Structure Spinning

$$H = [I]\omega$$

- Upper section is despun (for example Earth pointing). Lower section (contains subsystems) spins at a rate typically 10 to 60 rpm



Major System Consequences

- power
- thermal
- communications
- limited mounting space
- transmission across bearing
- greater freedom of configuration

Balance

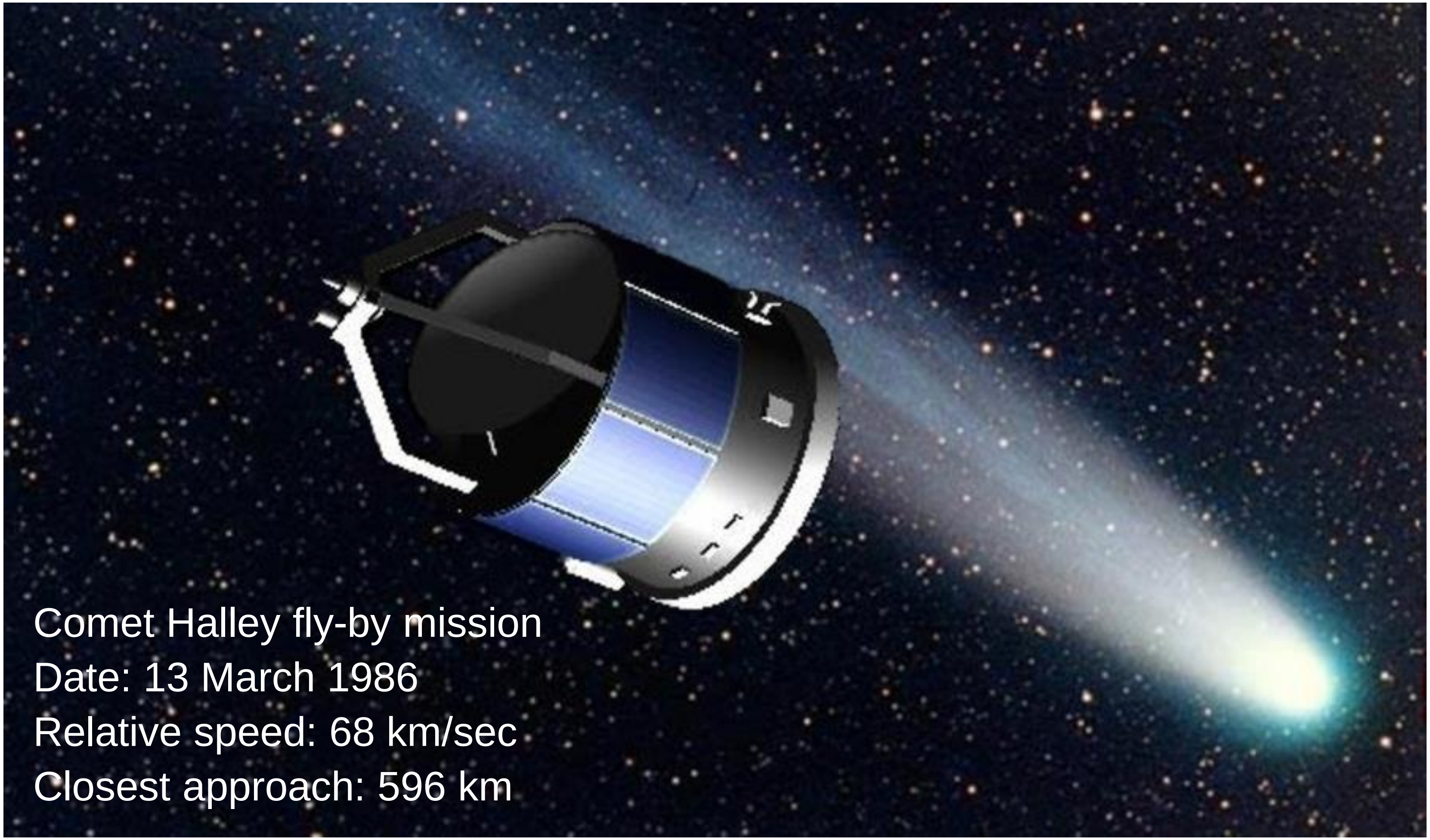
The spinning part needs to have equal inertias about axes orthogonal to the spin axis

Nutation still occurs and must be damped by the ACS

Note that methods 1 and 2 have “large” I and “small” ω in the product I ω

Spacecraft Categories – Dual Spin

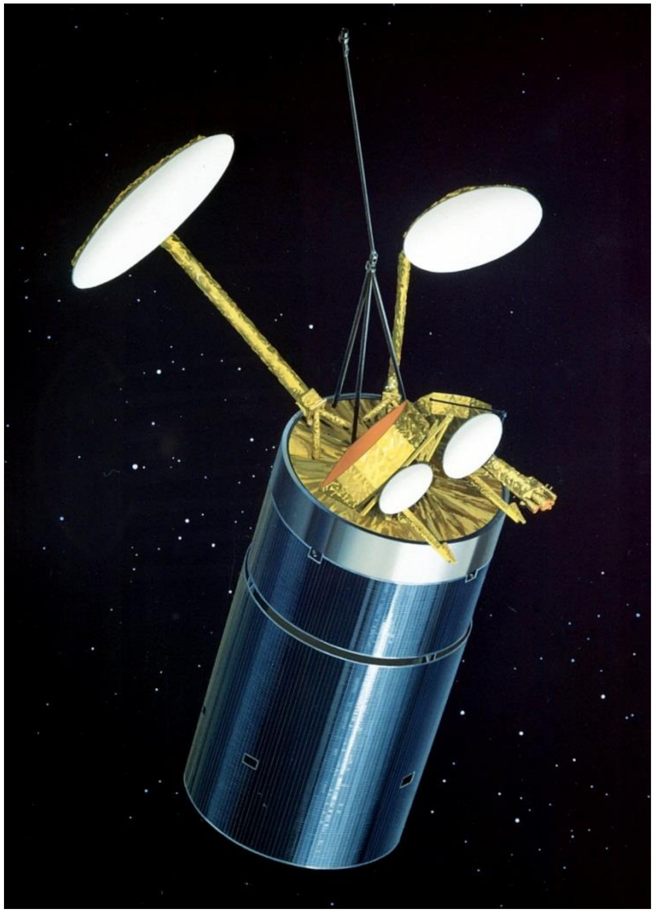
Examples: Giotto



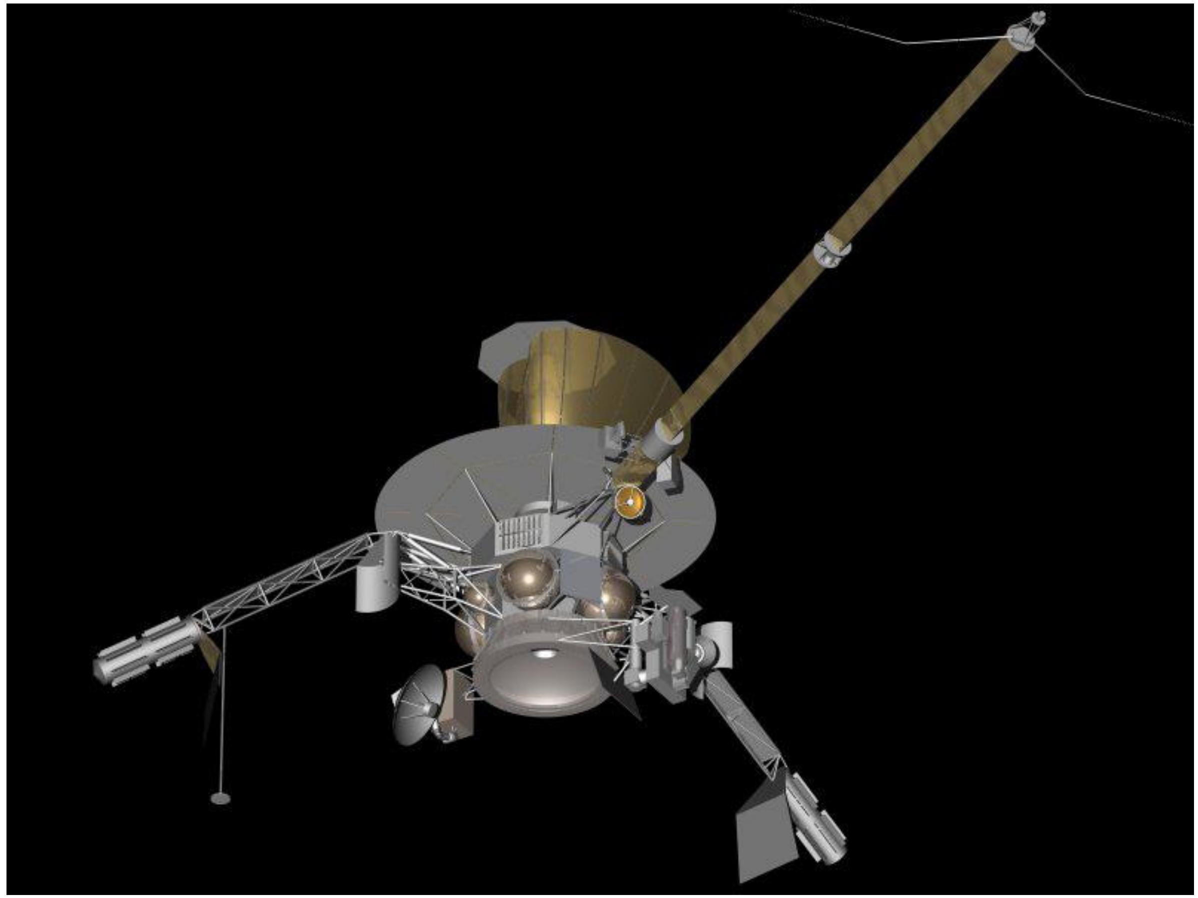
Spacecraft Categories – Dual Spin

Examples:

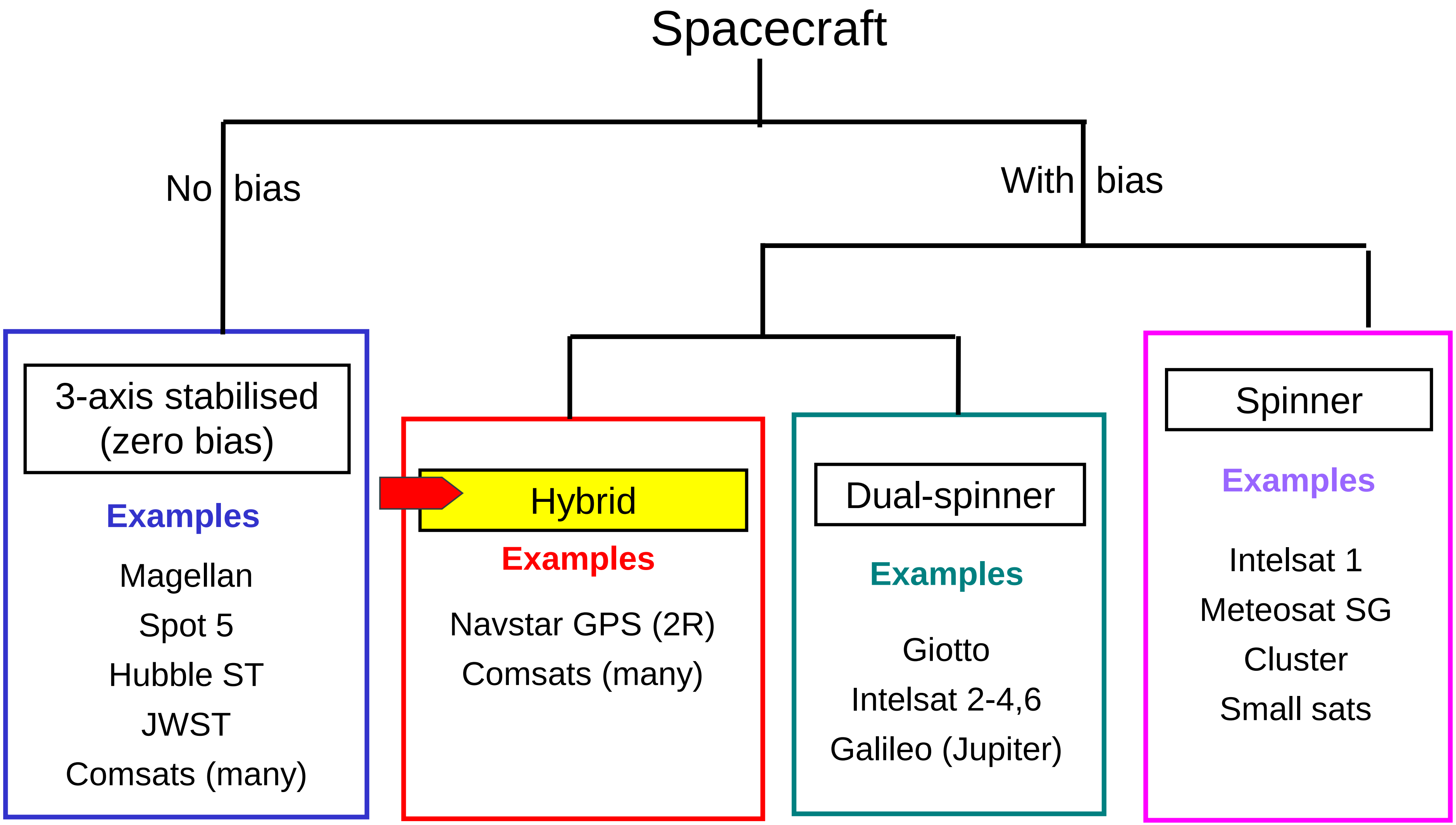
Intelsat 6



Galileo (Jupiter)



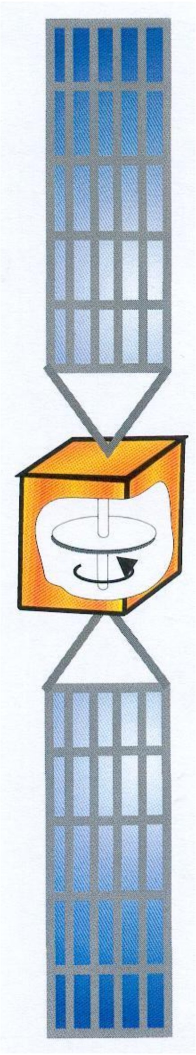
Spacecraft Categories



Spacecraft Categories - Hybrid

Bias using a momentum wheel

- A rapidly rotating wheel (a momentum wheel with a rotation rate of typically 6500 rpm) is installed within the spacecraft



Configuration

The freedom of the 3-axis stabilised spacecraft, but with the interior installation of a momentum wheel (or array of momentum wheels)

Nutation

... still occurs and must be stabilised by the ACS

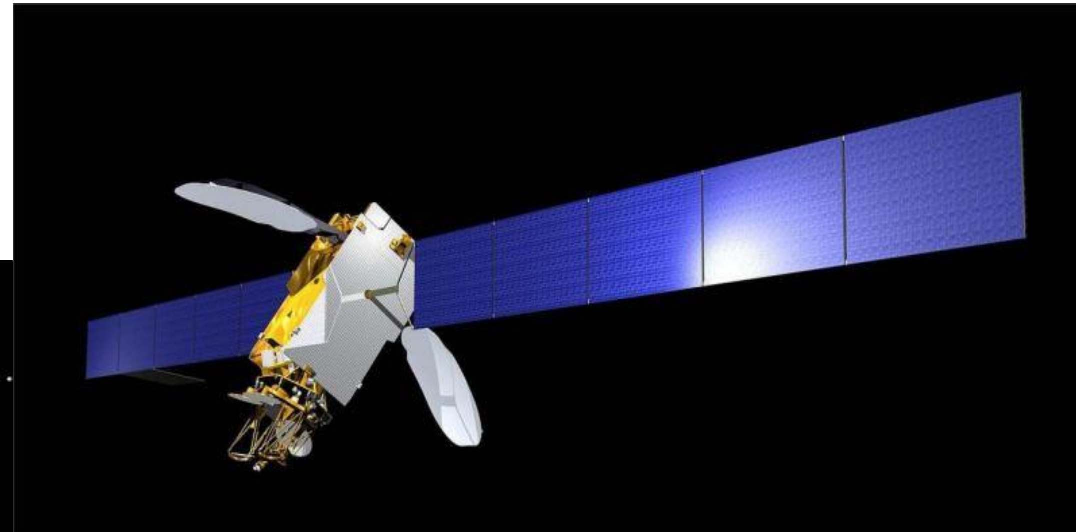
Momentum Storage

The wheel provides momentum storage for one component of momentum, accommodating fluctuations of about ± 10% of the bias

Spacecraft Categories - Hybrid

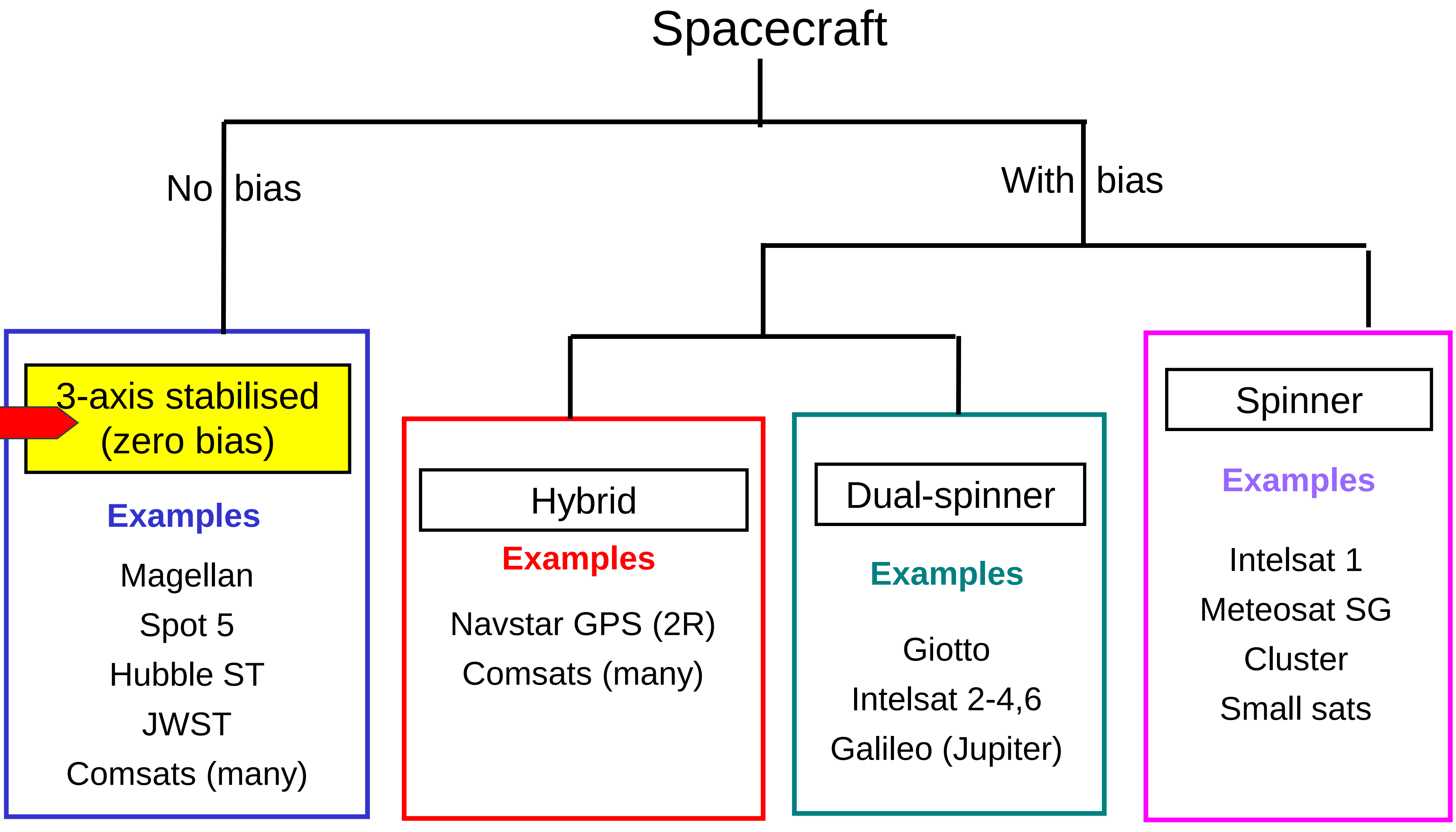
Examples:

Navstar GPS



Eurostar 3000

Spacecraft Categories

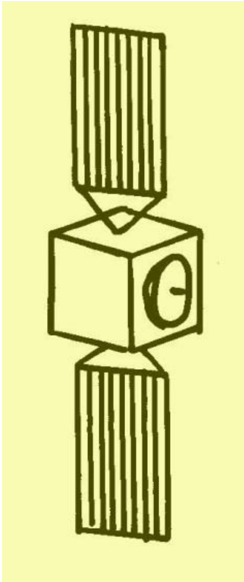


Spacecraft Categories – 3 axis

No momentum bias

- The spacecraft has no significant rotating components (and therefore has effectively zero angular momentum)

Used when full motion around all axes is required for the mission

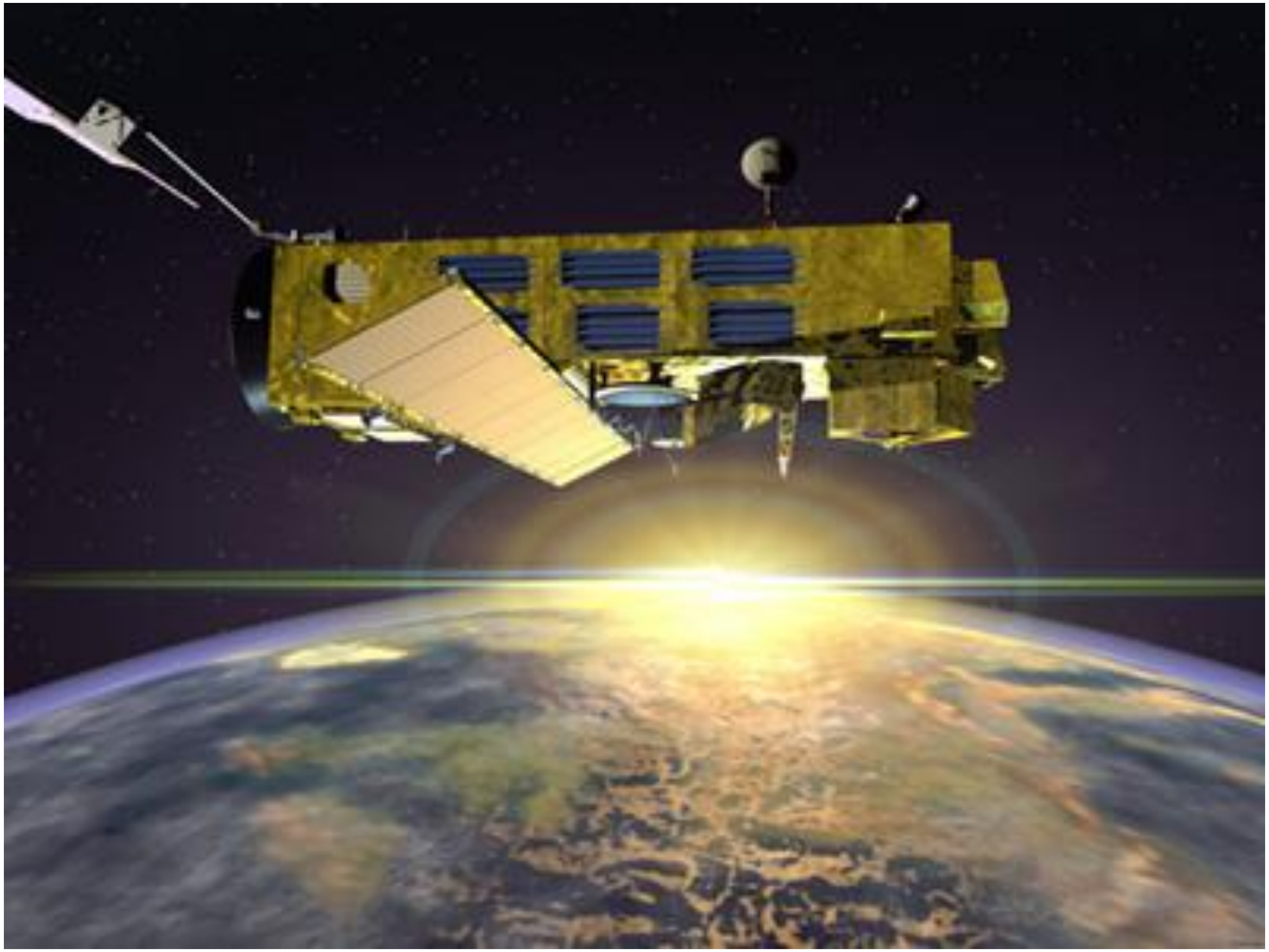


Example:

Hubble Space Telescope

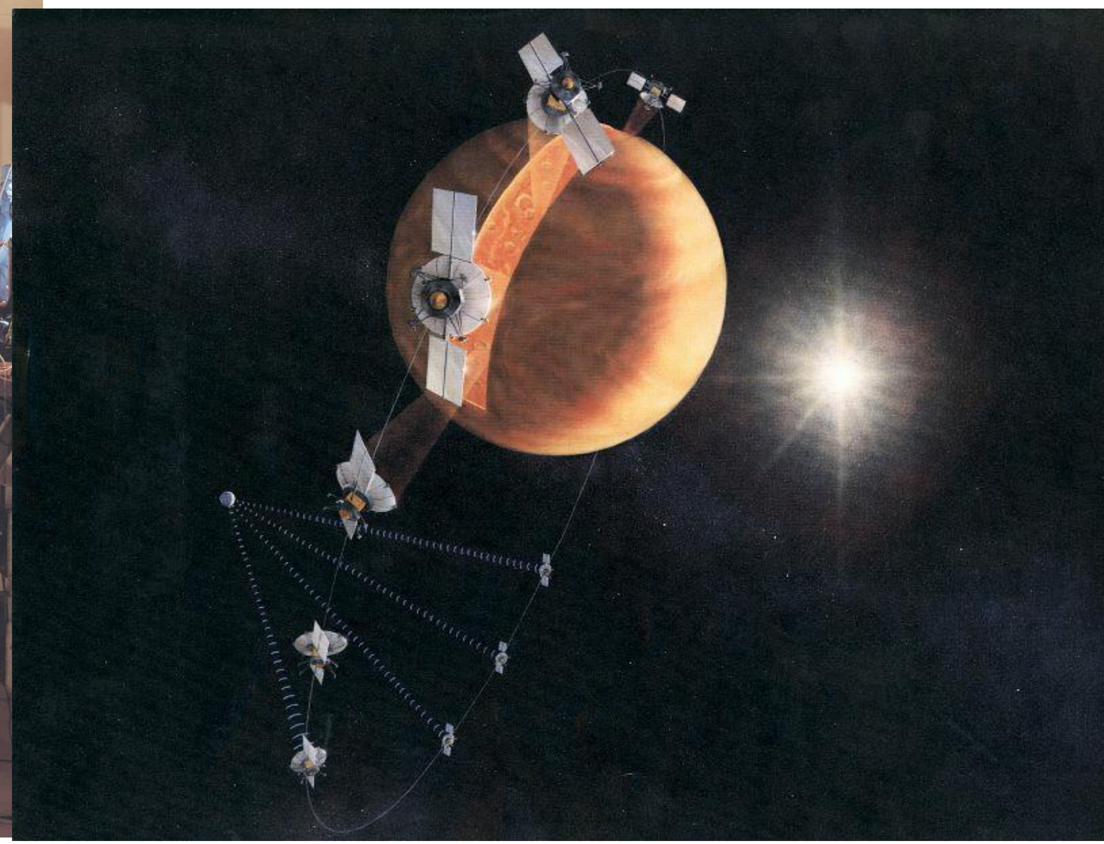
Spacecraft Categories – 3 axis

Example: Envisat 1



Spacecraft Categories – 3 axis

Example: Magellan VOIR mission (Venus Radar mapper)



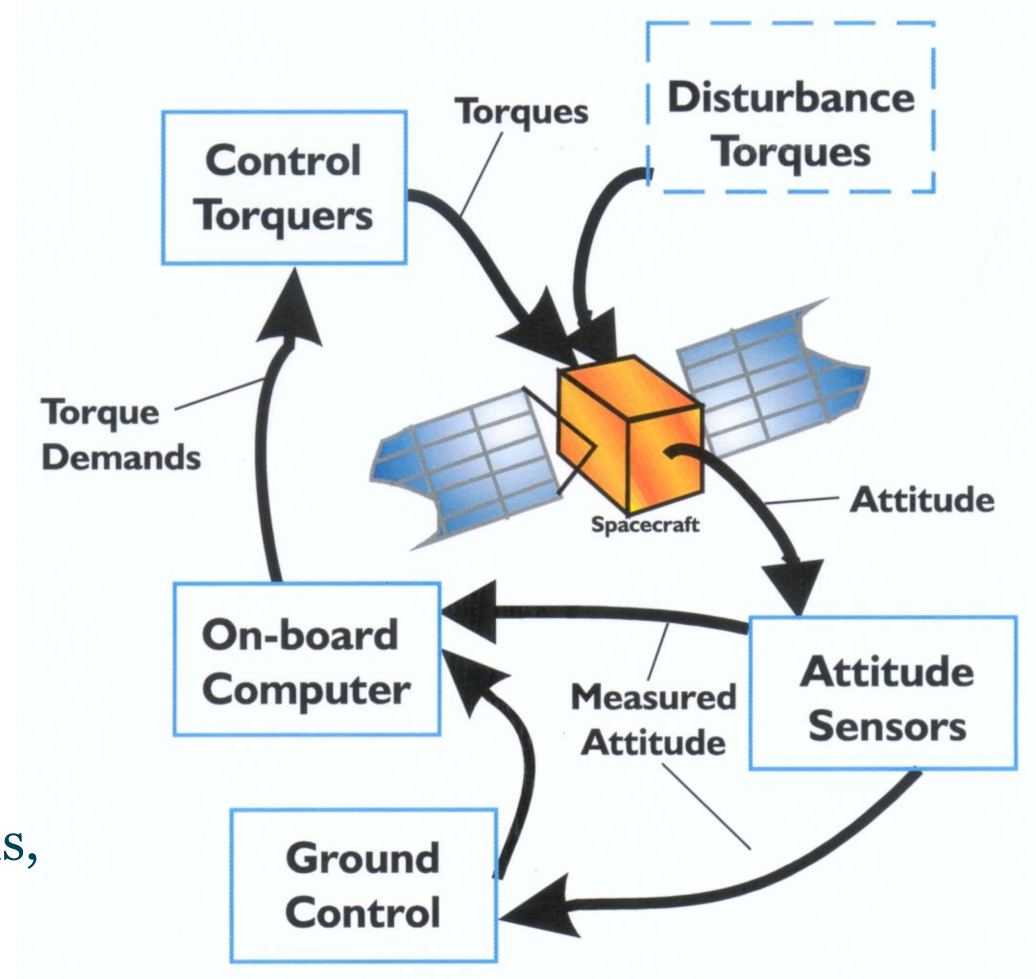
Attitude Control Introduction

Typical ACS operation showing flow of information:

Services required:

- power,
- propulsion,
- on-board data handling,
- communications,

etc.



Torques and Torquers

Categories of Torques:

External:

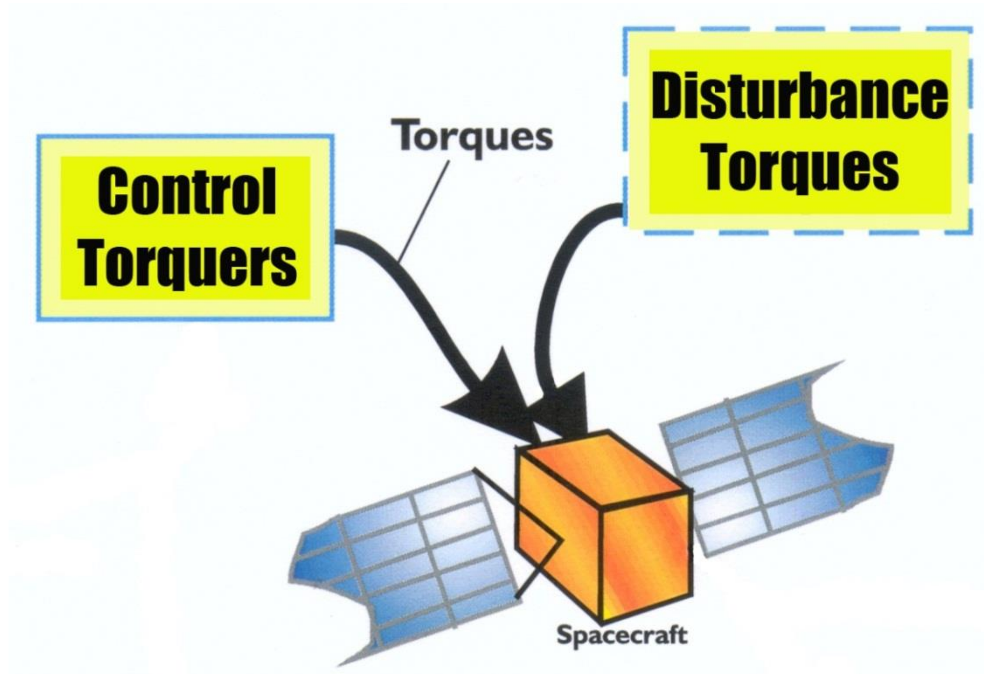
- Due to interactions with the environment

→ changes the overall angular momentum of the system

Internal:

- Due to interactions between two parts of the spacecraft

→ overall angular momentum of the system is conserved

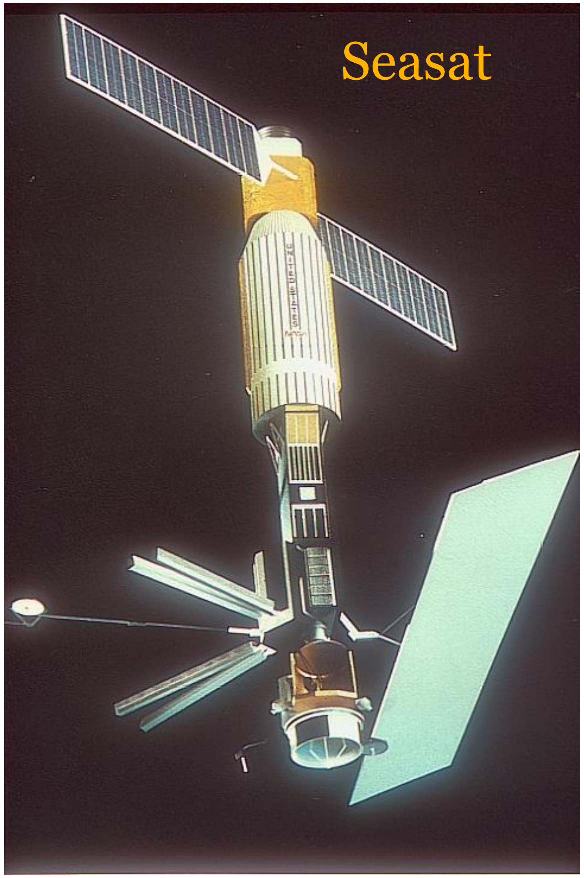


Torques and Torquers

External torques and torquers

A. Naturally occuring (disturbance) torques

- Aerodynamic < 500 km
- Gravity gradient < 30,000 to 40,000 km
- Solar radiation all heights
- Magnetic < 30,000 to 40,000 km
- Thrust misalignment all heights



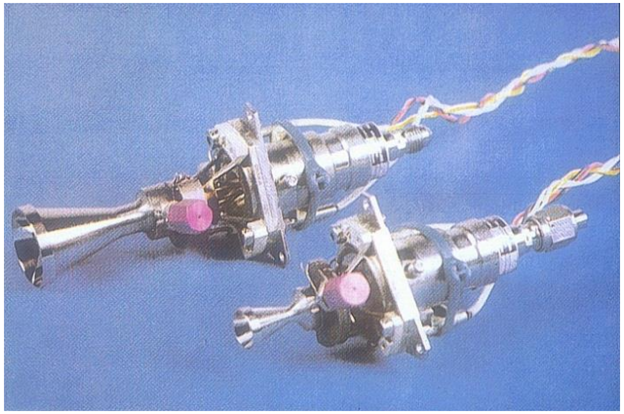
Note that: the altitude ranges given are very approximate

Torques and Torquers

External torques and torquers

B. Controllable external torquers

- Gas jets (thrusters)
  - Suitable for any torque size
  - ON-OFF control only
  - Require propellant
- Magnetorquers
  - No torque about field line
  - Require on-board magnetic field model
  - require power (no propellant)

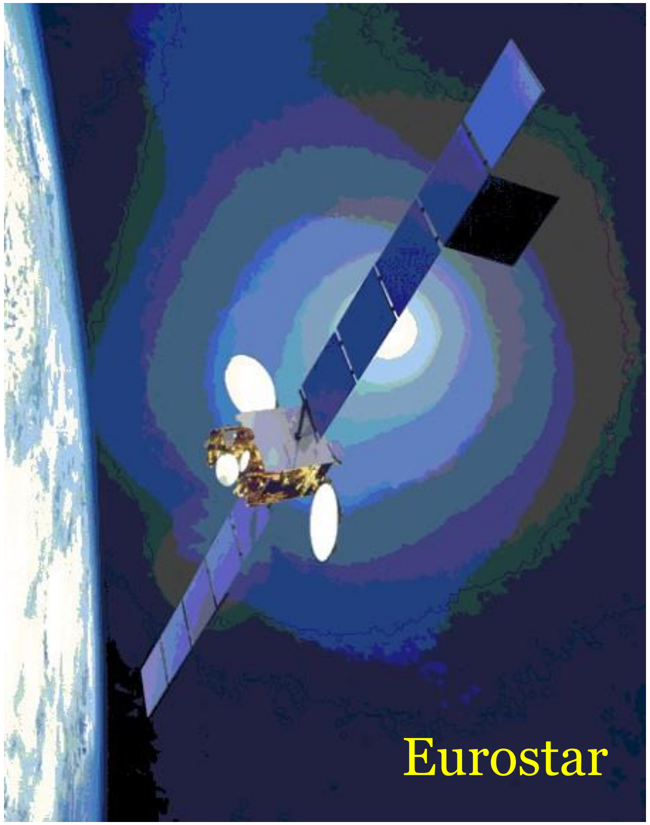


Torques and Torquers

External torques and torquers

- Adjustable spacecraft geometry (to utilise aerodynamic or solar radiation pressure torques)
    - Low torque capability
    - No propellant required

Note: A control torquer of type B is a necessity, to control the total spacecraft angular momentum



Torques and Torquers

Internal torques and torquers

- These do no affect the total angular momentum build-up of the spacecraft. They transfer momentum from one part of the spacecraft to another.

A. Internal disturbance torques

- Mechanisms (e.g. deployment of a solar array)
- Fuel movement (sometimes referred to a ‘fuel slosh’)
- Astronaut movement

Torques and Torquers

Internal torques and torquers

B. Controllable internal torquers

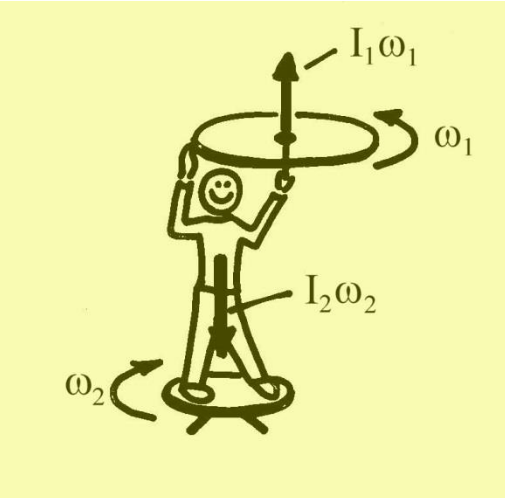
- Dual spin mechanisms
- Reaction wheels (commonly used for large ‘slew manoeuvres’)
- Momentum wheels (used to generate momentum bias)

Torques and Torquers

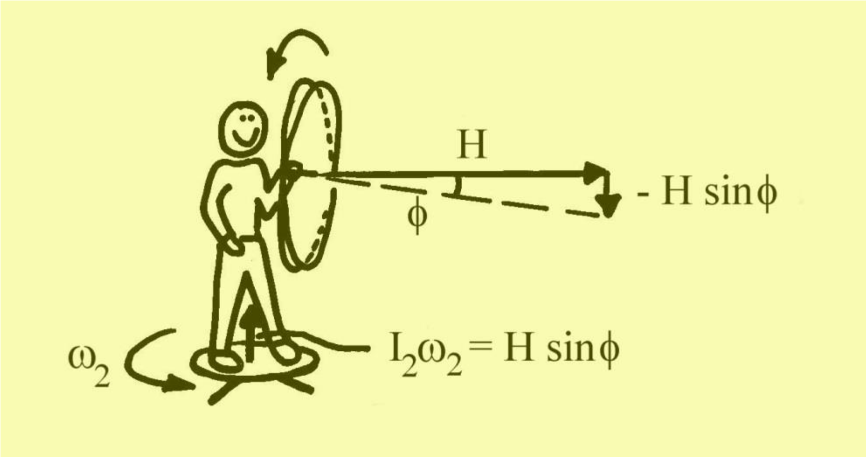
Demonstrations of internal torquers

– Reaction wheel demo

$$I_1 \omega_1 = I_2 \omega_2$$



– Gimballed momentum wheel demo (sometimes referred to as a ‘control moment gyro’)



Torques and Torquers

Use of momentum storage

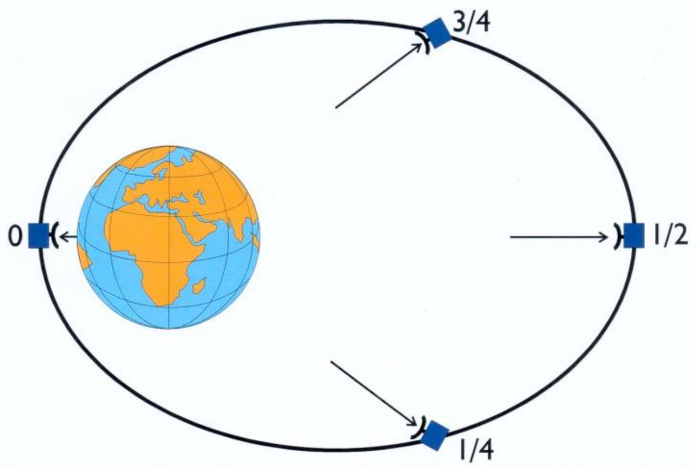
These wheel devices store angular momentum, with their torque motor controlling the flow of momentum between the wheel and the spacecraft. Their function, if installed, is primary pointing control. The use of external torquers are required to prevent excessive build-up of angular momentum

Control of spacecraft pointing can be achieved avoiding the frequent use of external torquers (thrusters or magnetorquers) …

Torques and Torquers

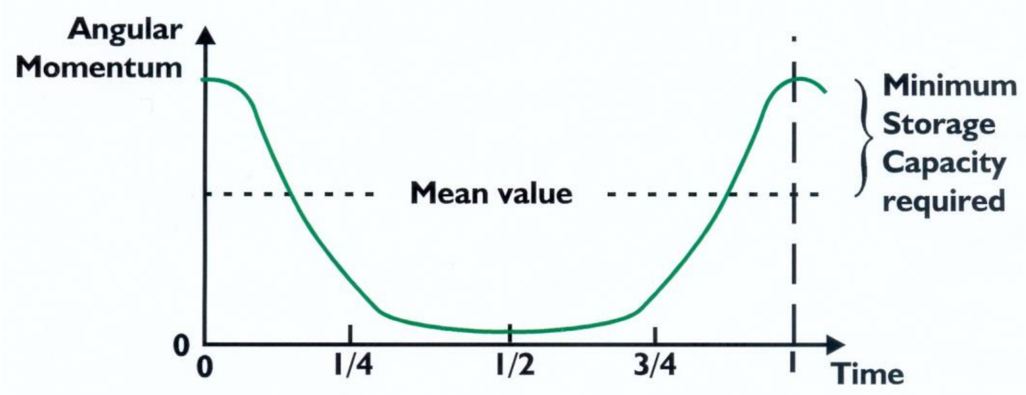
Use of momentum storage

Momentum storage capacity can be chosen so as to avoid the use of external torquers (fuel) for controlling repointing and other events in which the 'before' and 'after' momenta are equal
(i.e. periodic variation in momentum)



Example: Earth-pointing from an elliptic orbit ...

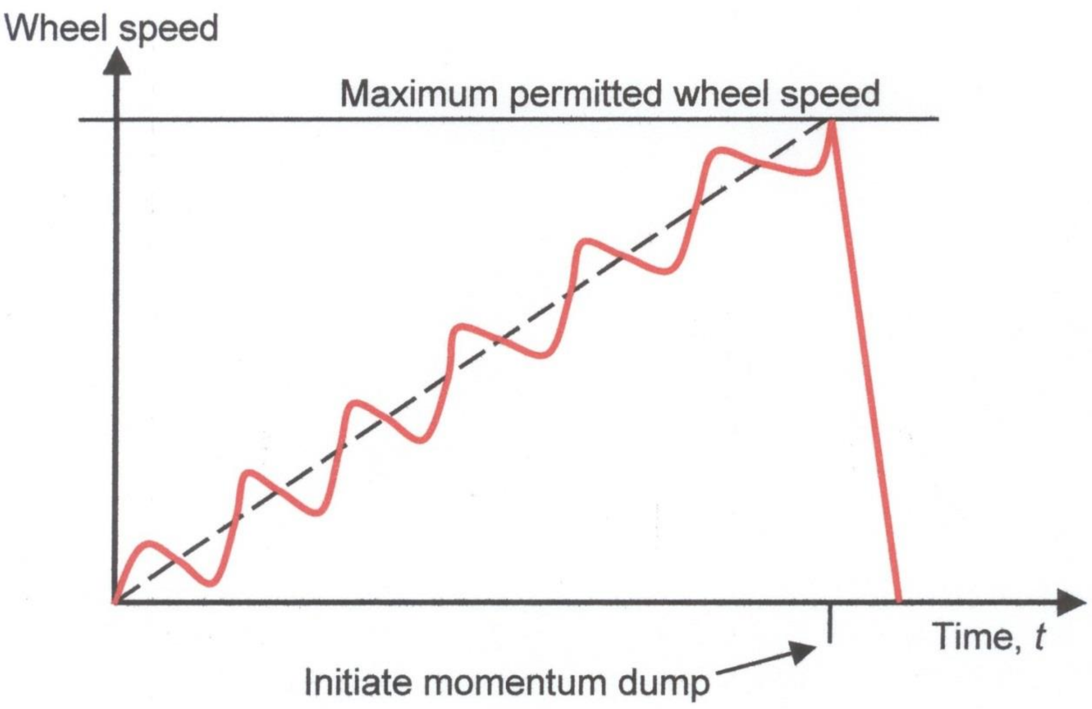
The local vertical's angular rate, and therefore the spacecraft's angular momentum, varies throughout one orbit



Torques and Torquers

Momentum dumping (or ‘wheel desaturation’)

Disturbance torques can cause the mean angular momentum of the system to increase. Pointing control then requires progressively higher wheel speeds



Initiate momentum dump once max wheel speed is attained:

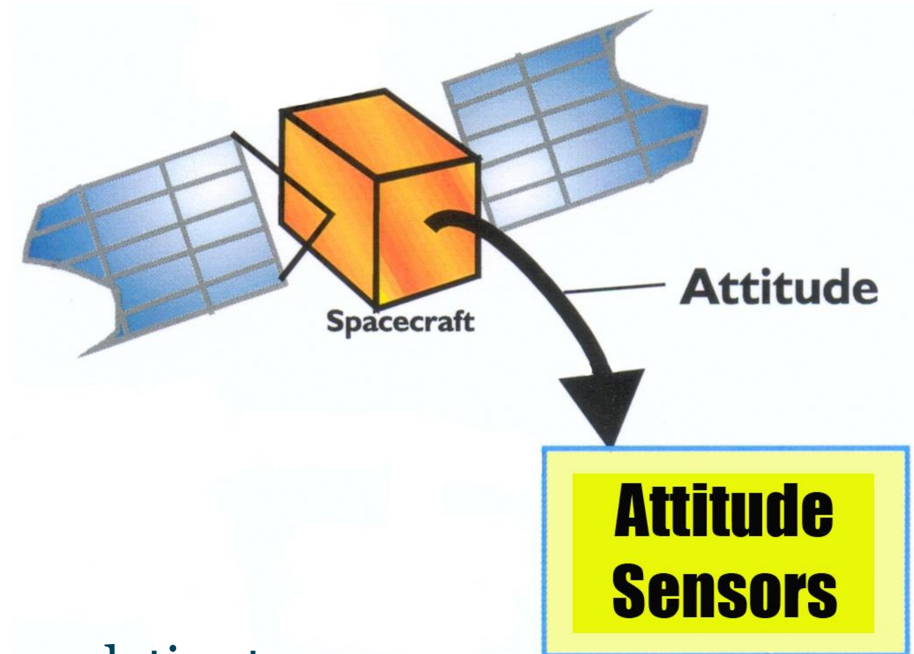
-Torque wheel to slow it down

-While switching to external torquers for pointing control

Attitude sensors

Categories of sensors

Note that: Attitude control is less accurate than its measurement



Reference Sensors

… which give attitude information relative to a reference source (e.g. a star)

Inertial Sensors

… which measure changes in attitude

Attitude sensors

Categories of sensors

A. Reference sensors

- These give information about the vector direction from the spacecraft to a reference object, in the spacecraft body axes.
- Potential accuracy is limited by the characteristics of the reference object:

Note that: the accuracies given are very approximate best performances

Potential Accuracies

Stars	~ 1 arcsec
Sun	~ 1 arcmin
Earth (horizon)	~ 6 arcmin
Magnetometer	~ 30 arcmin
GPS	~ 6 arcmin*

*Depends on receiver baseline

Attitude sensors

Categories of sensors

B. Inertial sensors

- These are gyroscopic devices which give ‘change-of-attitude’ information only
- They need to be calibrated regularly using reference sensors (☆)
- They will continue to function whilst a reference object is eclipsed.

(☆) Note: Spacecraft must carry sensors of Type A

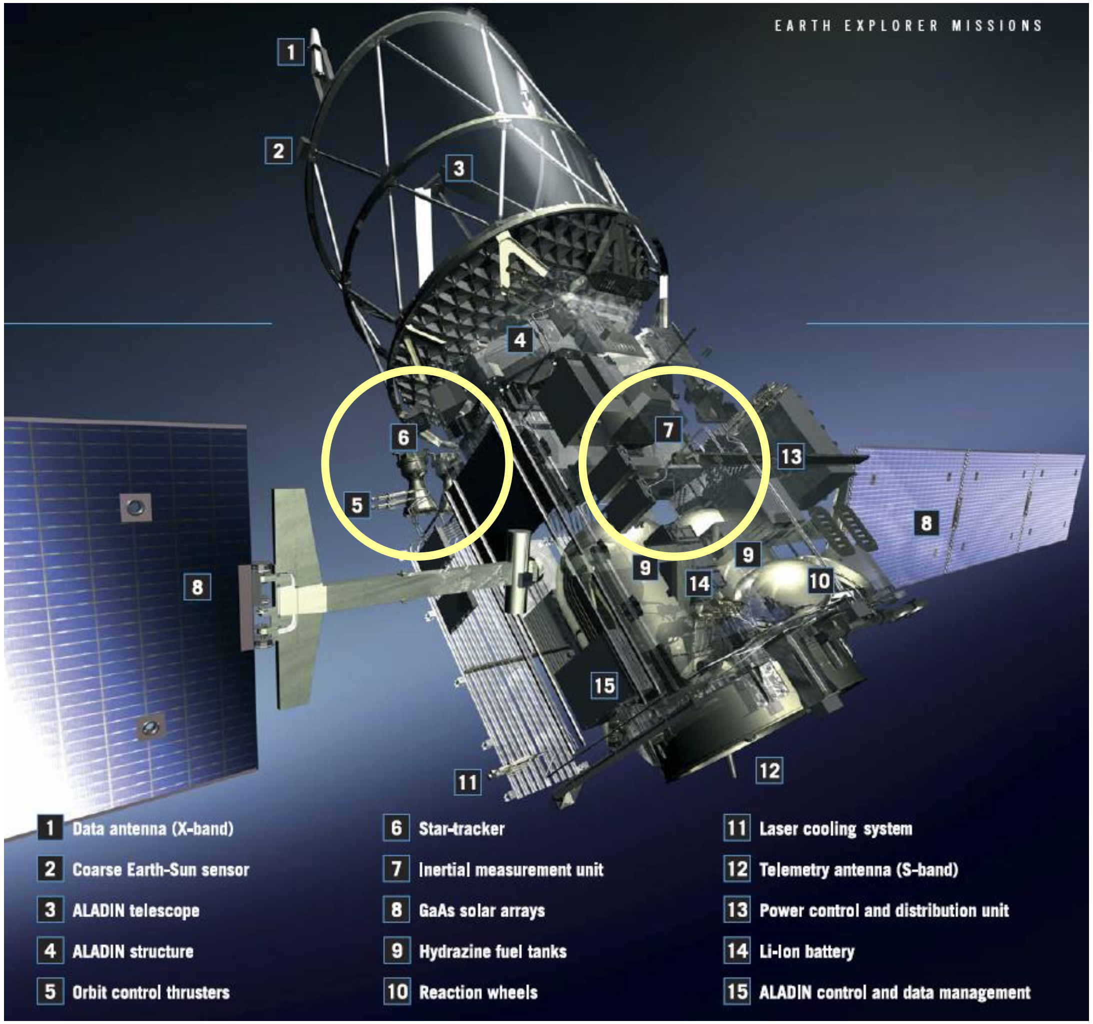
Attitude sensors

Example: Space shuttle attitude sensing system

– Gyros and star trackers.

Attitude sensors

Example: AEOLUS – Combination of star mapper and IMU



On-board Processing – closing the loop

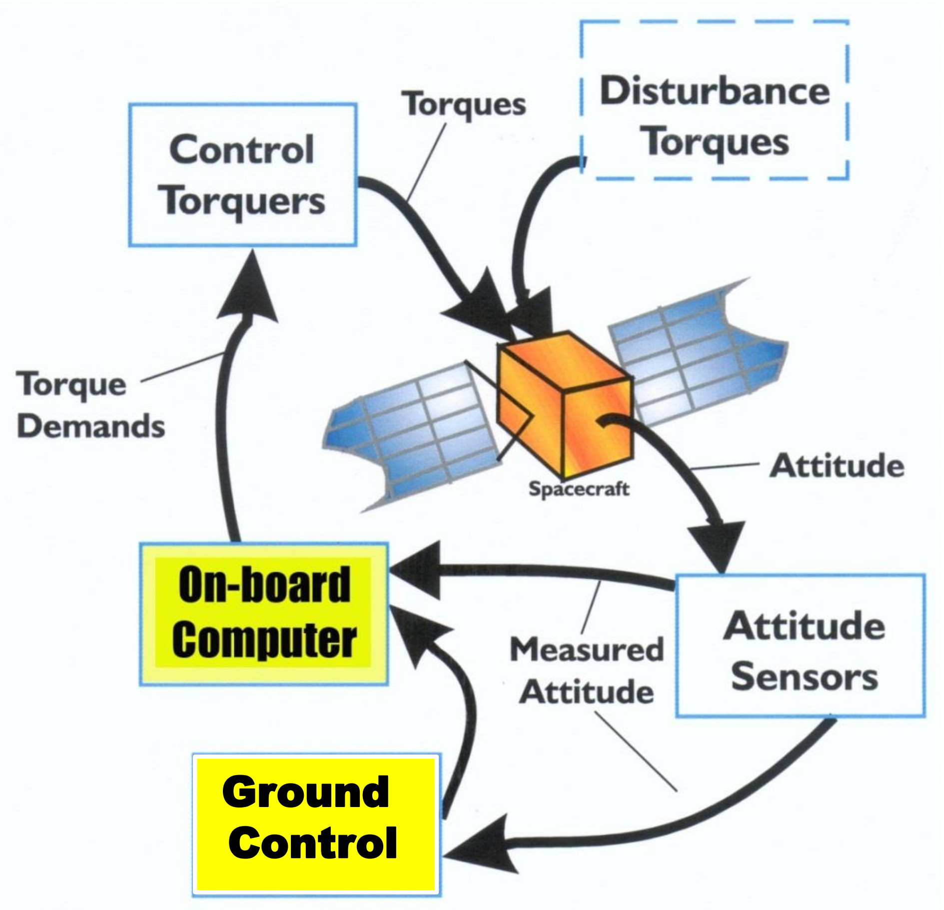
On-board verses ground:

- The amount of autonomy given to the OBC varies considerably

- In general, modal control will be done by the OBC, with monitoring, resetting commands from Ground Control

Operational modes:

Standby
Initial Acquisition Mode (IAM)/Safe Mode (SM)
Thruster Control Mode (TCM)
Normal Mode (NM)



Impact of ACS on the spacecraft system

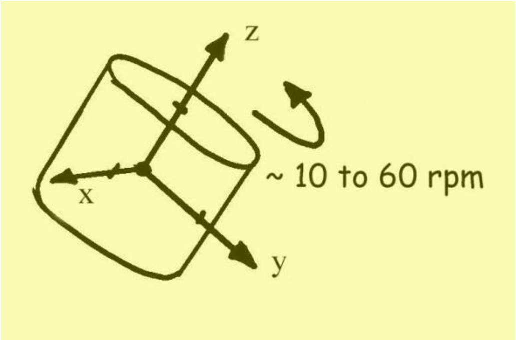
ACS has major interactions with other subsystems

- **Major system consequences for Type 1 (pure spinner) and Type 2 (dual-spinner)**
  - Power: Power limited.
  - Thermal: Spin distributes solar thermal input equitably. This decreases thermal design complexity, but placement of radiator surfaces can be problematic.
  - Communications: Antenna pointing problematic. This difficulty is eased in Type 2 configurations.
  - Payload accommodation: Limited physical space for non-scanning payloads
  - Transmission across electromechanical bearing: Type 2

Impact of ACS on the spacecraft system

– <u>Mass distribution:</u> The inertia matrix must take a particular form …

$$[\mathbf{I}] = \begin{pmatrix} I_{xx} & 0 & 0 \\ 0 & I_{xx} & 0 \\ 0 & 0 & I_{zz} \end{pmatrix}, \quad (I_{xx} = I_{yy})$$



Further for long-term stability, we require $I_{zz} > I_{xx}$.

– <u>Nutation:</u> Spinning introduces this oscillatory mode. This must be damped out using

- Passive dampers
- Active damping via control torquers

Impact of ACS on the spacecraft system

- **Major system consequences for Type 3 (hybrid) and Type 4 (3-axis)**

  - Power: Deployed solar arrays may be used, providing greater power generation capability.
  - Thermal: Significant thermal gradients can occur, increasing complexity of thermal design.
  - Communications and payload accommodation: Greater flexibility than for Types 1 and 2.
  - Mass distribution and nutation: No major constraints, although Type 3 (hybrid) will exhibit nutation.

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ACS Conclusions

- Attitude stabilisation type + diverse attitude pointing requirements

  ⇨ Profound effect upon spacecraft configuration

- Mass distribution has an important effect on attitude motion
  - Stability
  - Response to control torques

- There are many workable alternative designs for an ACS

Chapter 6 Summary

Key points:

Attitude Control Introduction

- Purposes and requirements of the Attitude Control Subsystem
- ACS typical feedback control loop

Rotational Dynamics

- Basic principles of angular momentum
- The inertia matrix and its importance to vehicle response and design
- Gyroscopic precession and gyroscopic rigidity (momentum bias)

Momentum Management

- How the overall momentum is managed for the spacecraft
- Key principles of momentum management, the use of momentum bias and how it affects the systems response to applied torques

Spacecraft Categories

- The four active types of spacecraft stabilisation
- The consequences of these types on the spacecraft design

Torques and Torquers
Attitude Sensors
On-board processing

- Categorisation of torques and torquers and examples of each
- The practical use of momentum storage leading to momentum dumping
- Categorisation of sensors used in the ACS subsystem
- Modes of operation

Impact of the ACS on the Spacecraft System

- Important impacts of the ACS subsystem on the design and operation of the spacecraft

Chapter 6 Summary

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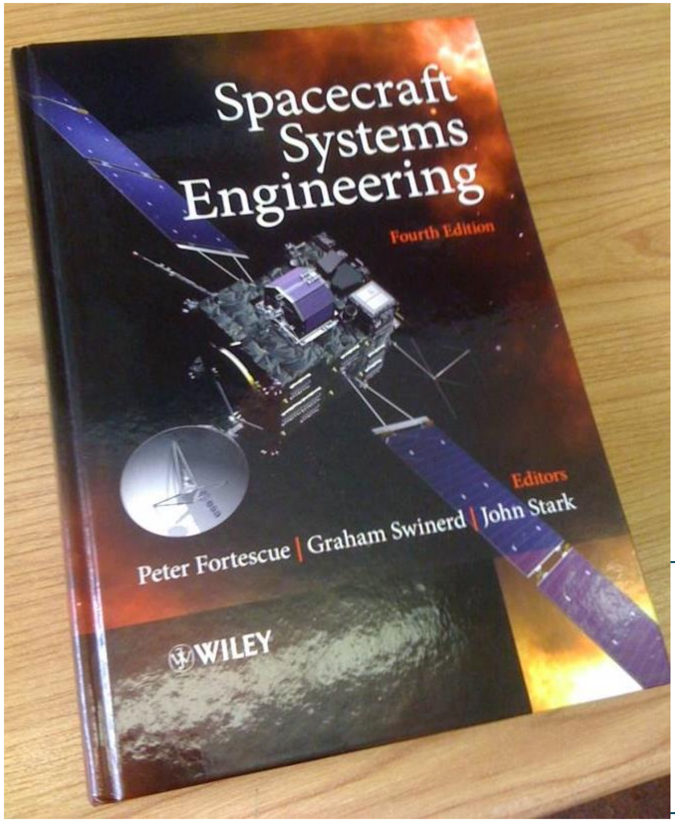

Read Chapter 9 of Fortescue, Stark & Swinerd