ADCS – IV
Attitude Hardware and Attitude Concepts

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Summary of last lecture

Disturbance forces

- Atmospheric drag, Solar radiation pressure, Third body
- Restricted three body problem → Lagrange points → Halo orbits

GEO perturbation

Conclusion for near Earth orbits:

- J_2 acceleration is dominant perturbation for low Earth orbits
- Atmospheric drag dominant perturbation at very low altitudes

For geostationary orbit:

- J_2 less important than solar or moon perturbation (North-South drift)
- Tesserial harmonic (East-West drift) and solar radiation (change of *e*)

Type of satellite orbits

Coordinate systems (Reference frames)

Questions to lecture ADCS - III

- Which perturbations produce an acceleration proportional to surface area over mass?
- What is an equilibrium point?
- What does it mean the motions have chaotic behavior? Do you know an example?
- What are Lagrange points? What are the assumptions to calculate them?
- What is an Halo orbit?
- What are the main perturbations for GEO satellites and mention shortly the effects?
- What is the picture that you have for the tesserial harmonic (J_{22})?
- Which (basic) types of coordinate system do you know?
- What do we mean with orbit station-keeping box?
- Can you explain qualitatively how the figure-8 ground trace for an inclined geosynchronous orbit is produced?

Outline

Objective and description of attitude

Hardware

- Sensors (determination)
- Actuators (control)

Attitude control

- Passive
- Active

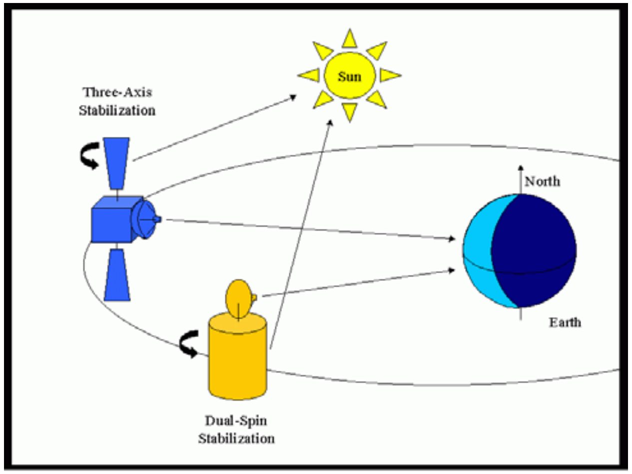
Introduction to attitude concepts

Environmental torques

Introduction

Most instruments of spacecraft have to point into specific direction:

- Solar panels to maximize Sun exposure
- Specific telescopes like in Hubble satellite
- Communication satellite with their antennas
- Photographic cameras have to point to given location
- Thrusters of spacecraft have to be aligned correctly (for maneuvers)
- Additional instruments or scientific sensors



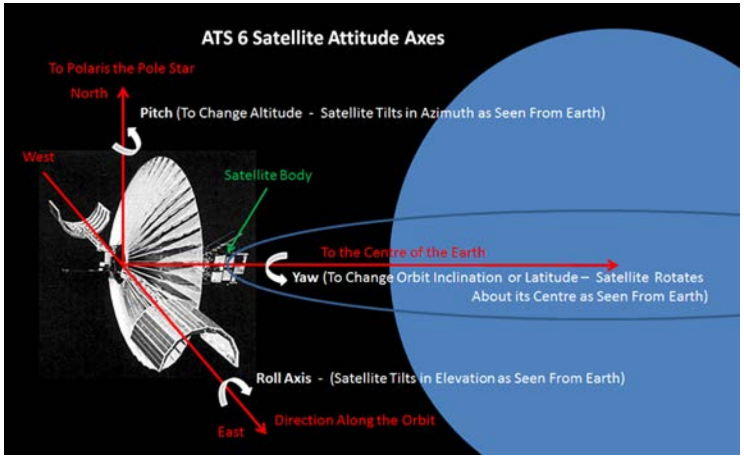
Main objective of attitude

Orientation of spacecraft (with respect to other systems of reference) is called **attitude**

Spacecraft attitude characterized by orientation of spacecraft-fixed coordinate system with respect to reference coordinate system

Objective:

Determine orientation of spacecraft-fixed reference frame with respect to known inertial reference frame



Description of attitude

Spacecraft with instruments and antennas has to point into specific directions
- Solar arrays must point into Sun
- Thruster must point into required direction

Find orientation of spacecraft in space relative to other frame
Attitude: orientation of spacecraft body axes relative to fixed inertial frame

To control attitude, spacecraft operators (or computer, if autonomous system) must have ability to:
- Attitude **determination**: use **sensor** to estimate attitude
- Attitude **control**: maintain specific attitude with given precision using **actuators**
- Determine error between current and desired satellite attitude (attitude error)
- Apply **torques** to remove attitude error

ADCS versus GNC subsystem

ADCS
Attitude Determination and Control System

Controls nominal attitude for satellite body axes such that errors are within defined limits

Attitude controlled by applying torques

Provide pointing and rates stabilization

Provides spacecraft attitude knowledge to support mission objectives

GNC
Guidance Navigation and Control

Controls nominal orbit which satellite should maintain within defined limits

Orbit controlled by applying forces

Provides position and velocity knowledge

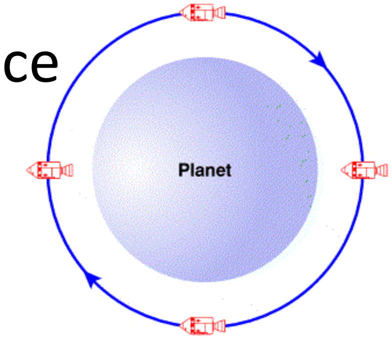
Provides timing, magnitude, duration, and direction of burns for orbit transfer and station keeping maneuvers

Note distinction between:
attitude control which deals with rotation about spacecraft axes
guidance control which deals with objects position

Separate motion into: - motion of center of mass
- rotational motion around center of mass

Need of attitude determination and control

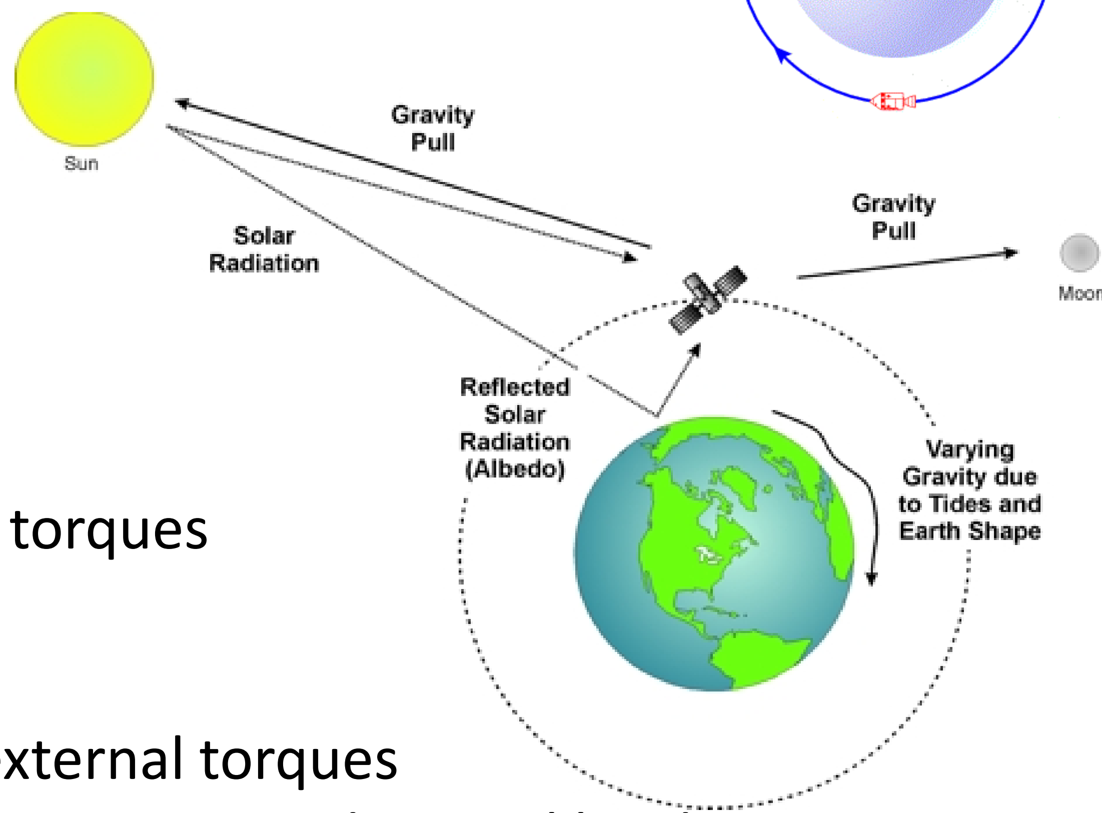
If only Kepler motion satellite remains inertial fixed in space



But disturbances exist

- Earth magnetic field
- Atmospheric drag
- Solar radiation
- Gravity gradient
- Gravity (n-body problem)

Disturbances produce external torques

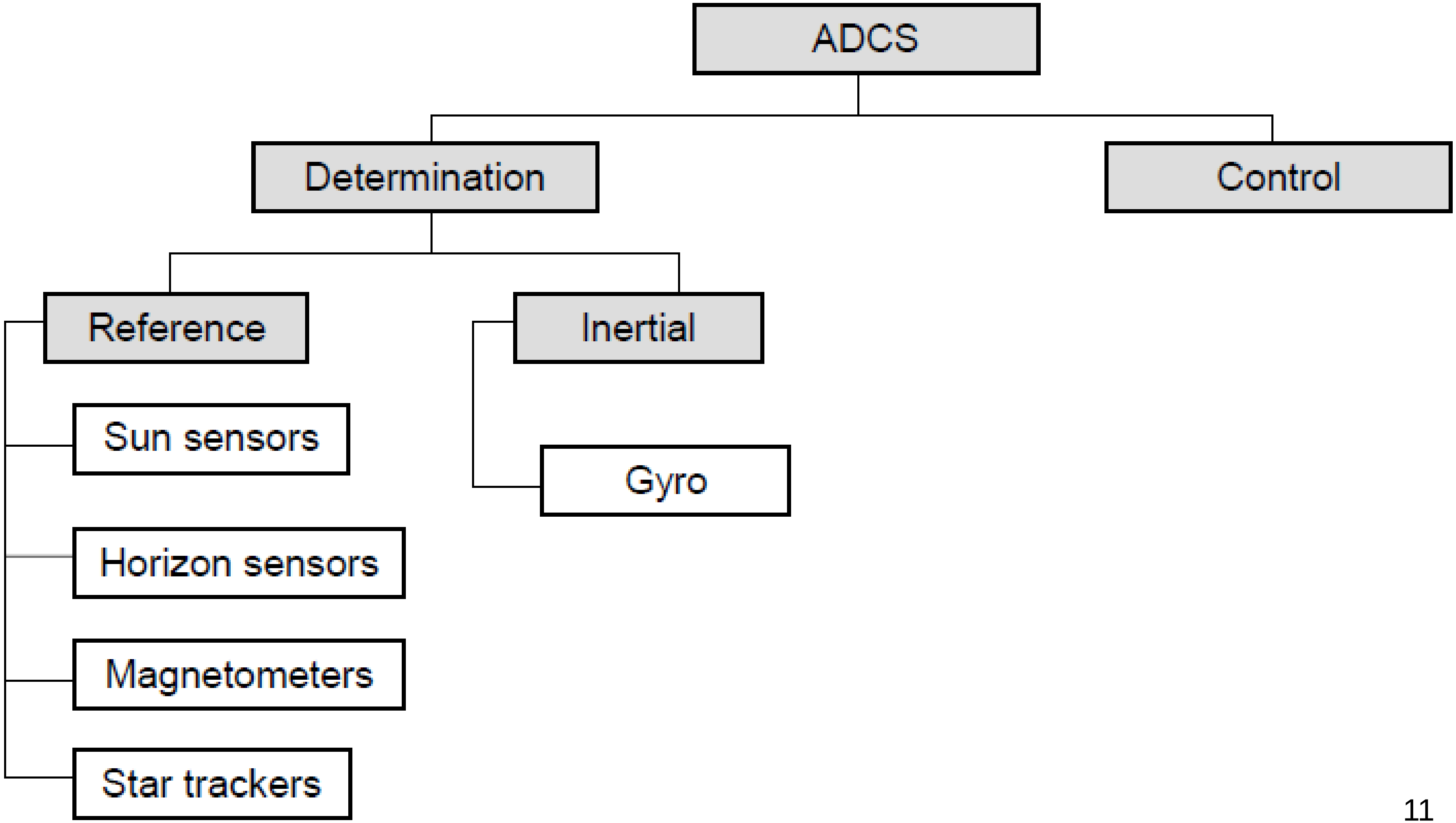


To compensate for unwanted external torques spacecraft needs attitude determination and control hardware

1. Attitude determination requires sensors
2. Attitude control requires actuators

Attitude Hardware: Sensors for Attitude Determination

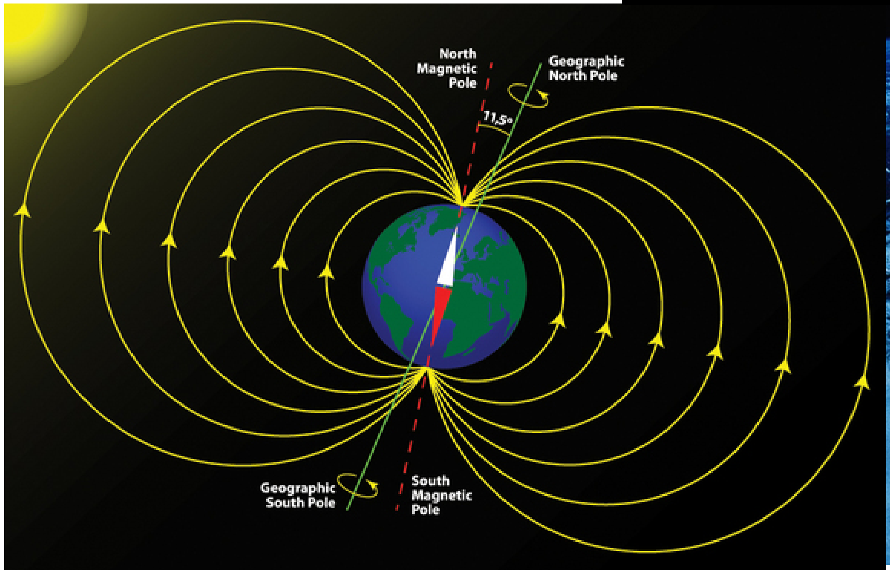
Sensor for attitude determination



What do sensors sense?

External references used to determine spacecraft absolute attitude:

- ❑ Sun
- ❑ Stars
- ❑ Earth horizon
- ❑ Earth magnetic field



Sensors

Sun sensor (measure position of Sun)
Simple Sun sensor provide unit vector to Sun using masked photocells

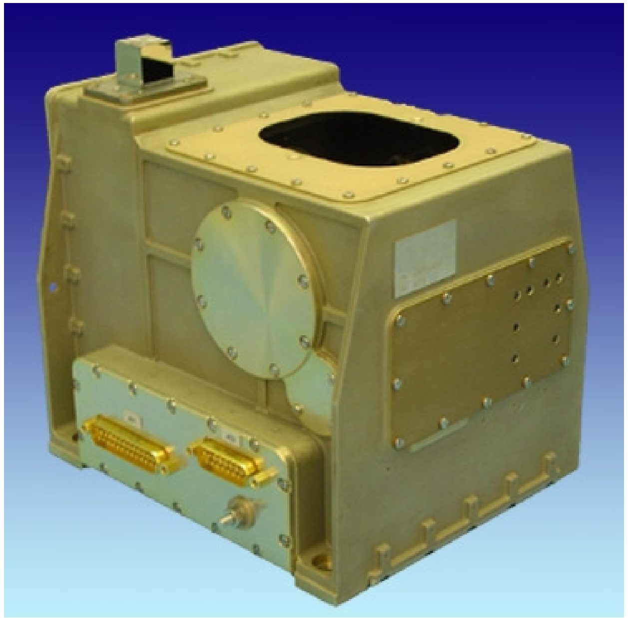
Star sensor (compare image of sky with some expected image)
Star camera searches star catalogue database to determine direction

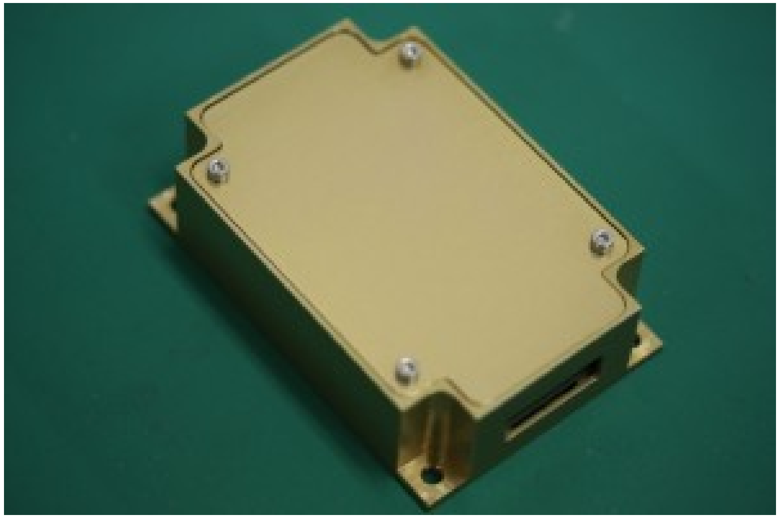
Earth sensor (measure position of Earth or attitude with respect to horizon)
Earth sensors operating principle is based on electromagnetic modulation of radiation from Earth´s horizon

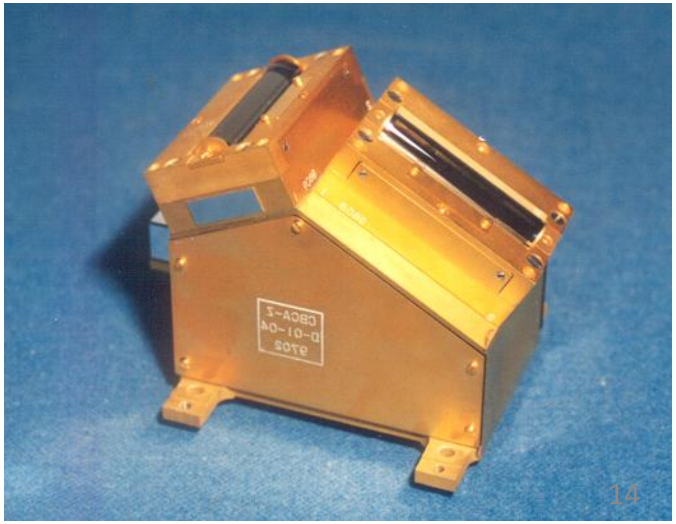
Magnetometers (measure magnitude and direction of magnetic field)
Earth magnetometer is measuring instrument to measure strength or direction of Earth magnetic field

Gyroscopes (measure rotation of spacecraft without external reference)

Do you recognize a sensor ?







Two types of attitude sensors

Two types of attitude sensors:

Reference sensor:

Measures attitude with respect to some reference frame
defined by position of objects in space (e.g. Sun, Earth, stars, etc.)

Inertial sensor:

Measures continuously changes in attitude relative to a gyroscopic rotor
Detects if satellite is not in an inertial frame of reference
Detects rates of accelerations of angles calculated via integration

Pro and cons for reference and inertial sensors

Basic performance trade:

Reference sensors
- Give direct measurement and fix reference frame
  (do not need initial conditions)
- May be temporarily blinded or otherwise unavailable
  (e.g. for Sun sensor can have problems during periods of eclipse)

Inertial sensors
- Always available
- Need to be updated (any drift must be detected using an external reference)
- Errors increase progressively when making continuous measurements

Common to combine reference and inertial:
- Reference sensors used to calibrate inertial sensors at discrete times
- Inertial sensors can measure continuously between each calibration

Sensor selection

Need sensors for variety of purposes

Mission may require:

- High accuracy attitude determination
- Image stabilization (remove movements)
- Slewing (retargeting)

Satellite functionality may require:

- Recovery from tumbling
- Acquiring Sun
- Pointing for trajectory change maneuvers

Different mission goals may need different hardware:

- Choose hardware for each mission goal (or all goals with one hardware)
- Redundancy important
- Decide performance versus cost versus weight versus volume versus reliability versus availability

Potential accuracy of attitude measurement

Reference object	Potential accuracy
Stars	1 arcsecond
Sun	1 arcminute
Earth	6 arcminutes
Magnetometer	30 arcminutes

From
P. Fortescue

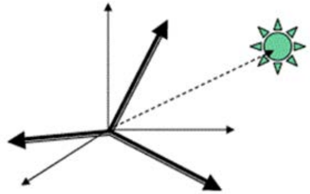
Arcminute = 1/60 degree Arcsecond = 1/360 degree

Ultimate accuracy associated with object used by sensor
(Depends on angle object subtends and fuzziness of horizon)

Control algorithm is only as good as hardware

Mission requirements dictate spacecraft sensor configuration

Sun sensor



- Sun sensor measures angle between Sun and reference angle
- Simple Sun sensor provide unit vector to Sun using masked photocells
- Large, bright, easily acquired reference
- Problem with eclipse
- Accuracy limited of Sun sensor is about several arc seconds (about 0.05 degree) for precise sensors and 0.5 degree for coarse sensors
- One Sun sensor measurement does not give complete attitude but only a direction (only two degrees of freedom on vector are sensitive to attitude)
- Two measurements are required to determine attitude:

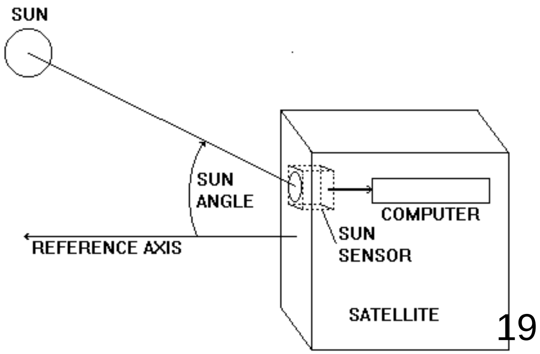
  - by second independent sensor (but not same object)

  - by same sensor but separated significant in time
- Three basic classes:

  - Sun analog sensor

  - Sun digital sensor

  - Sun presence sensor

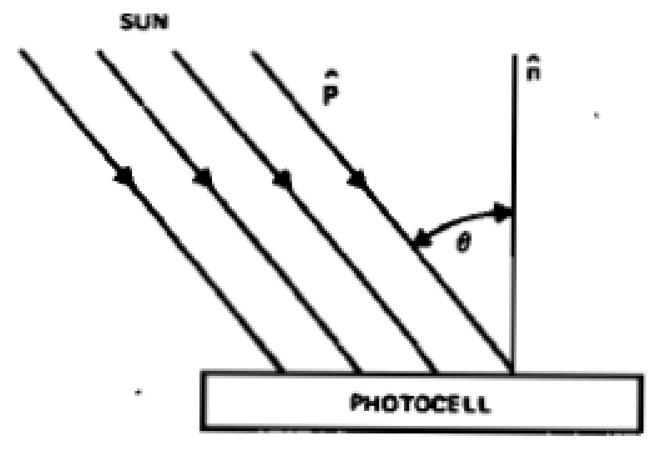


Analog Sun sensors

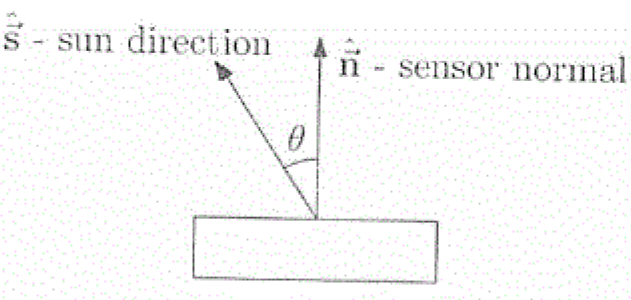
Analog

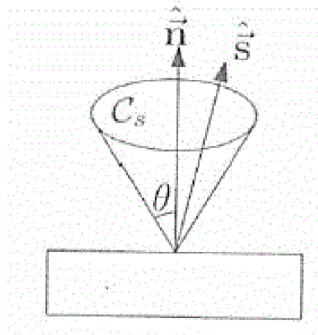
- Basic implementation: Measure output current of solar cells
- Output current proportional to cosine of angle of incident of solar radiation
- Compare brightness on various detectors to deduce angle of incident
- Usually low accuracy, small size, low cost, no power required

Analog sensor
Current I
$I(\Theta) = I(0)\cos(\Theta)$



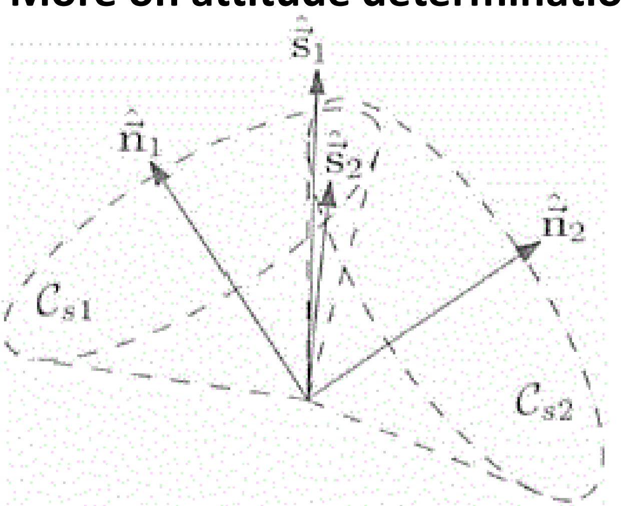
Cone from analog Sun sensor

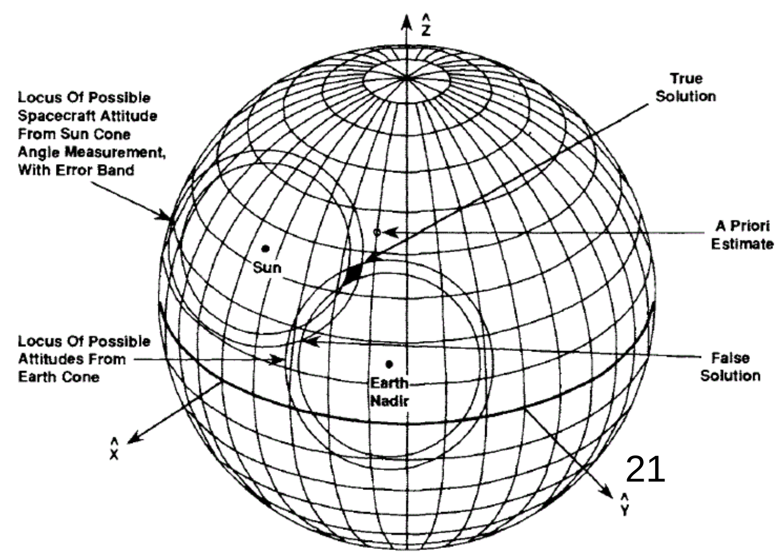




Analog Sun sensor provides angle ϴ of Sun vector relative to sensor normal
⇒ Cone where Sun vector must lie

Combinations of pair of analog Sun sensor give additional information
Pair of analog Sun sensors with normal n_1 and n_2
⇒ pair of cones on which Sun vector must lie
⇒ pair of possible Sun vectors s_1 and s_2
Additional measurement needed to determine true Sun vector
Possibility add third Sun sensor → three intersecting cones → give Sun vector
More on attitude determination in lecture ADCS - VII

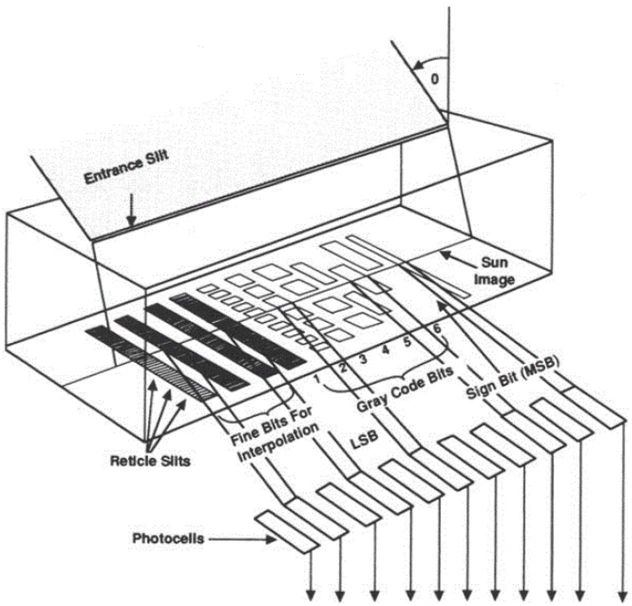




Digital Sun sensor

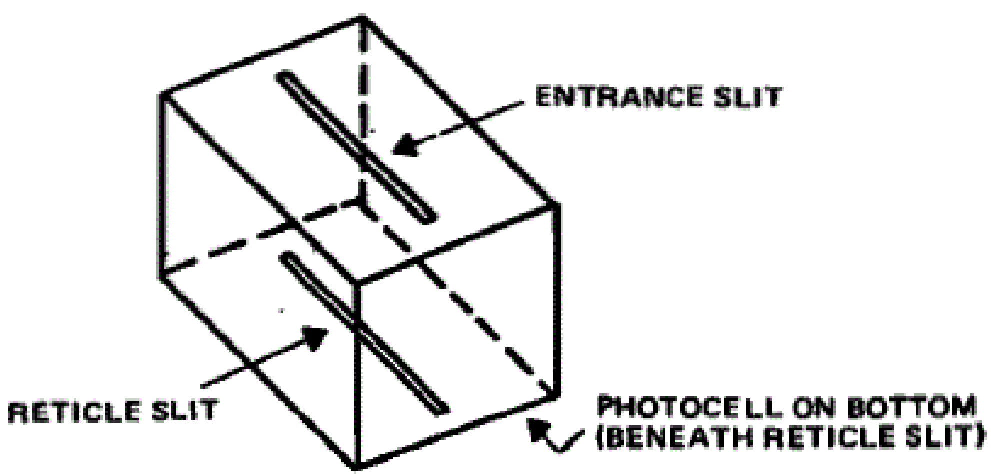
Digital

- Digital output of Sun sensor allows to determine plane in which Sun lies
- Two such detectors mounted orthogonally can determine spacecraft Sun vector in body axes
- More complex than analog Sun sensor
- Transparent block of material with known refractive index
- Light from Sun passing through slit forms line over photodetector: slit etched in top, receptive areas etched in bottom
- Usually higher accuracy, larger size, higher cost, need more power than analog



Sun presence sensor

- Provide information if Sun is in field of view
- Frequently used for spinning spacecraft
- Sun presence detectors used to:
  - protect instrumentation
  - activate hardware
  - position spacecraft or experiments
- Two slits and photocells which indicates Sun presence



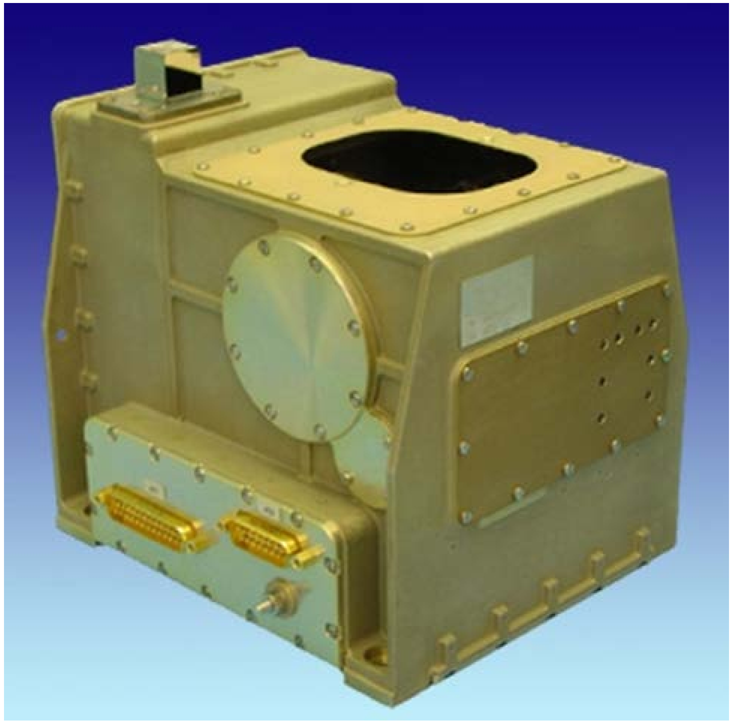
Earth sensor

For near-Earth satellite

- Earth is second brightest celestial object
- Covers up to 40% of sky (extended source to sensor)
- It is NOT enough to detect Earth even for coarse attitude determination
- **Main goal is to locate Earth horizon**

Most common means of determining Earth nadir vector

Earth sensor sense position of horizon of Earth (called also horizon sensor)



Earth sensor

- Main goal is to detect horizon but poorly determined in some wavelengths
- Typically look at narrow 14- to 16-μm CO_2 bands where Earth shape is same at night as well as day and works also during eclipse
- Sensor only useful if Earth lies within sensor field of view
- Sun and Moon should not come within sensor field of view
- Main error sources

  - should account for Earth flattening

  - radiance effects (detector looks at radiation off atmosphere and effective height of atmosphere varies with season → need algorithm to correct)

  - intrusion of other objects like Sun and Moon when near horizon

  - need to optimized for given altitude (elliptical orbits can reduce accuracy)

Earth sensors

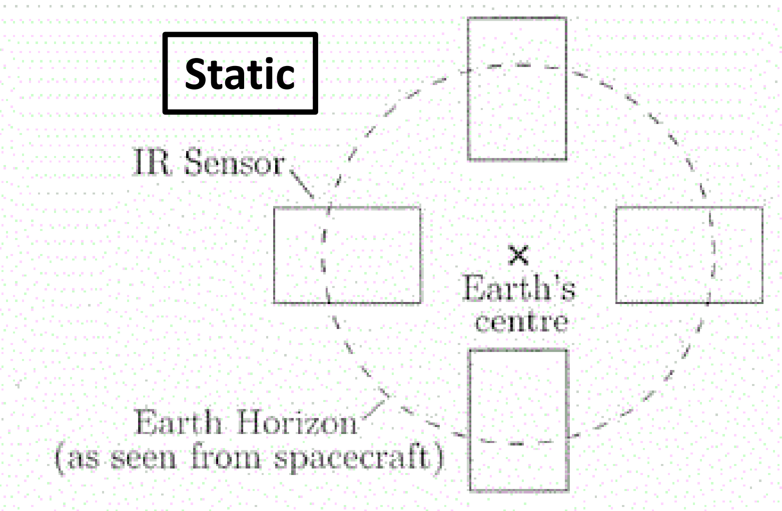
Two main types: **scanning** (panoramic) and **non-spinning** (static) sensors

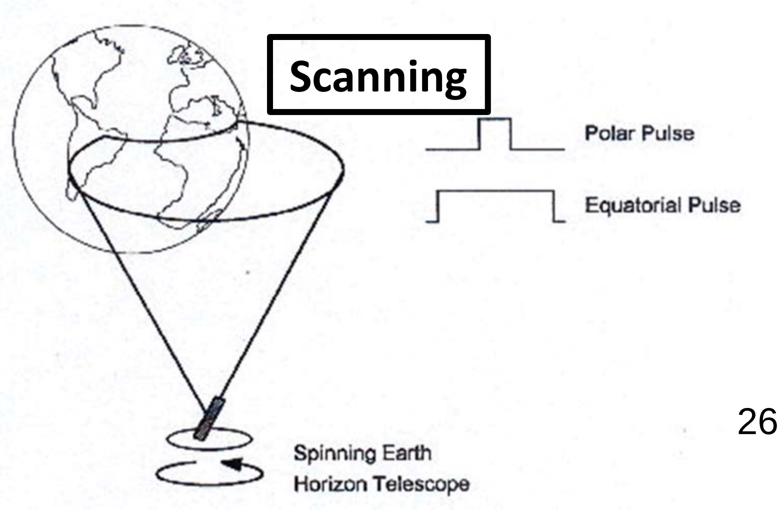
1. **Static Earth horizon sensor**:

- Sense infrared radiation from Earth´s surface with field of view slightly larger than Earth
- Sensor signal proportional to fraction of Earth disk contained within field of view
- Wider field of view than scanning Earth sensors

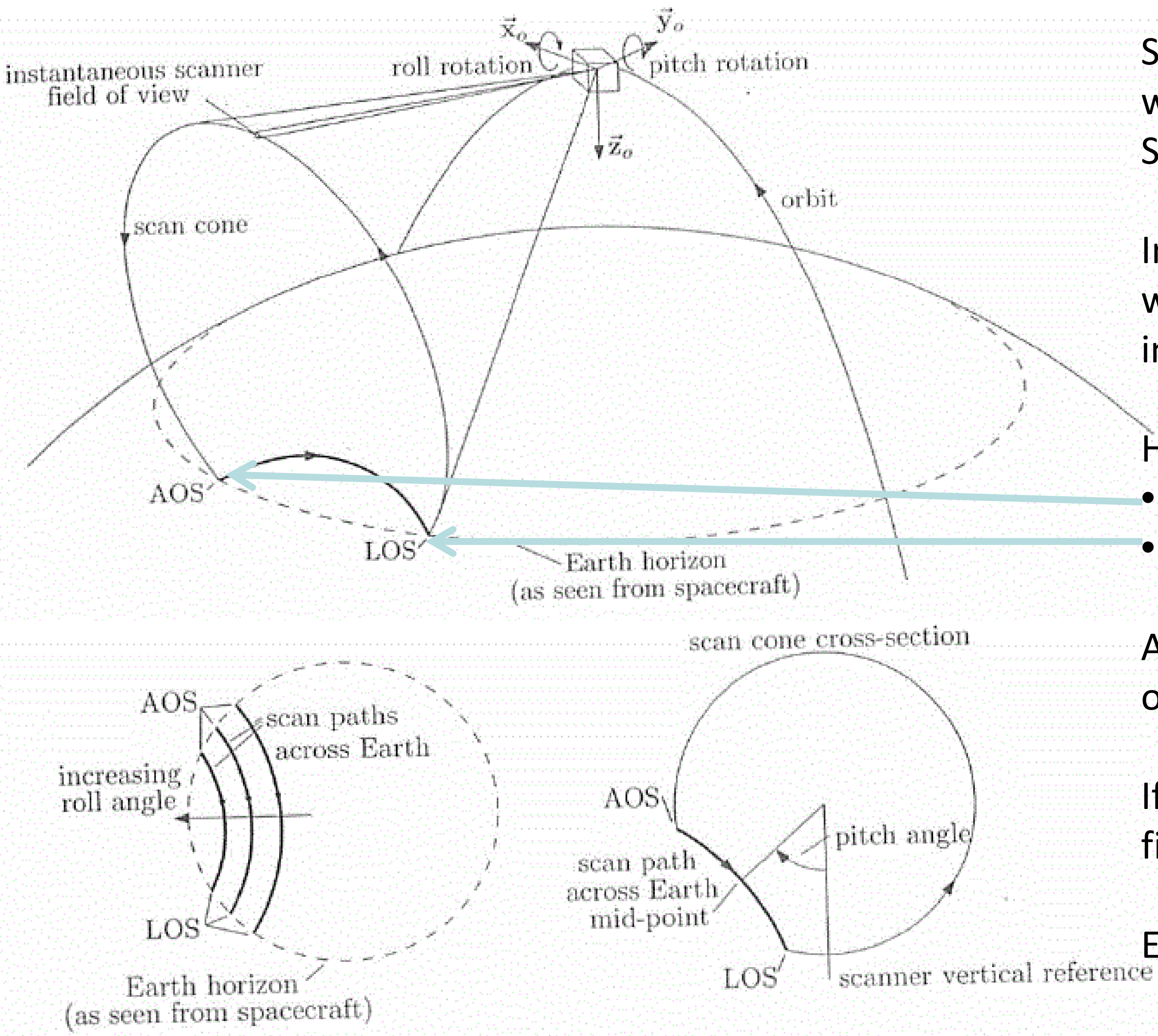
2. **Scanning Earth horizon sensor**:

- Spinning causes device to sweep out area of cone and electronics inside sensor detects when infrared signal from Earth received and lost
- Narrow field of view, mechanical scan, simple optics, single detector





Scanning Earth sensor



(a) Roll angle determination

(b) Pitch angle determination

Scanning Earth sensor
with rotating optical device
Sweeping out a cone

Infrared sensor detects
when Earth lies in scanner
instantaneous field of view

Horizon crossings
- Acquisition of signal
- Loss of signal

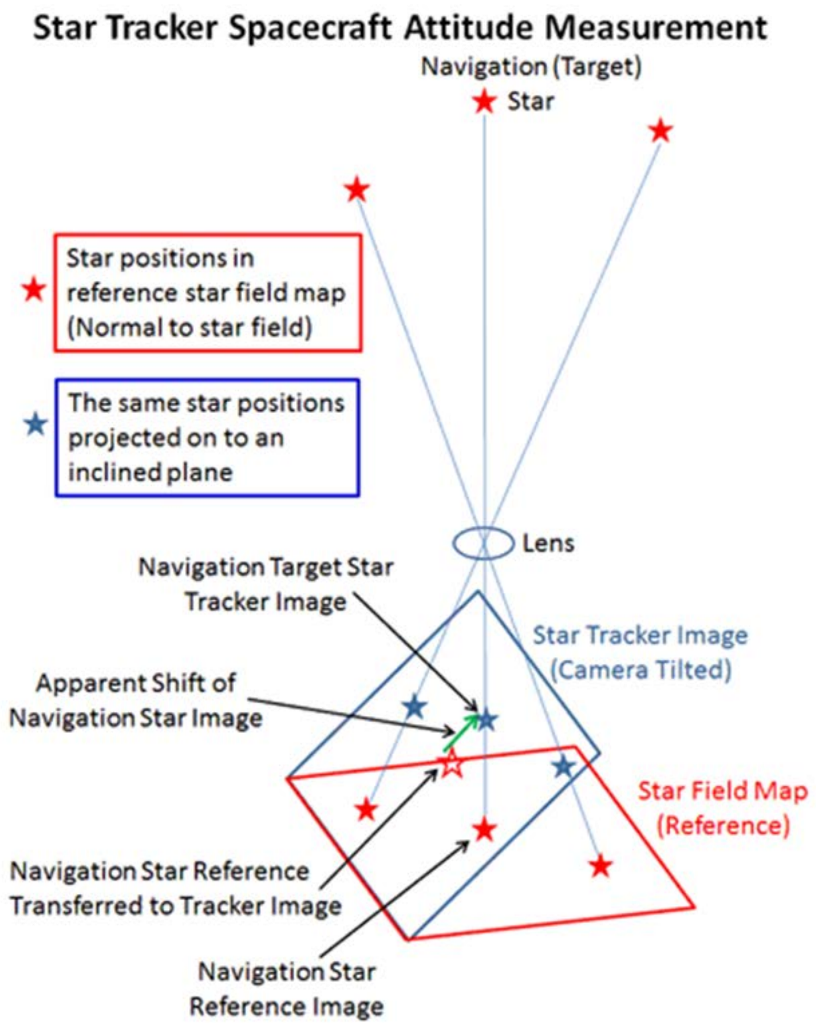
AOS and LOS depend
on scanner roll angle

If vertical reference
find scanner pitch angle

Exist also dual scanners

Star sensor

- **Most accurate attitude sensor**
- Absolute attitude determination with accuracy down to order of arc-second
- Starlight taken by CCD camera and compare it to star catalog
- Instrument has narrow field of view
- Determination of direction to two different stars could be enough for attitude determination
- Star sensors generally do not function well at angular rates above some degree per second (due to their small field of view)
- Required first a coarse sensor when high angular rates
- Suffer from occultation from Sun, etc.
- Heavy, expensive and need more power



Star sensor

- Star camera searches star catalogue database to determine view direction
- Star location catalog helps identify target
- One of the most used stars is Sirius (brightest)
- Star location on focal plane determines angles to star
- Basic components:

  - Optical system to put star image on focal plane

  - Some sort of Sun shade which closes if Sun gets too close

  - Detector (on focal plane typically CCD array)

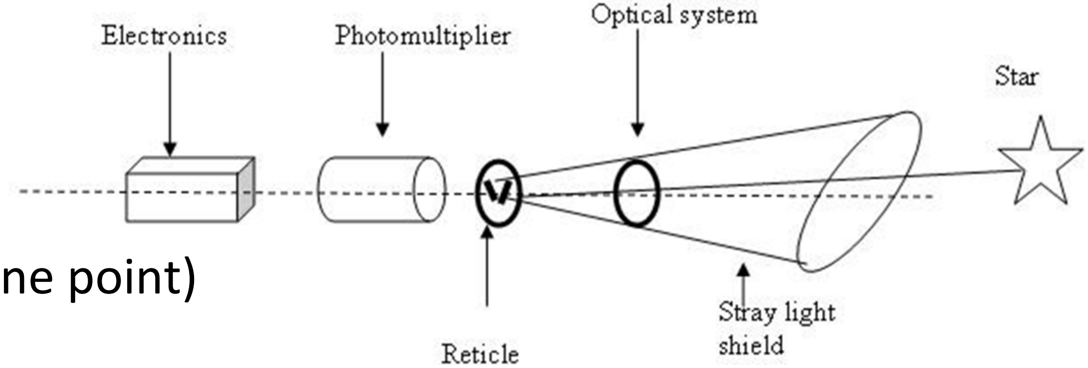
  - May have thermal control to minimize distortion

  - Read-out
- Algorithm:

  - Patter recognition

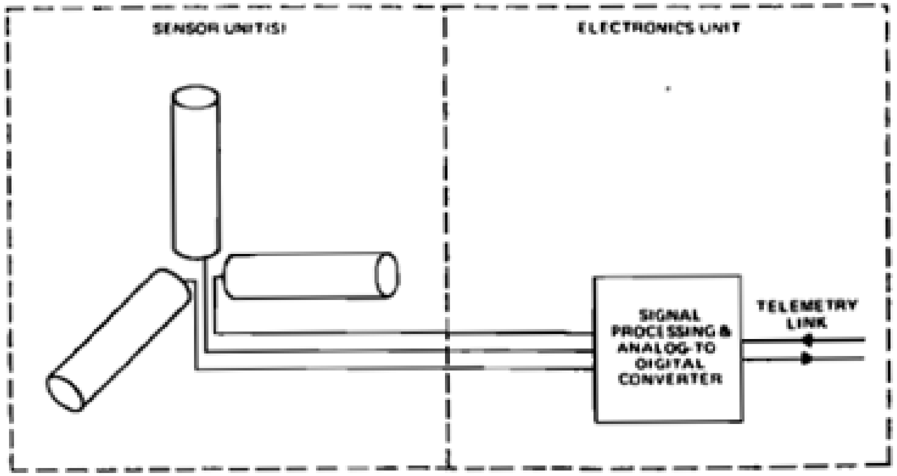
  - Star tracking

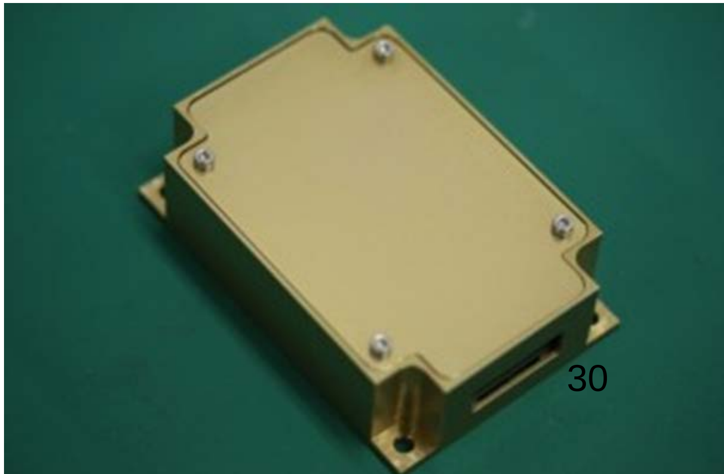
  - Often two modes (acquire and fine point)



Magnetometers

- Measure direction and magnitude of local magnetic field
- Available for low altitudes (<≈1000 km), simple, robust, relatively low cost
- Accuracy usually limited more by quality of on-board Earth field model and by effects of on-board fields than by device itself
- Three magnetometers required to determine Earth´s magnetic field vector
- Usually mutually orthogonal magnetometers
- Magnetometers consist of two parts: Magnetic sensor and electronic unit
- Electronic unit transforms magnetic sensor measurement into usable format
- Induction magnetometers based on Faraday´s law $\nabla \times E = -\frac{\partial B}{\partial t}$
- Almost all attitude system magnetometers are fluxgate magnetometers

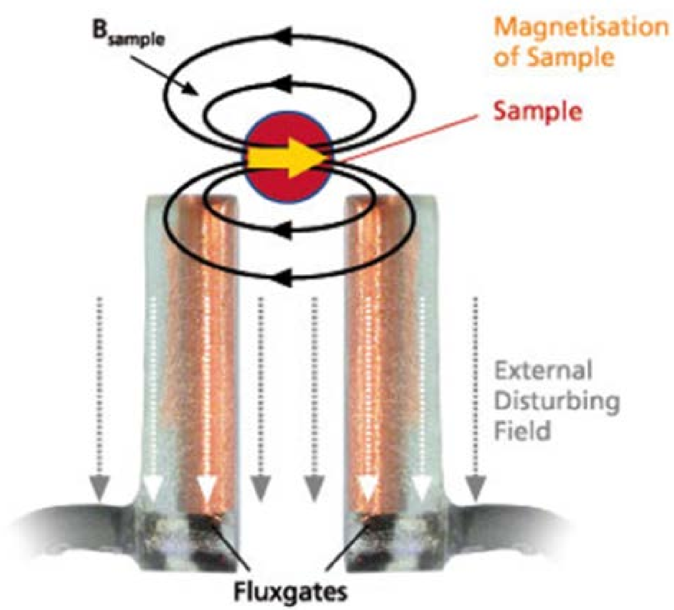


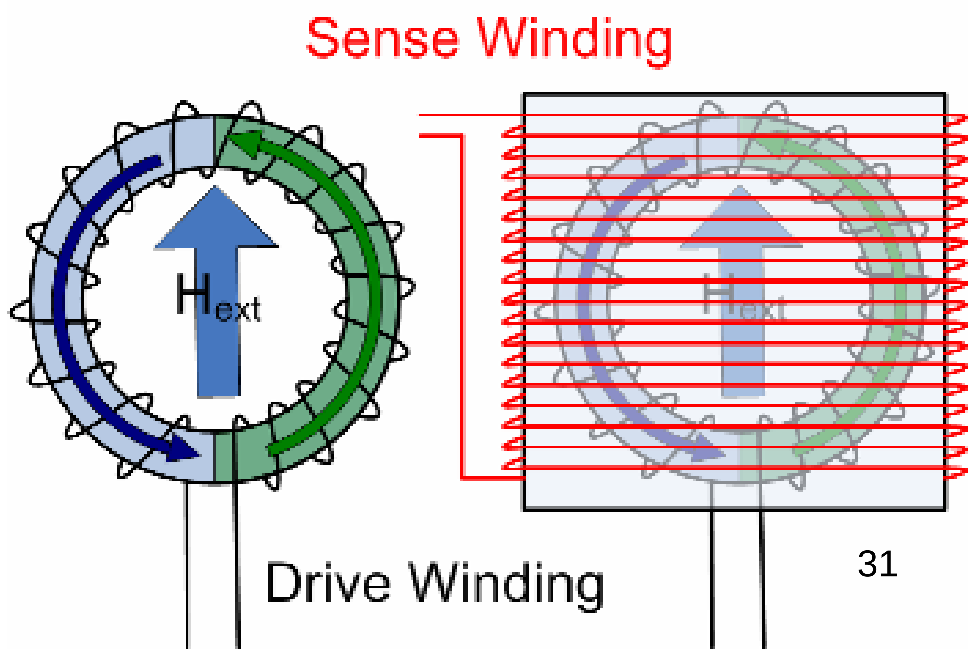


Fluxgate magnetometers

Fluxgate magnetometer

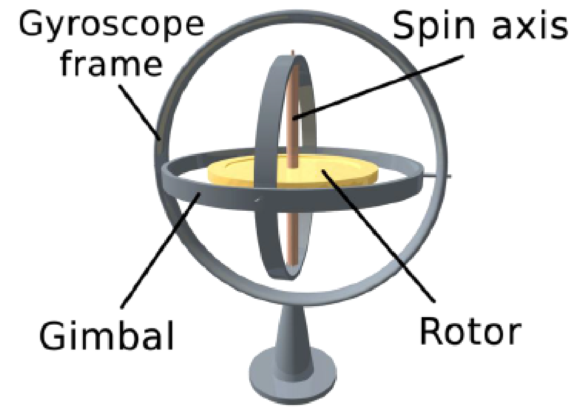
- Alternating current (drive winding) passed through one coil
- Metal magnetized by electromagnetic field
- Corresponding magnetic field sensed by second coil (sense winding)
- If magnetically neutral background → input and output current match
- Distortion of oscillating field is measure of one component of Earth´s magnetic field

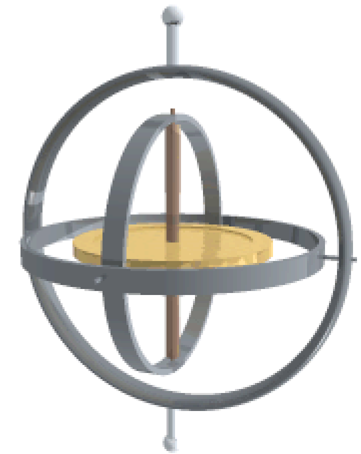




Gyroscope

- Gyroscope is spinning wheel in which axis of rotation is free to take any orientation
- Devices that sense rotation in 3-space, without reliance on observation of external objects
- Orientation of spinning axis unaffected by rotation of mounting due to conservation of angular momentum
- **Rate gyroscopes** are attitude sensors and measure rate of change of angle with time
- **Rate-integrating gyroscopes** are attitude sensors and measure total spacecraft attitude displacement (consist of damping fluid which resist motion of precession)
- Set of three orthogonal gyroscopes measures three components of spacecraft's inertial angular velocity
- Gyroscopes require initialization by some other sensor, as they can only measure changes in orientation
- **Control moment gyroscopes** are **not** attitude sensors but used to generate attitude control torques



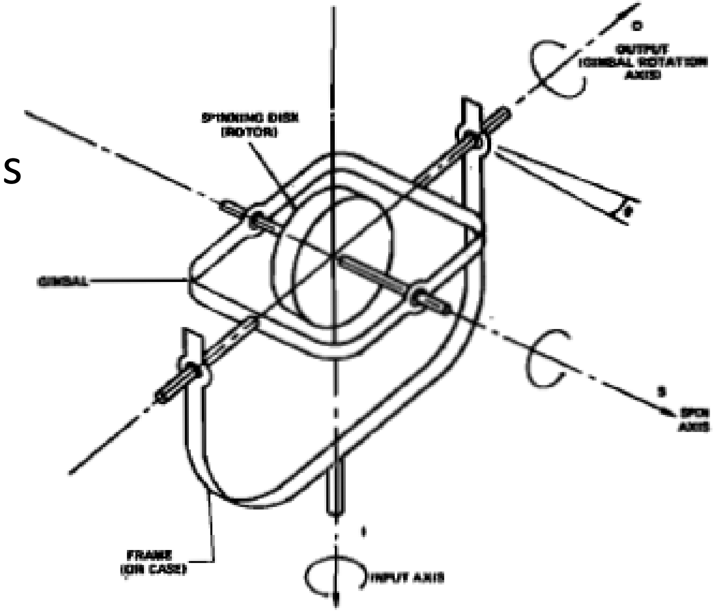


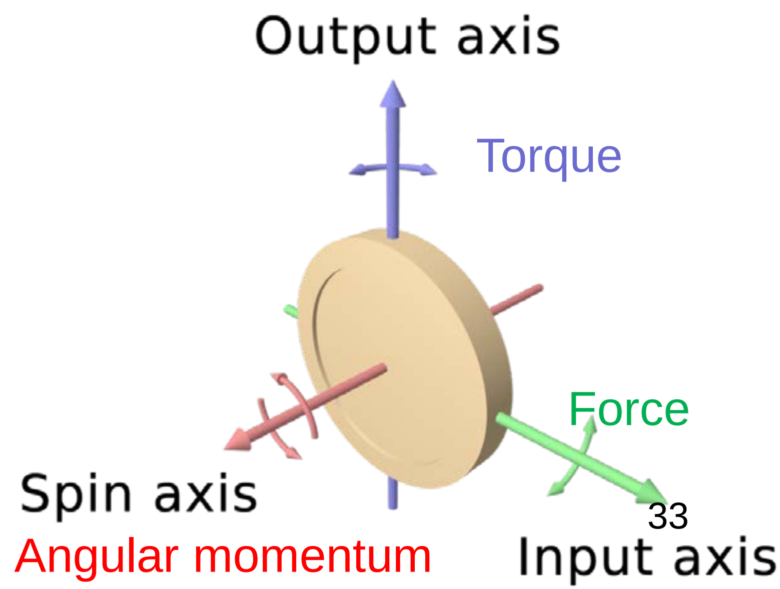
Gyroscope has freedom to rotate in all three axes

Rotor maintains its spin axis direction regardless of orientation of outer frame

Gyroscope basic construction geometry

- Angular momentum vector fixed in magnitude and parallel to gyroscope spin axis
- Vector maintains inertial orientation
- If torques exist → spacecraft motion about gyroscope input axis causes gimbal supporting spin axis to precess about output axis (or gimbal rotation axis)
- Output obtained from motion of gimbal
- Onboard computer determines from motion of gimbal orientation of apparatus with respect to spinning disk
- Law $\dot{\vec{h}} = \vec{T} = \vec{r} \times \vec{F}$





Different gyroscopes

Optical Gyroscopes

Sagnac interferometer measures rotational rate

(different distance that light travels due to rotation of ring, Δt)

- Δt = 0, photons traveling in opposite directions
  complete circuit in same time
- Δt > 0, travel length and time are different

Ring Laser Gyroscopes

Laser in optical path creates photon resonance at fix wavelength

Frequency change in cavity is proportional to angular rate

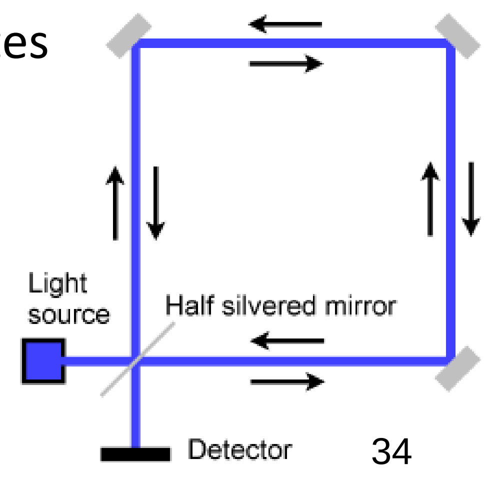
Three Ring Laser Gyros needed to measure three angular rates

Fiber Optic Gyroscopes

Long length of fiber cable wrapped in a circle

Photon source and sensor are external to fiber optics

Other Gyroscopes



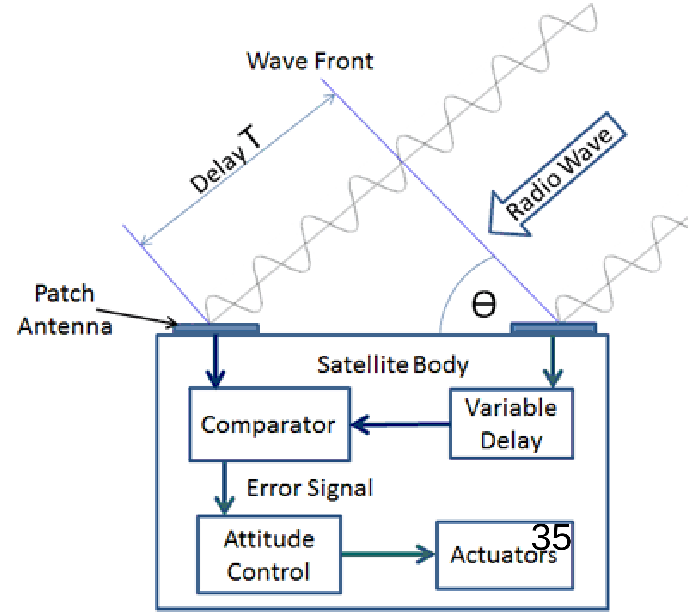
GPS interferometry

- Determine attitude from phase difference of GPS signal received from two antennas separated by baseline (Means: determine attitude from phase difference measurement between antennas mounted at different locations)
- Waves in phase undergo constructive interference (reinforcement), while waves out of phase undergo destructive interference (cancellation)

  → Determine phase difference or delay between two waves coming from same source
- In short: **use interferometry from multiple antennas**
- Figure: Delay time T depends on angle ϴ between plane of antennas and plane of wave front

  → Determine angle between satellite and direction of radio wave signals
- Problems:
  - Needs several GPS antennas at large distance (greater distance between antenna pairs means greater accuracy)
  - Signal at higher altitude

Radio Interferometry Attitude Control



Pros and cons for sensors

Sensor	Comment +++ positive	Comment --- negative
Sun	Bright and unambiguous	Simple, reliable, cheap Not visible during eclipse
Earth	Always available, bright and unambiguous	Static: cheap, simple Scanning: expensive, orbit-dependent Large angle for nearby satellites May require scanning motion Must be protected from Sun
Magnetometer	Economical, needs low power, always available for low altitude satellites	Cheap, poor resolution ($\approx 0.5^{\circ}$) Only useable at low altitude Spaceship must be magnetically clean
Star tracker	Available almost everywhere in sky with very high accuracy ($\sim 0.001^{\circ}$)	Sensors heavy, complex and expensive Identifying targets is slow and complex Sensors need protection from Sun Need sophisticated algorithms
Gyroscope	Requires no external sensors Very accurate for limited time intervals	Best short-term reference, costly Only senses changes in orientation Can be subject to drift Needs recalibration for time to time

Attitude determination: Sensor and typical performance

Sensor	Typical accuracy [deg]	Typical application
Sun	0.2 – 1.0	Direction must be known to align solar panel
Horizon (Earth)	0.02-0.1	Earth orbit, LEO to GEO
Magnetometer	0.5 - 1.0 mainly do to uncertainty of magnetic field	Earth orbits < 6000 km
Star tracker	0.0002-0.1	High precision pointing
GPS	-	Used for large space structures

C.D. Brown

For very rapid and accurate sensing,
star trackers and gyroscopes are often used together

Remind:
Two nonparallel directions needed to uniquely measure orientation

Typical spacecraft sensor configuration

Most precise measurements (e.g. scientific satellites)

- Star trackers

Moderate accuracy requirements

- Coarse digital Sun sensors
- Earth sensors
- Magnetometers

Low-altitude satellites

- Sun sensors
- Earth sensors
- Magnetometers

High-altitude (e.g. geosynchronous) satellites

- Optical sensors
- Gyroscopes
- Remember that Earth´s magnetic field too weak for use

Attitude Control

Attitude control requirements

- Any design will start with list of requirements (driven by mission)
- Principle requirement is to point satellite payload (instrument, antenna, solar array, etc.)
- Attitude stability is required for almost all satellites applications
- Additional attitude control requirements can include:
  - Point with given accuracy
  - Hold deviations below given level
  - Know in which direction and location point
  - Move satellite instruments to target within given time
  - Avoid pointing sensitive instrument to Sun
- Required accuracy depends on payload and mission goals
- Achievable accuracy depends on hardware

Three-axis and spin stabilized spacecraft

Method to categorize spacecraft is through stability:

Spin stabilized spacecraft

- Angular momentum of spin stabilized spacecraft will remain approximately fixed in inertial space for extended periods
- Environmental torques relative small in relation to angular momentum

Three-axis stabilized spacecraft

- Keep all three axes pointed in specific directions → orientation of three mutually perpendicular spacecraft axes must be controlled
- Active attitude control required because environmental torques will cause spacecraft orientation to drift
- Note: Full three-axis knowledge requires at least two directions (e.g. Sun vector and Earth vector or two different stars)

Choice of attitude control method

Choice of attitude control method has strong influence on configuration of spacecraft

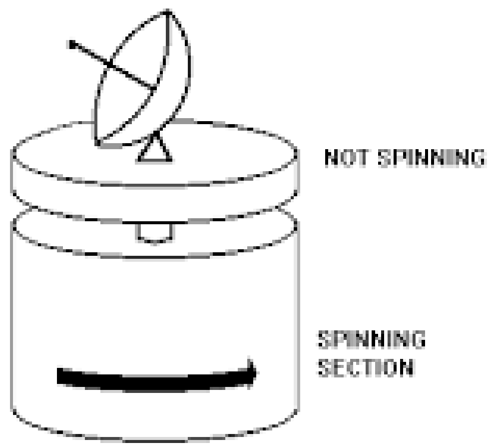
- Spin stabilized
- Dual-spin stabilized
- Gravity-gradient stabilized
- Three-axis stabilized

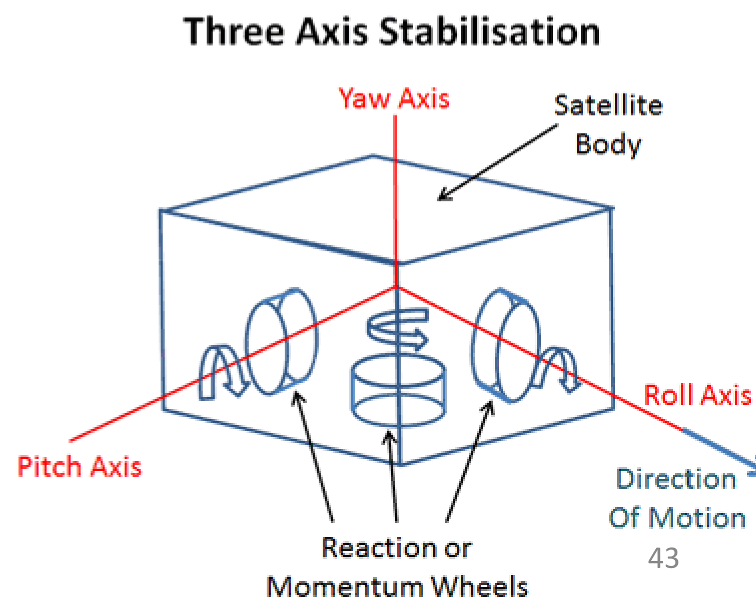
Choice of attitude control system is a decision which must be taken early in mission planning

Typical configurations

Spin stabilized:
Attitude remain fixed in space
Spinning axis resists perturbing forces
Behaves like spinning gyroscope

Gravity-gradient stabilized:
Possible point in one direction
with few degrees accuracy > 5^o





Dual-spin stabilized:
Lower section spins to provide
gyroscopic stability and upper
section does not spin

Configuration of control system

Requirements will suggest some sort of spacecraft configuration (overall arrangement) for determination and control system

Specified spacecraft configuration and system requirement

- Requirements must be assigned to all subsystems and components
- Each component has to be implement in robust way
- All subsystems combined should meet overall system requirement

Properly assigned requirements essential for successful mission

- Problems and resources must be shared equitably among various subsystems
- Take care about that every subsystem affects every other subsystem

Define for mission specific attitude objectives and control tasks

Attitude objectives and tasks

Attitude objectives:

- **Detumbling**: Tumbling motion must be stabilized or mission will fail
- **Repointing**: Reorient spacecraft to target specific point

Attitude control tasks:

1. Measuring attitude by attitude sensors
2. Correcting attitude through actuators by applying torques
3. Control (algorithm that determines magnitude and direction of torque in response to disturbance)

Typical attitude control task

Tumbling spacecraft after separation
high angular rate with arbitrary orientation

Slow down angular speed
low angular rate with arbitrary orientation

Reach coarse attitude for power and thermal orientation
search e.g. Sun for low attitude accuracy

Achieve attitude for instrument operations
orientation with high accuracy

Slew to support orbit operation
oriented to support orbit maneuvers with sporadically disturbance

How to stabilize spacecraft with respect to disturbance torques?

Take into account:

If satellite is not attitude stabilized, small disturbances will cause satellite to tumble

Two attitude control methods:

Passive attitude control
(Lecture ADCS - IX)

$$\frac{\mathrm{d}\vec{h}}{\mathrm{d}t} = \frac{\mathrm{d}(\mathbf{I}\vec{\omega})}{\mathrm{d}t} = \vec{T}_{disturbance}$$

Exploit existing disturbance torques

Active attitude control
(Lecture ADCS - X)

$$\frac{\mathrm{d}\vec{h}}{\mathrm{d}t} = \frac{\mathrm{d}(\mathbf{I}\vec{\omega})}{\mathrm{d}t} = \vec{T}_{control}$$

Apply with actuators control torque

Attitude control methods: Passive versus active control

Passive stabilization control:

- Passive control relays on interaction of spacecraft and terrestrial fields (Earth´s gravity-gradient, Earth magnetic field, solar radiation)
- Passive control directly yields system with desired stable attitude behavior
- In general attitude sensor not required
- Mostly used for low cost university spacecraft missions

Active stabilization control:

- Use control system to maintain desired attitude
- Requires hardware (sensor / actuators), which consumes power and fuel
- Possibly passive stabilization is not in desired direction or has not enough accuracy

Main motivation for active control:

- Mission requirements (high accuracy), passive approach not sufficient
- Even on passive systems, perhaps need active corrections periodically because of unexpected perturbations

Actuator systems

Two classes of actuator systems:

Passive actuator system:

Use mechanisms exploiting orbit environment to correct pointing direction of satellite (e.g. solar radiation pressure, gravity-gradient, magnetic field)

- Gravity-gradient stabilization
- Spin stabilization (Single-spin, Dual-spin)
- Magnetic stabilization

Active actuator system:

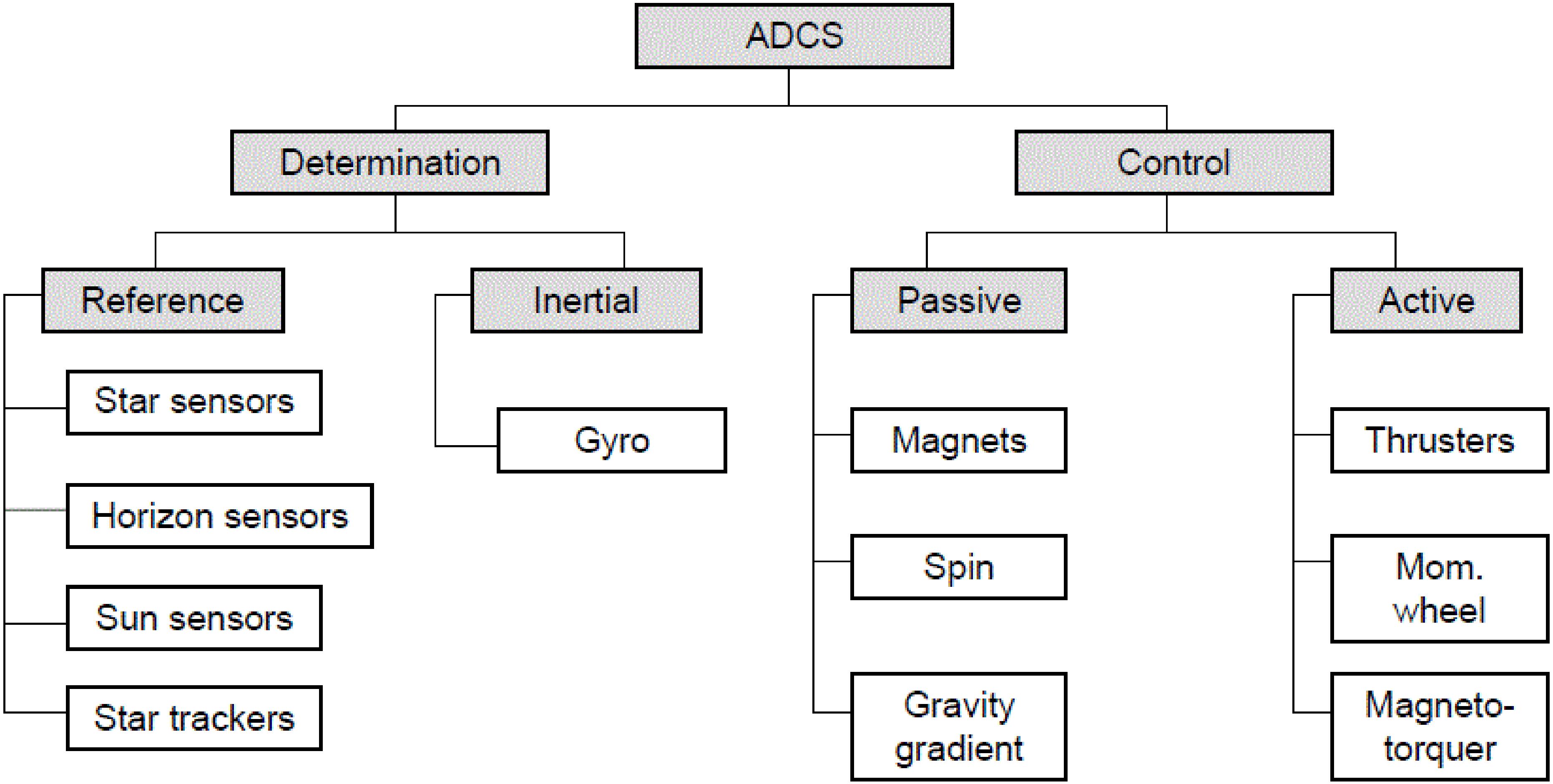
Active control of satellite using propulsion system to repoint spacecraft

Mostly used for three-axis stabilization

- Thruster
- Magnetic torque
- Momentum wheels, reaction wheels
- Control momentum gyroscope

Attitude Hardware: Actuators for Active Attitude Control

Actuators for active attitude control



Active control with actuators

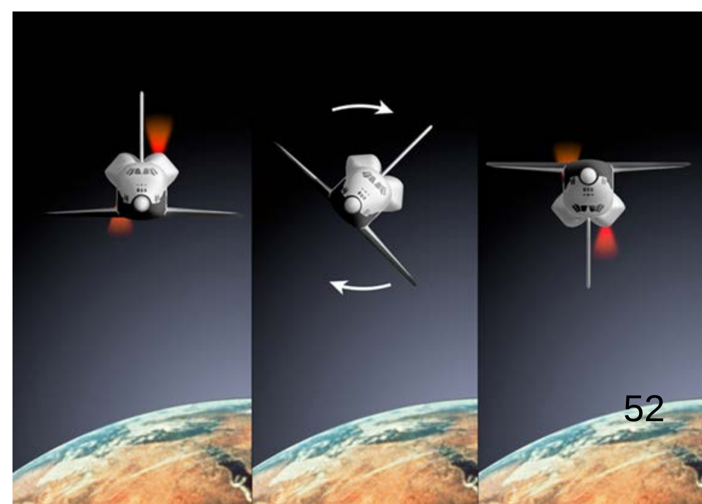
Active control typically used for three-axis stabilization

Active control more complex and expensive than passive control, but delivers high precision pointing

Require actuators for each rotational axis of spacecraft

Best method for missions with frequent payload slews (space telescopes)

Main example are thrusters:
Fire thrusters (small rockets)
in pairs to start rotation,
then fire opposite pair to stop rotation



Thruster concept

Expel mass (d/dt m = mass flow rate) with given exhaust velocity v_e

→ Thruster exerts force onto spacecraft

$$F = \dot{m} v_e$$

If thruster has momentum arm with respect to spacecraft mass center

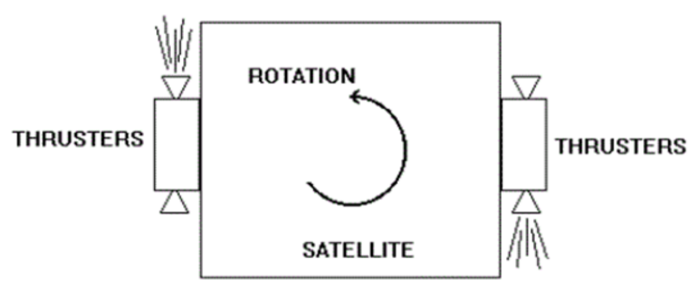
→ Torque produced about center of mass

$$\vec{T} = \vec{r} \times \vec{F}$$

Single thruster changes also spacecraft linear momentum

→ Use thruster in pair so that two forces add to zero

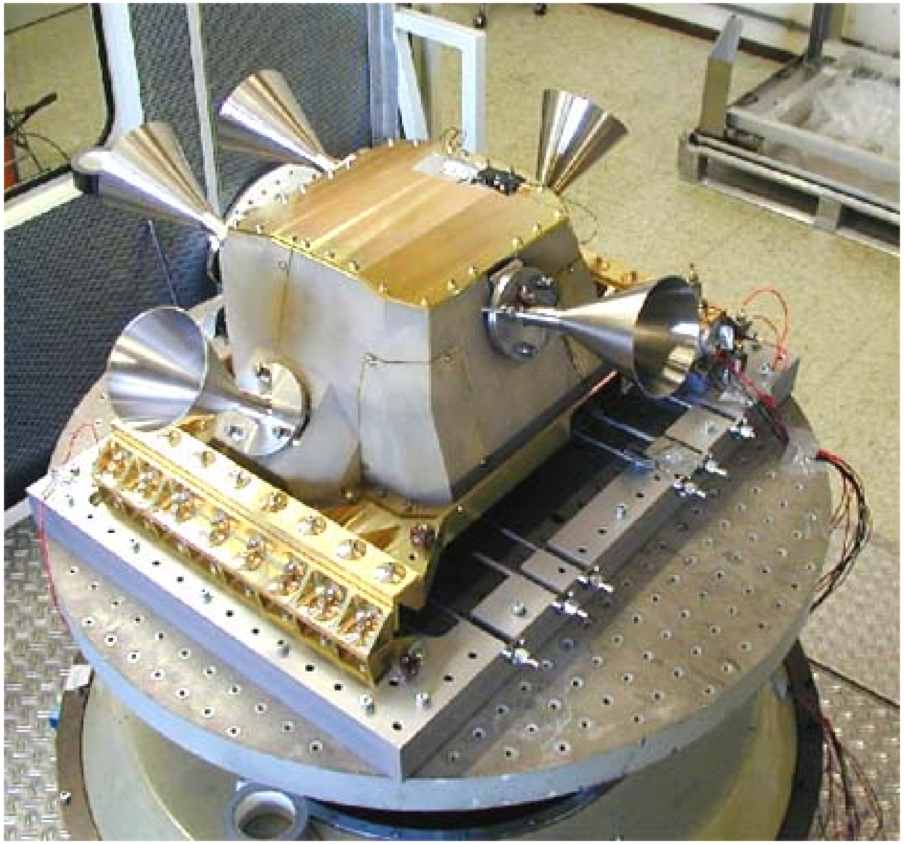
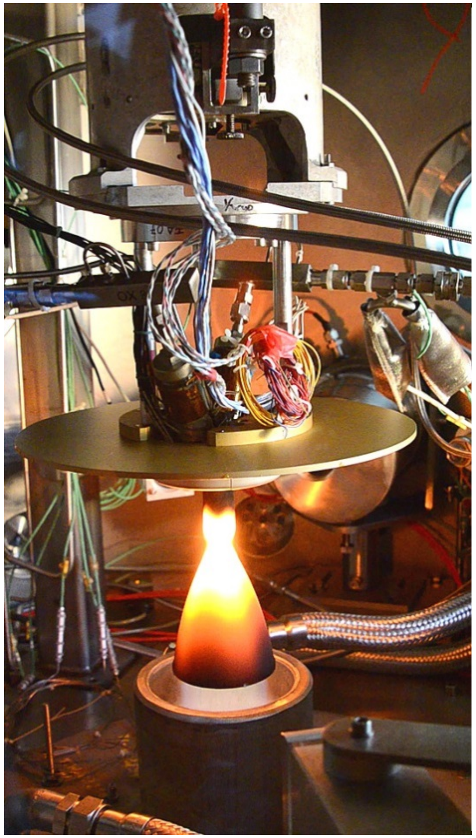
$$F_1 + F_2 = 0 \qquad\qquad T_1 + T_2 = 2rF$$



Attitude control with thrusters

- Common and effective solution to provide spacecraft attitude control
- However thruster use fuel
- Common on satellites intended to operate in relative high orbit, where magnetic field or gravity-gradient are not available
- Potentially largest source of torque with high control
- Usually need redundant set of thrusters
- Direct control of angular rate
- Reaction control thrusters are typically on-off devices using
  - Cold gas
  - Hypergolic / Catalytic propellant
  - Ion / plasma rockets
- Thrusters commanded in pairs to cancel velocity change
- Life limiting factors: Useful lifetime limited by amount of fuel or failure (Failure caused by valve failure, leaks, etc.)
- Most common use: Unload wheels, stop tumbling (e.g. after deployment)

4 N to 200 N bipropellant thrusters


Different type and size of thruster for different mission goals
Thrusters are not extremely accurate and so they are rarely used to control finer motions of attitude
Many maneuvers (like slewing) are usually left to other mechanisms

Momentum wheel and Reaction wheel

Momentum wheel:

- Operates at high revolution per minute to provide spin stability
- Usually rotates about given axis aligned with spacecraft axis

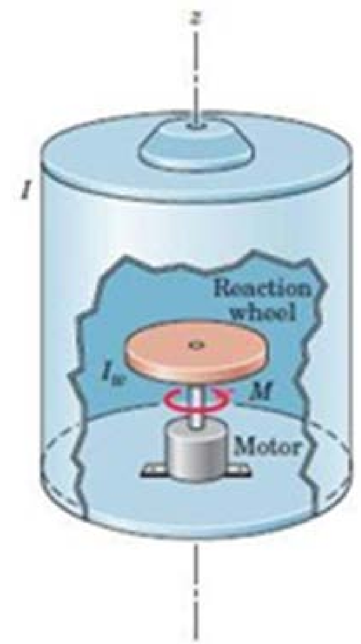
Cheese movie: https://www.youtube.com/watch?v=cRJv6z_bxQg

Reaction wheel:

- Operates at changing revolution per minute to control and adjust total angular momentum between spacecraft and reaction wheel
- Give very fast response relative to other systems
- Three orthogonal wheels vary all components of angular momentum in space
- Mostly used fourth wheel to have redundancy

Reaction wheel concept

Spinning wheel mounted on metal disc whose rate of rotation can be adjusted by reversible electric motor



Transfer momentum to or from spacecraft by changing wheel speed but has no influence on total angular momentum

Torques produce internally in spacecraft → total angular momentum conserved and influence spacecraft orientation

Consider rotation about given axis with:
I_w = wheel momentum of inertia about spin axis
ω_w = wheel angular velocity relative to satellite
I = moment of inertia of satellite without wheel
ω = satellite angular velocity relative to inertial frame

Conservation of angular momentum:

$$I_w(\omega_w+\omega)+I\omega=0$$

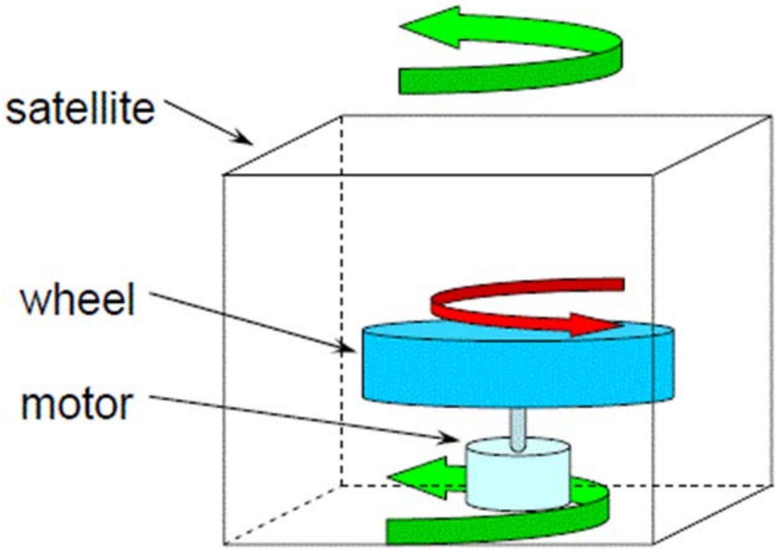
Reaction wheel function

Correct for disturbing torques:

External torques give rise to unwanted angular momentum

Control system applies control torques to reaction wheels to leave spacecraft angular momentum unchanged

E.g. when clockwise disturbance torque imposed on spacecraft → attitude control system holds attitude constant by rotating reaction wheel counterclockwise



Reaction wheel function

Slewing maneuvers:

Rotate spacecraft by very small amounts to keep telescope pointed at star (because of Earth rotation) by slowing down or accelerating wheel

Typical example:

Space telescope should be turned to observe new celestial object

Momentum borrowed from wheels and later returned to wheel

No net change of momentum of wheel integrated over time

Reaction wheel: Momentum dumping

When disturbing torques do not average out over one orbit

- Wheel speed will increase to hold spacecraft attitude
- Risk to saturate wheel (wheel spinning as fast as it can and cannot counterbalance further disturbing torques)
- Stored momentum needs to be cancelled

  → Process is called momentum dumping

Momentum dumping devices (reduce wheel speed):

- Thrusters (in high orbit)
- Magnetic torques (useful for near Earth)

Remarks on reaction and momentum wheels

- Common choice for active attitude control
- Provide quick and accurate control
- Mostly used for internal torques control only (for external torque control requires momentum dumping, when wheels reach maximum speed)
- Momentum wheel operates at high revolution per minute and provides spin stability
- Avoid operation of wheel near saturation (limited control)
- Wheels not operated near 0 revolution per minute, because of nonlinear wheel response
- Three reaction wheels necessary for three axis control (but four and more wheels usually used for redundancy)
- Control logic simple for three independent axes but can get complicated with redundancy

Control momentum gyroscopes

Control moment gyroscopes (CMG) operate similar to reaction wheels, but:

- fixed speed (magnitude of the angular momentum vector fixed)
- mounted on gimbals (direction of angular momentum vector can change)

Single gimbal control achieved by rotation of gyroscope though some angle

https://www.youtube.com/watch?v=JTWA6tUREi8

Torque applied at gimbal produces change in angular momentum perpendicular to existing angular momentum vector

Torque on input axis (change direction of angular momentum) produces torque on output axis

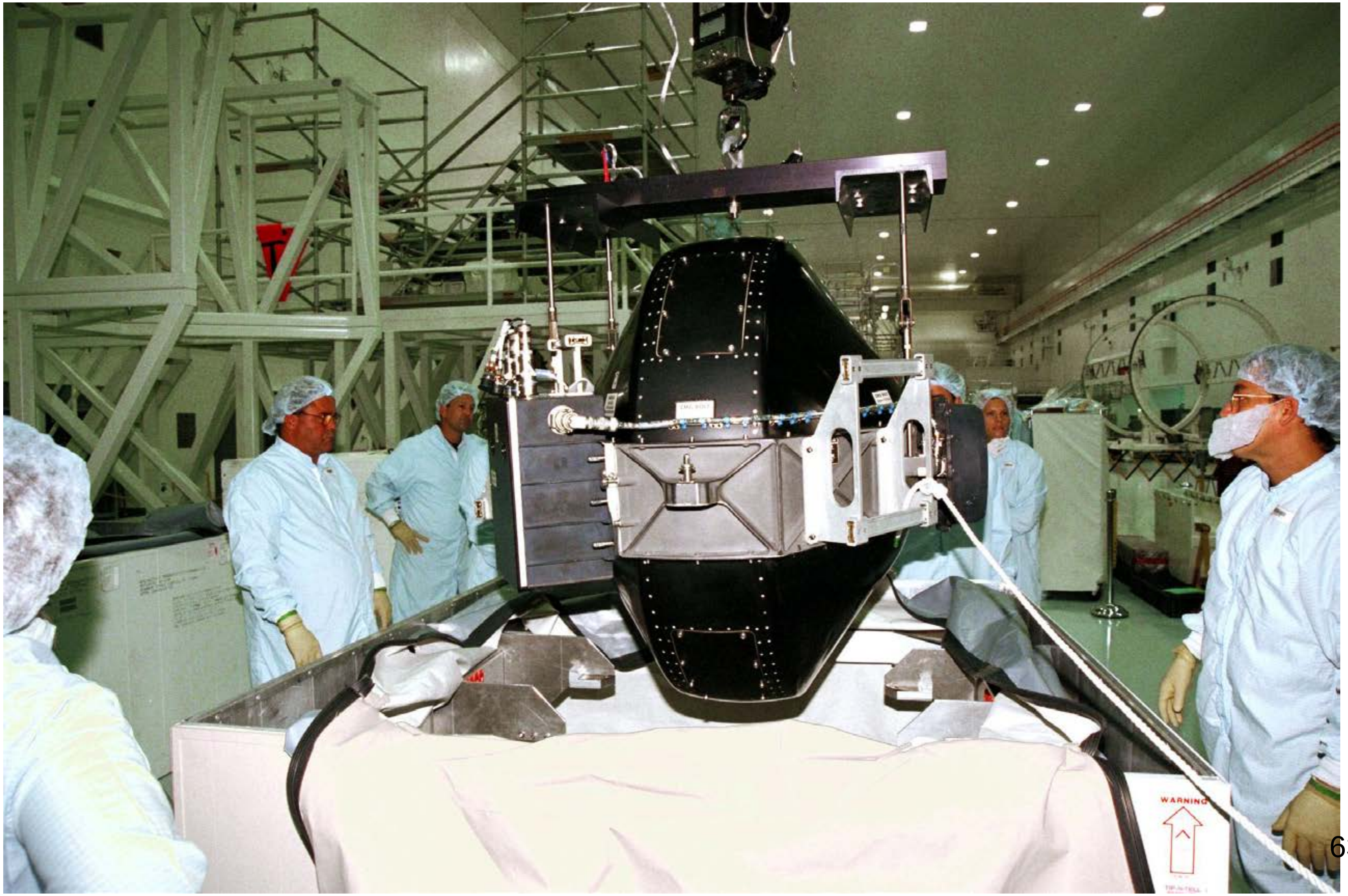
→ modifying satellite direction

Use spinning wheel which can be quickly rotated to change its spin axis

CMG used for fast attitude slews and for applications with high torque demands

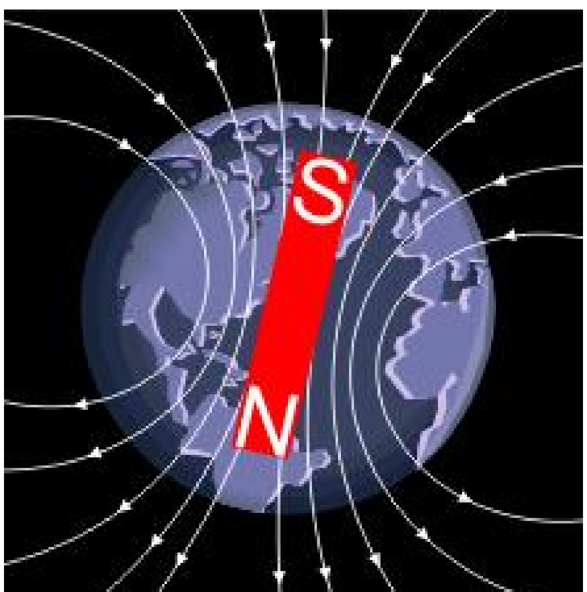
CMG provide 50 times more control torque than reaction wheels for same mass and power

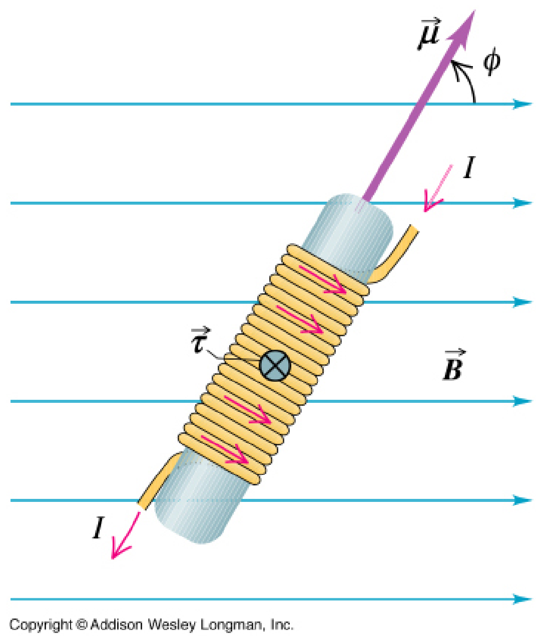
Control momentum gyroscope for International Space Station



Magnetic torque

- Attitude control with help of Earth´s magnetic field (***B***)
- Magnet in satellite interacts with Earth´s magnetic field
- Fixed magnets are too heavy, so produce magnetic dipole momentum (***μ***) from current carrying electromagnetic coils
- Torque $\vec{T} = \vec{\mu} \times \vec{B}$ tends to rotate satellite
- Satellite use magnetic torque for cheap attitude control
- Mostly used for dumping excess angular momentum from reaction wheels
- Not used for interplanetary missions, because magnetic field intensity drops with distance

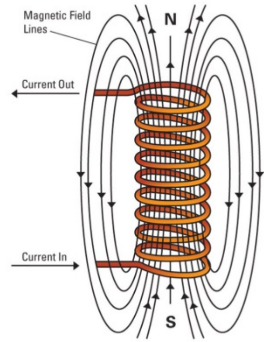




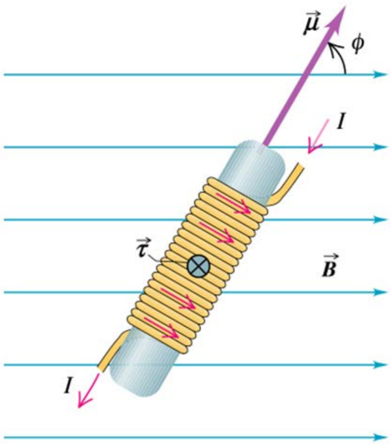
Note:
Magnitude of Earth´s magnetic field inversely proportion to distance

$$B \sim \frac{1}{r^3}$$

Magnetic torque with electromagnetic coils



- Earth and other planets with magnetic fields can produce magnetic torque on spacecraft
- At low altitudes Earth magnetic field interacts with current loops (wanted or unwanted) within spacecraft generating torques
- Torque of any magnetic field on current-carrying coil given by
  $\vec{T} = \vec{\mu} \times \vec{B} = NA\vec{I} \times \vec{B} = NAIB\sin\phi$ with $\vec{\mu} = NA\vec{I}$
  where N = number of loops, A = included area of loops, I = current
- Magnetic torquer (torque rod) use this interaction to generate torque for momentum management
- Control algorithm needs good knowledge of Earth magnetic field
- Earth magnetic filed tilted 11 degrees with respect to Earth rotation axes and can be modeled as dipole



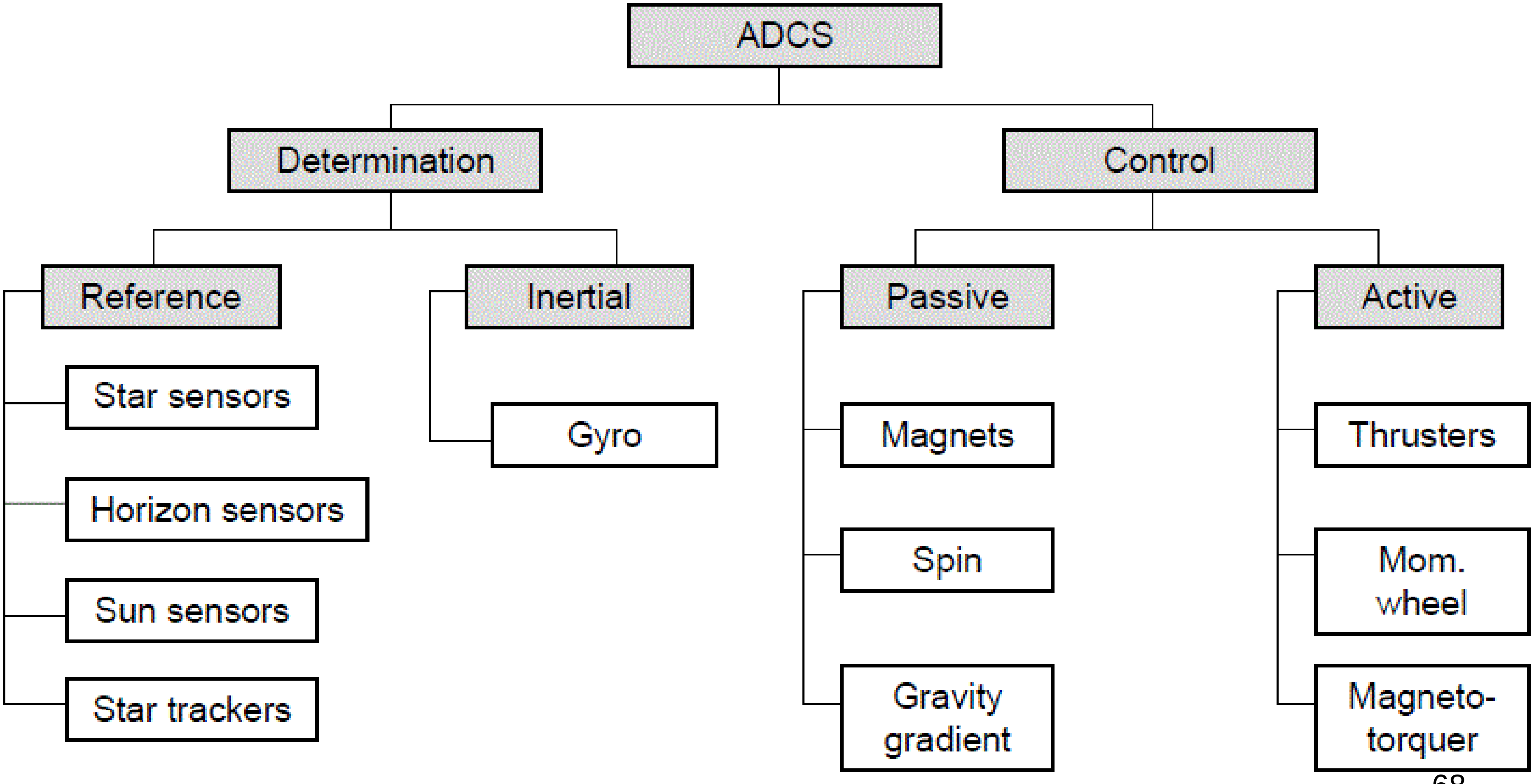
Earth magnetic field can be beneficial:
- Source of control torques for momentum management
- Direction of field used to coarse attitude determination

Actuators

Actuator	Accuracy [deg]	Comment
Thrusters	0.1	• Quick, high authority, costly, consumable • Used in any environment • Provides stabilization, station keeping and attitude control • Large impulses for major orbit maneuvers • Small impulse attitude control
Momentum wheels	0.01	• Quick, costly, high precision • Primarily for stabilization/attitude control • One, two or three axis stabilization
Reaction wheels	0.01	• Quick, costly, high precision • Need thrusters for "momentum dumping"
Control moment gyros	0.1	• High authority, quick, heavy, costly
Magnetic torque	1 - 2	• Near Earth only, slow, lightweight, low cost

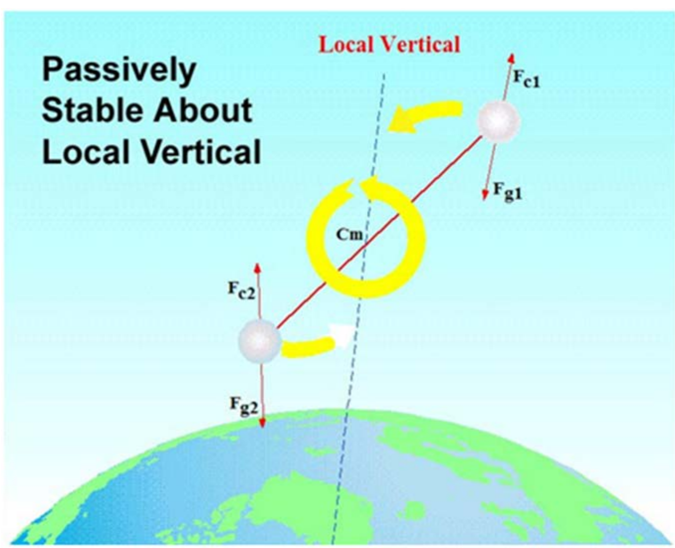
Passive Attitude Control

Passive attitude control



Gravity-gradient stabilized

- Force decreases with radius from center of Earth $F = G\frac{mM}{r^2}$
- Gravitational force stronger on portion of spacecraft near Earth than further away
- Forces are unequal and torque rotates satellite (satellite swings like pendulum)
- For near vertical attitude, unequal forces tend to align satellite with vertical
- Gravity-gradient stabilization takes advantage of tendency of spacecraft to align long axis with gravity vector
- For stabilization gravity-gradient torque greater than any other disturbance torque (usually met for orbits lower than 1000 km)



More in lecture ADCS - IXB

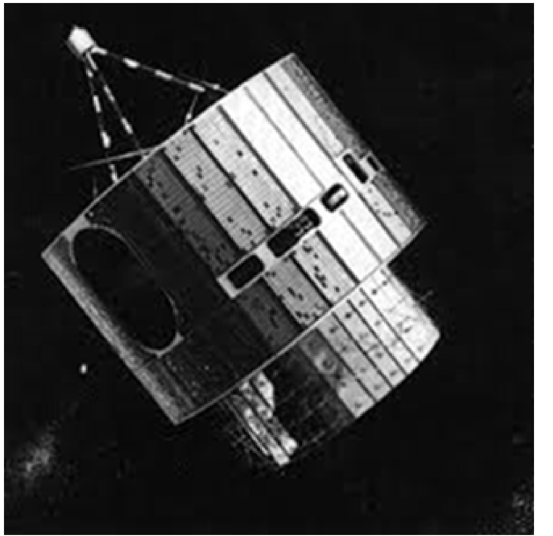
Spin stabilization

- Intrinsic gyroscopic stiffness of spinning body used to maintain its orientation in inertial space (conservation of angular momentum)
- Simple and low cost method for attitude stabilization
- Generally not suitable for imaging payloads
- Poor power efficiency since entire spacecraft body covered with solar cells

Vela

More in lecture IXA

Early GEO satellite

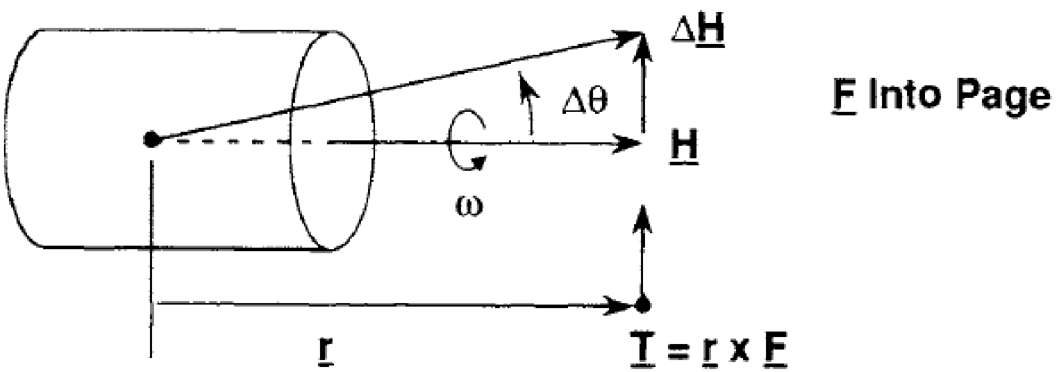


Spin stabilization

What does it mean: **Intrinsic gyroscopic stiffness** of spinning body used to maintain its orientation in inertial space

- If no external torques → angular momentum vector remains fixed in space (constant in magnitude and direction)
- If external torque **T** (components perpendicular and/or parallel to momentum vector **h**)

  - Parallel torque spins spacecraft spin momentum up or down
  - Perpendicular torque causes displacement of **h** in direction of **T**



$$\dot{\mathbf{h}} = \frac{\Delta \mathbf{h}}{\Delta t} = \mathbf{T}$$

If spin → linear growth

$$\Delta\theta = \frac{\Delta \mathbf{h}}{\mathbf{h}} = \frac{\Delta \mathbf{h}}{\mathbf{I}\boldsymbol{\omega}} = \frac{\mathbf{T}\Delta t}{\mathbf{I}\boldsymbol{\omega}}$$

Gyroscopic stability due to angular momentum in denominator
Higher angular momentum → Smaller perturbation angle ΔΘ

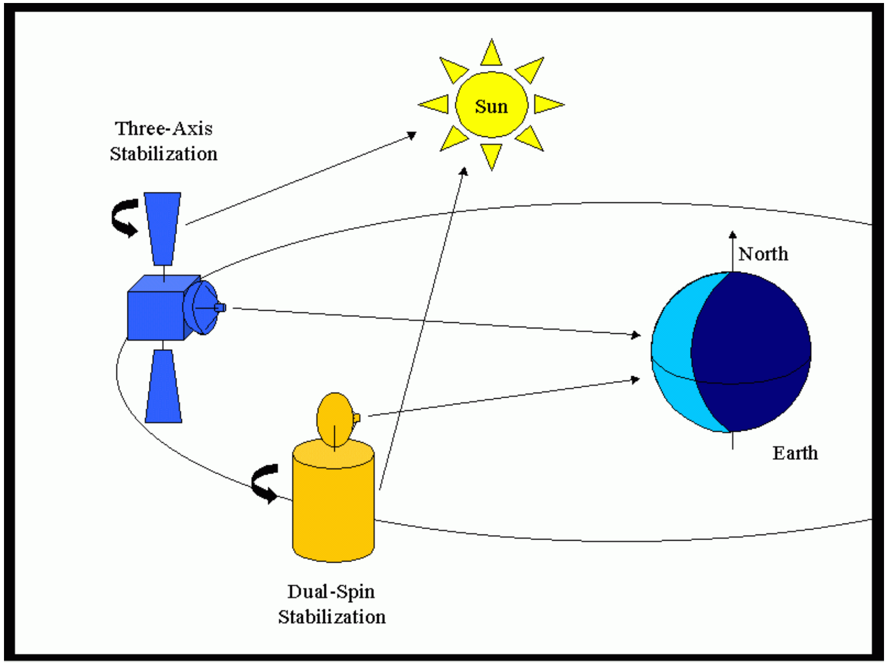
If **no spin** $\mathbf{T} = \mathbf{I}\ddot{\boldsymbol{\theta}} \Rightarrow \theta = \frac{1}{2}\frac{T}{I}t^2$ torque will produce **quadratic growth**

Dual-spin stabilization

Simplicity of spin-stabilized spacecraft, but not spinning platform on top

Mount payload on not spinning platform for better pointing

More in lecture IX



GEOTAIL

Attitude control technique

Method	Accuracy [deg]	Comment
Spin stabilization	~0.1	• **Passive**, simple, low cost, long-life • Provides only stabilization in one axis • Other devices (like thruster) still required • No fixed pointing • Low solar cell efficiency
Gravity-gradient stabililization	~1 – 5	• **Passive**, simple, low cost, long-life • Provides passive Earth pointing • Low accuracy
Dual-spin stabilization	~0.1	• **Passive**, can be complex and expensive • Provides both fixed pointing (on not spinning platform) and scanning motion • Requires not spinning mechanism
3-axis stabilization	~0.001	• **Active**, expensive, complex • Actuators for each body axis • High pointing accuracy • Rapid attitude slews possible

Attitude control: Passive versus active Performance and constraints

Passive:	**Active:**
Few degrees	0.001-1 degrees
Pointing in one direction	Pointing in several directions
Simple and no power	Complex and power required
Cheap	Expensive

Simple means: control through use of environment and natural physical properties of satellite
Complex means: control through use of complex sophisticated instrumentation (actuators)

Introduction to attitude concepts

Angular momentum and external torques

Goal is to relate external torques to angular velocity to understand influence on attitude dynamics

Fundamental quantity in rotational dynamics:

1. Angular momentum ***h*** about defined origin

$$\boxed{\vec{h} = \vec{r} \times m\vec{v}}$$

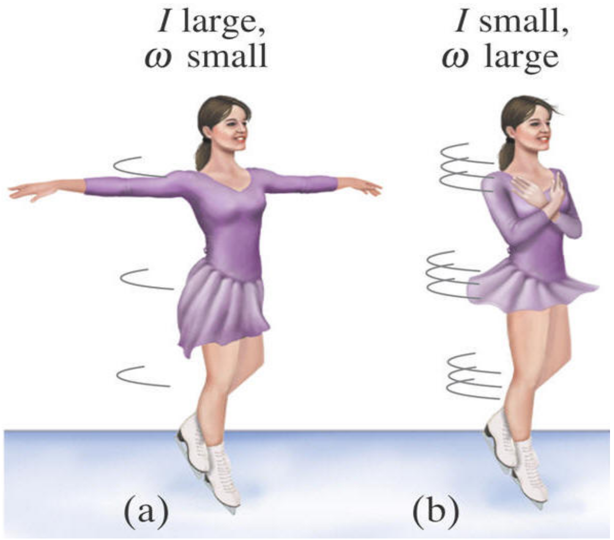
2. Angular momentum referred to an inertial fixed point is only changed if forces on it have an angular momentum ***T*** about this fixed point

$$\boxed{\frac{\mathrm{d}\vec{h}}{\mathrm{d}t} = \vec{T}}$$

Principle of conservation of angular momentum

Angular momentum is constant in absence of external torques

$$\boxed{\frac{\mathrm{d}\vec{h}}{\mathrm{d}t} = 0} \qquad \vec{h} = const.$$



Angular momentum is proportional to moment of inertia ***I*** and angular speed ***ω***

$$\vec{h} = \mathbf{I}\vec{\omega}$$

Angular momentum is equivalent to linear momentum for rotational dynamics ($m \rightarrow \mathbf{I}$, $\boldsymbol{v} \rightarrow \boldsymbol{\omega}$)

Moment of inertia

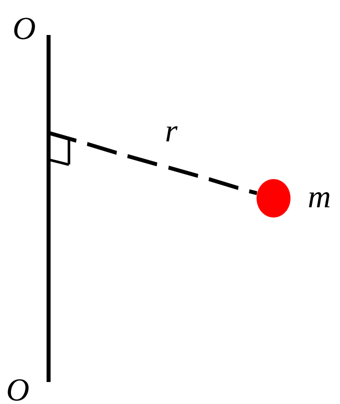
Moment of inertia

Measurement of distribution of mass of an object relative to given axis, where **r** is perpendicular distance between mass and axis

Moment of inertia has information how difficult it is to rotate object around given axis

For a particle

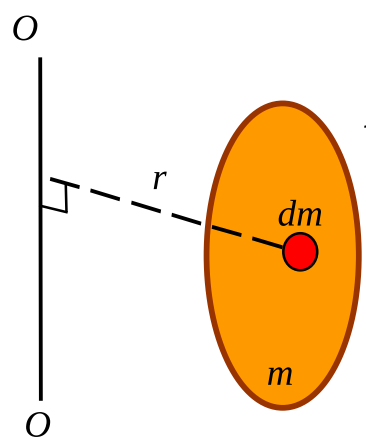
Moment of inertia depends on mass and distance **r** to axis of rotation



$$I_O = r^2 m$$

For a rigid body

For rigid body free to rotate in 3 dimensions: Moment of inertia given by symmetric 3 × 3 matrix



$$I = \sum r^2 dm = \int_m r^2 dm$$

Moment of inertia matrix

$$\vec{h} = \mathbf{I}\vec{\omega}$$

h = angular momentum

I = moment of inertia matrix

ω = angular velocity

$$\vec{h} = \begin{bmatrix} h_x \\ h_y \\ h_z \end{bmatrix} = \begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{xy} & I_{yy} & I_{yz} \\ I_{xz} & I_{yz} & I_{zz} \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}$$

Symmetric matrix

Cross-term products of inertia matrix are equal (i.e. $I_{xy}=I_{yx}$)

Principal moments of inertia matrix

Real symmetric matrix can be transformed (rotation matrix) into diagonal matrix with an appropriate choice of coordinate axes

Diagonal components are called **principal moments of inertia**

$$\mathbf{I} = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix}$$

Torques around principle axes act independently of each other

$$\frac{\mathrm{d}\vec{h}}{\mathrm{d}t} = \frac{\mathrm{d}(\mathbf{I}\vec{\omega})}{\mathrm{d}t} = \vec{T}$$

More on inertia matrix in lecture ADCS - VIII

Attitude kinematics

Kinematics relates velocity and position

For trajectory of center of mass (point), kinematics is given by simply

$$\frac{\mathrm{d}\vec{x}}{\mathrm{d}t} = \vec{v}$$

Similarly attitude kinematics are relations (differential equations) between angular velocity (**ω**) and attitude (**ϴ**) represented by rotation matrix, like directional cosine matrix, Euler angle, etc.

$$\frac{\mathrm{d}\vec{\theta}}{\mathrm{d}t} = \mathbf{C}\,\vec{\omega}$$

where **C** is a 3 x 3 matrix

More on attitude kinematics in Lecture ADCS - VI

Attitude dynamics (Euler equation)

Dynamics connects momentum (velocity) change with forces

Movement of center of mass is given by second law of Newton $\frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = \vec{F}$

Attitude dynamics connects angular momentum (velocity) with torques $\frac{\mathrm{d}\vec{h}}{\mathrm{d}t} = \vec{T}$

Angular momentum **h** of satellite about center of mass with fixed frame $\vec{h} = \mathbf{I}\vec{\omega}$

Angular momentum equation $\frac{\mathrm{d}\vec{h}}{\mathrm{d}t} = \vec{T}$ written in rotating reference frame

$\Rightarrow$ Euler equations $$\mathbf{I}\frac{\mathrm{d}\vec{\omega}}{\mathrm{d}t} + \vec{\omega} \times \mathbf{I} \cdot \vec{\omega} = \vec{T}$$

$\Rightarrow$ Describe attitude dynamics of a satellite

Attitude dynamics is mathematically identical to trajectory dynamics

$\Rightarrow$ Angular momentum **h** changed by torque **T** is
equivalent to say linear momentum **p** changed by force **F**

More on attitude dynamics in Lecture ADCS - IX

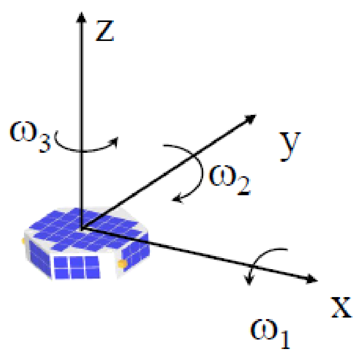
Attitude dynamics (Euler equation)

For all rigid body with inertia matrix
exist always inertia matrix with principal axes

$$\mathbf{I} = \begin{bmatrix} I_1 & 0 & 0 \\ 0 & I_2 & 0 \\ 0 & 0 & I_3 \end{bmatrix}$$

Write equation $\mathbf{I}\frac{\mathrm{d}\vec{\omega}}{\mathrm{d}t} + \vec{\omega} \times \mathbf{I} \cdot \vec{\omega} = \vec{T}$ in principal axis

$$I_1\dot{\omega}_1 + (I_3 - I_2)\omega_2\omega_3 = T_1$$
$$I_2\dot{\omega}_2 + (I_1 - I_3)\omega_1\omega_3 = T_2$$
$$I_3\dot{\omega}_3 + (I_2 - I_1)\omega_2\omega_1 = T_3$$



Euler equations are **three coupled non linear first order equations**, which connect angular velocity with torque

Disturbance torques

Disturbance torques

- Disturbance torque lead to reduction in pointing accuracy of spacecraft
- Torque magnitude dependent on spacecraft orbit type and orbit altitude
- Main reason for attitude control is existence of disturbance torque

External Environmental Torques

Aerodynamic

Gravity-gradient

Solar pressure

Magnetic

Etc.

Affects total angular momentum

Internal Torques

Crew motion

Hardware motion

Sloshing, Fuel motion

Solar panel deployment

Etc.

Total angular momentum conserved but influence spacecraft orientation

Aerodynamic torque

Aerodynamic force produces disturbance torque on spacecraft due to any offset that exists between aerodynamic center of pressure (cp) and center of mass

Torque given by distance of center-of-gravity and center-of-pressure

$$\vec{T}_a = \vec{r}_{cp} \times \vec{F}_a$$

Note:
r_{cp} varies with spacecraft attitude

Aerodynamic force:

$$\vec{F}_a = \frac{1}{2} \rho V^2 A_\perp C_D \frac{\vec{V}}{V}$$

T_a = aerodynamic torque
F_a = aerodynamic force (always aligned with velocity vector and opposite in sign)
V = spacecraft velocity
$A_\perp$ = surface area normal to velocity vector
ϱ = atmospheric density
C_D = drag coefficient (usually between 1 and 2.5 for spacecraft)

Example for aerodynamic torque

Consider satellite with:

$$A_{\perp} = 5\ \mathrm{m}^2$$

$$C_D = 2$$

$$h = 400\ \mathrm{km} \Rightarrow \rho = 4 \cdot 10^{-12}\ \tfrac{\mathrm{kg}}{\mathrm{m}^3}$$

$$r_{cp} = 0.01\ \mathrm{m}$$

Standard model atmospheric density

Assume circular velocity for this altitude

$$T_a = 1.2 \cdot 10^{-3}\ \mathrm{N}$$

$$\text{For} \quad I = 1000\ \mathrm{kg} \cdot \mathrm{m}^2$$

$$T = \tfrac{\mathrm{dh}}{\mathrm{d}t} = I\,\tfrac{\mathrm{d}\omega}{\mathrm{d}t} = I\,\tfrac{\mathrm{d}^2\theta}{\mathrm{d}t^2}$$

$$\theta(0) = 0$$

$$\omega(0) = \tfrac{\mathrm{d}\theta}{\mathrm{d}t} = 0$$

Quadratic error growth if uncorrected

$$\theta(t) = \tfrac{T}{I} t^2 = 1.2 \cdot 10^{-8} t^2\ \tfrac{1}{\mathrm{s}^2}$$

Seems small but
Drift of about 1 rad
after 10000 s (2 orbits)
→ Unacceptable

Gravity-gradient torque

Gravitational fields decrease with distance from center of planet
Spacecraft in orbit experiences stronger attraction on its “lower” side than on its “upper” side

$$\vec{T}_g = \frac{3\mu}{r^5} \vec{r} \times \mathbf{I} \cdot \vec{r}$$

$\mathbf{T}_g$ = gravity-gradient torque
μ = gravitational constant (398600 km^3/s^2) for Earth
$\mathbf{r}$ = vector from planet center to spacecraft
$\mathbf{I}$ = spacecraft inertia matrix

Solar radiation pressure torque

- Sun light has momentum and is reflected and absorbed by surface
- Change in momentum generates pressure on spacecraft,
  which depends on geometry and optical surface properties
- If average solar pressure vector has distance from center of mass
  → Solar radiation pressure produces disturbance torque on spacecraft

$$\vec{T}_s = \vec{r}_{cp} \times \vec{F}_s$$

Valid for near Earth

$$\vec{F}_s = (1+q)\, p_s A_\perp$$

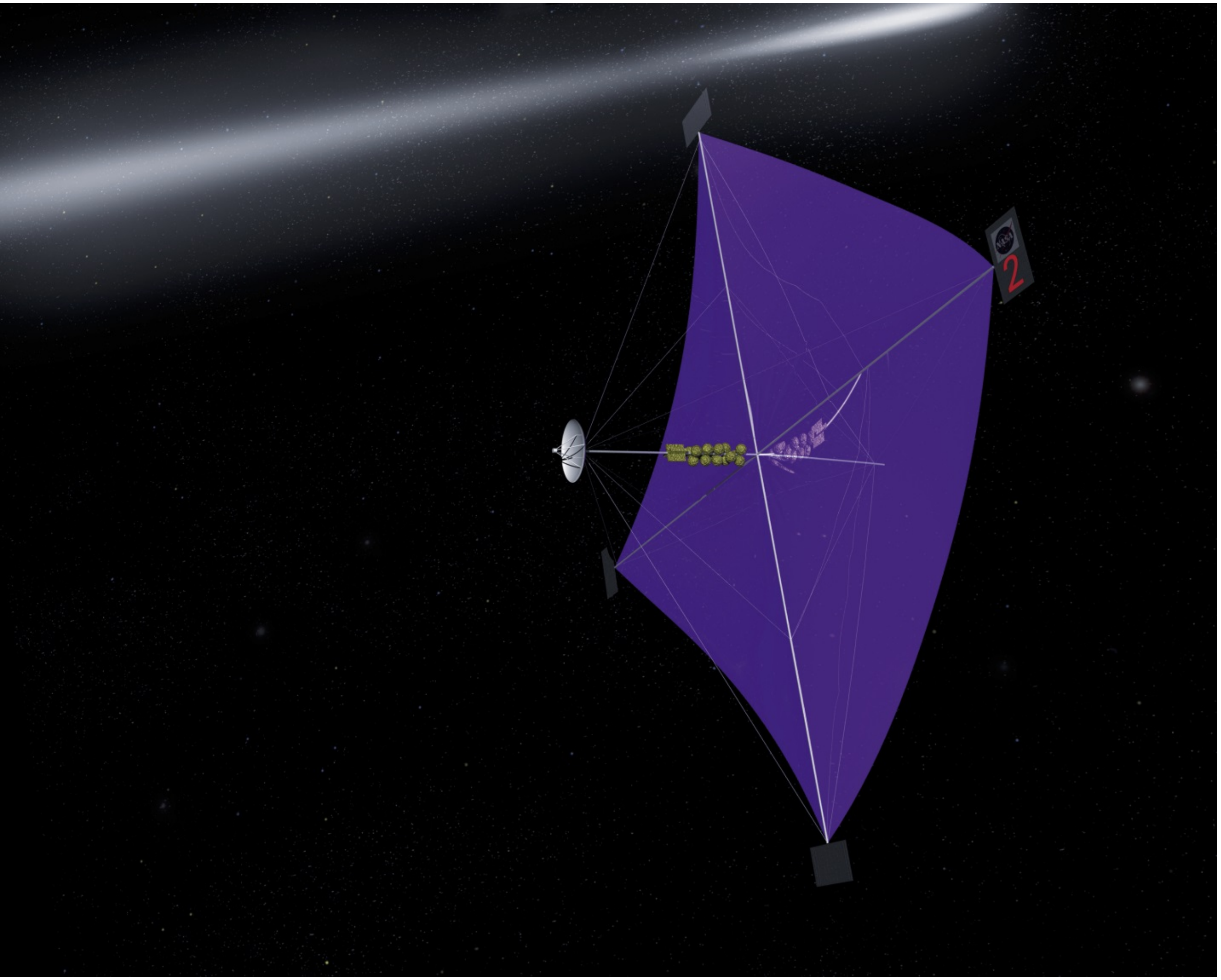
T$_s$ = solar radiation pressure
r$_{cp}$= vector from body center of mass to center of solar pressure
F$_s$ = solar pressure force
$A_\perp$= area of surface projected to sun line normal
q = surface reflectivity (between 0 and 1)

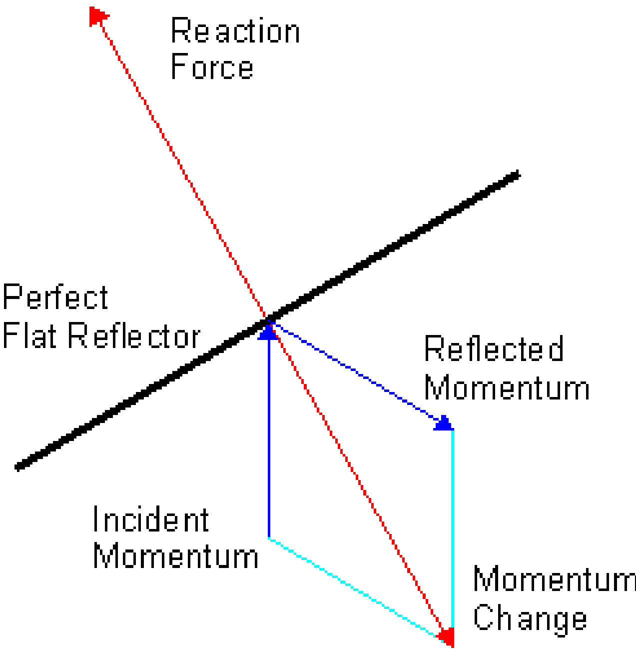
$$p_s = \frac{\Phi}{c} = \frac{1361\,\frac{\mathrm{W}}{\mathrm{m}^2}}{c}$$ solar pressure (solar flux density divided by speed of light)

Note:
Solar radiation torque is in first approximation independent of spacecraft position or velocity
Solar radiation torque much larger than solar wind torque

Solar sails

Solar sails are form of spacecraft propulsion using solar radiation pressure





Magnetic torque

Magnetic torque caused by
interaction between Earth´s magnetic field and any magnetization of spacecraft
(electronic components create equivalent current loop, which results in magnetic dipole)

Earth´s magnetic field produces torque on spacecraft dipole moment

$$\vec{T}_m = \vec{\mu} \times \vec{B}$$

Spacecraft magnetic dipole moment
(current loops and residual magnetic moment)

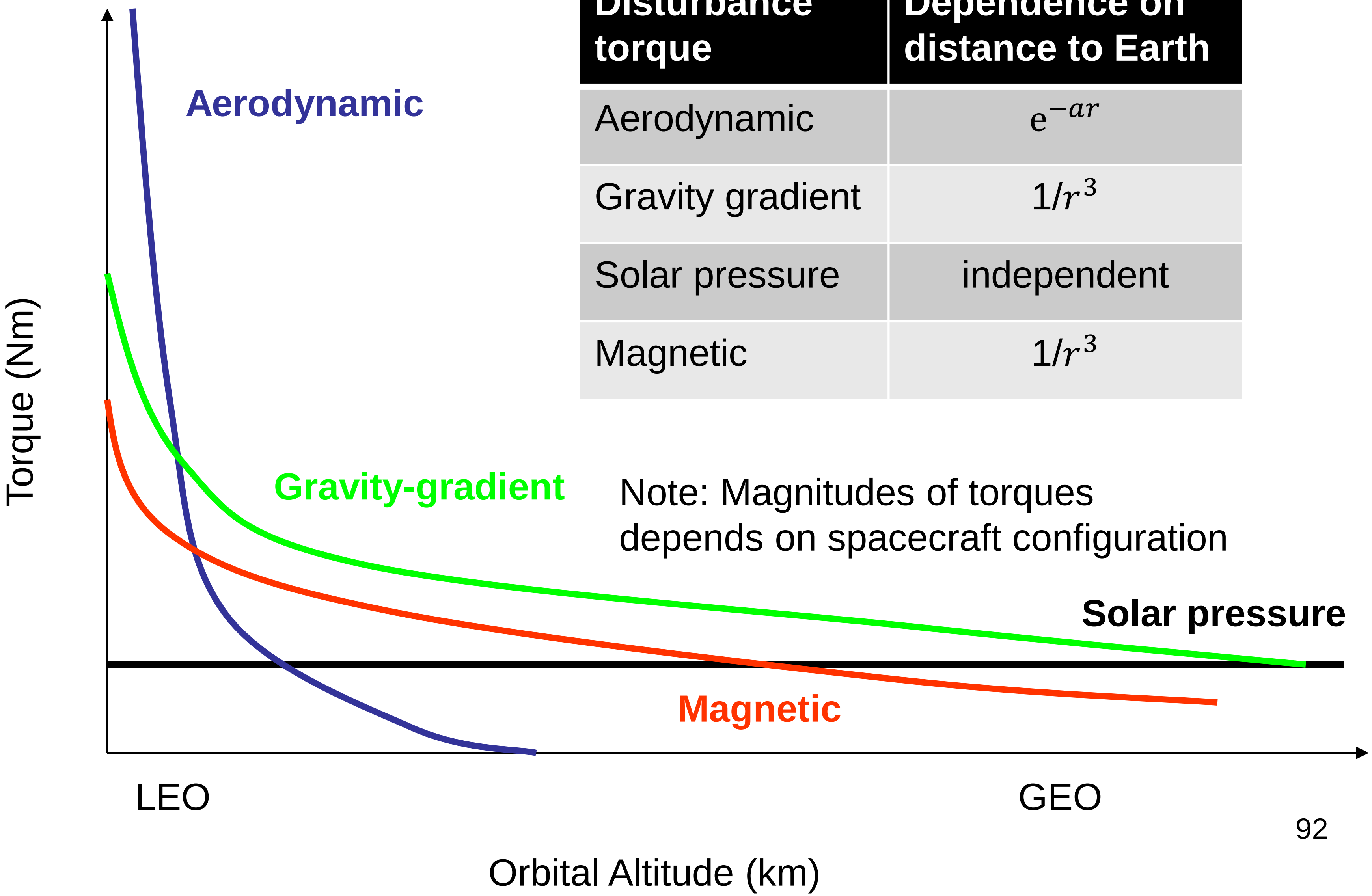
Earth´s magnetic field vector

$\mathbf{T}_m$ = magnetic torque
$\boldsymbol{\mu}$ = spacecraft magnetic dipole
$\mathbf{B}$ = strength of Earth´s magnetic field
(proportional to $1/r^3$, with r = orbit radius)
field strength varies by factor 2 depending on latitude

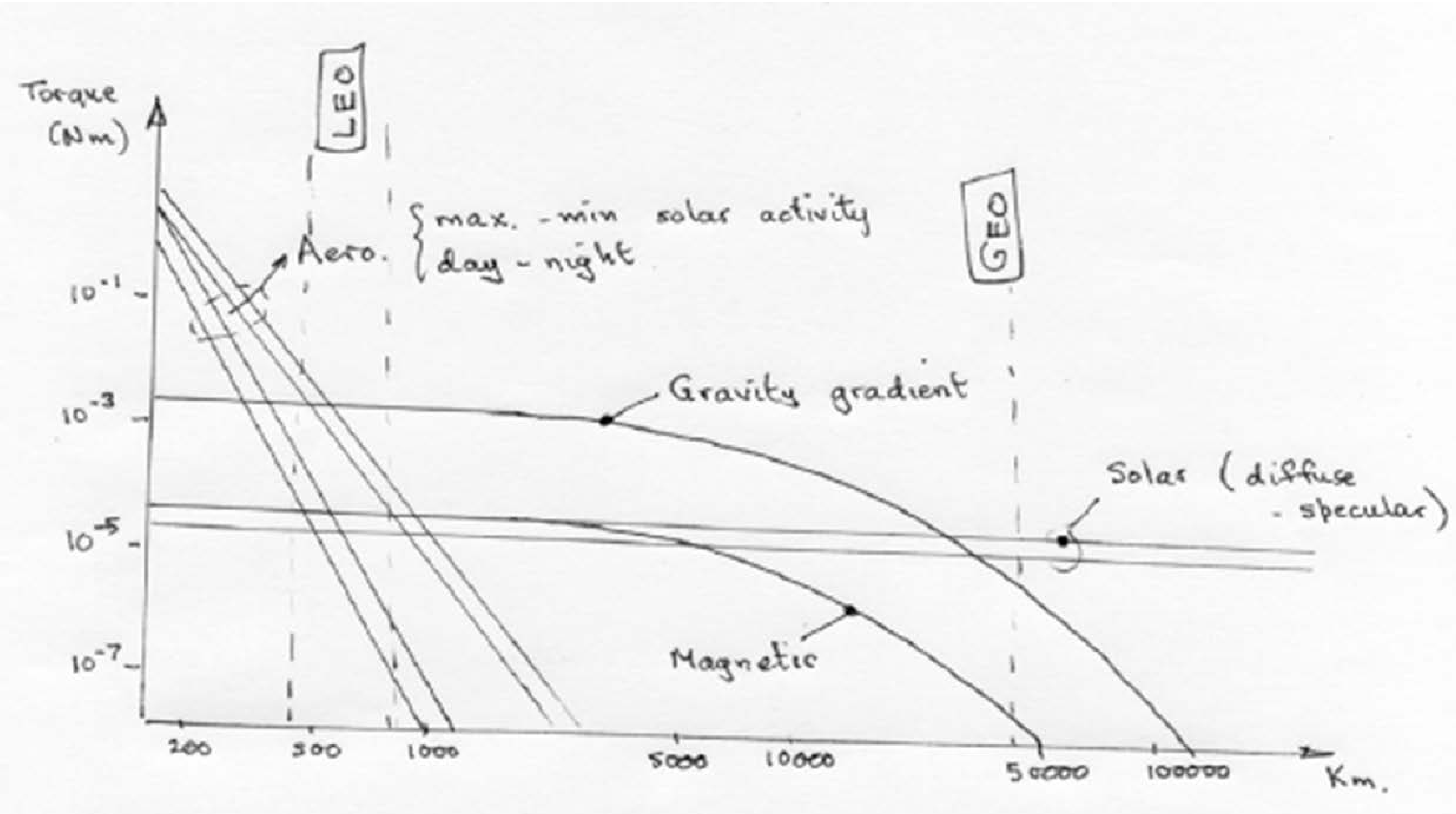
External disturbance torques for different Earth altitudes

Disturbance torque	Dependence on distance to Earth
Aerodynamic	e^{-ar}
Gravity gradient	$1/r^3$
Solar pressure	independent
Magnetic	$1/r^3$

Note: Magnitudes of torques depends on spacecraft configuration



External disturbance torque for different Earth altitudes



Same as before, but log-scale and some error bands

Torques for different Earth altitudes

Aerodynamic torque

from atmosphere at Earth (height < ≈400 km)

Gravity-gradient torque

from Earth gravity field ($\sim 1/r^3_{Earth}$) (height: 400-35000 km)

Magnetic torque

from Earth magnetic field ($\sim 1/r^3_{Earth}$) (height: 400-35000 km)

Solar radiation pressure torque

in solar system ($\sim 1/r^2_{Sun}$) (height > 400 km)

Remarks on torques for different altitude

Between interplanetary cruise and GEO
Solar radiation pressure is
primary source of disturbance torque if
any center-of-mass to center-of-pressure offsets

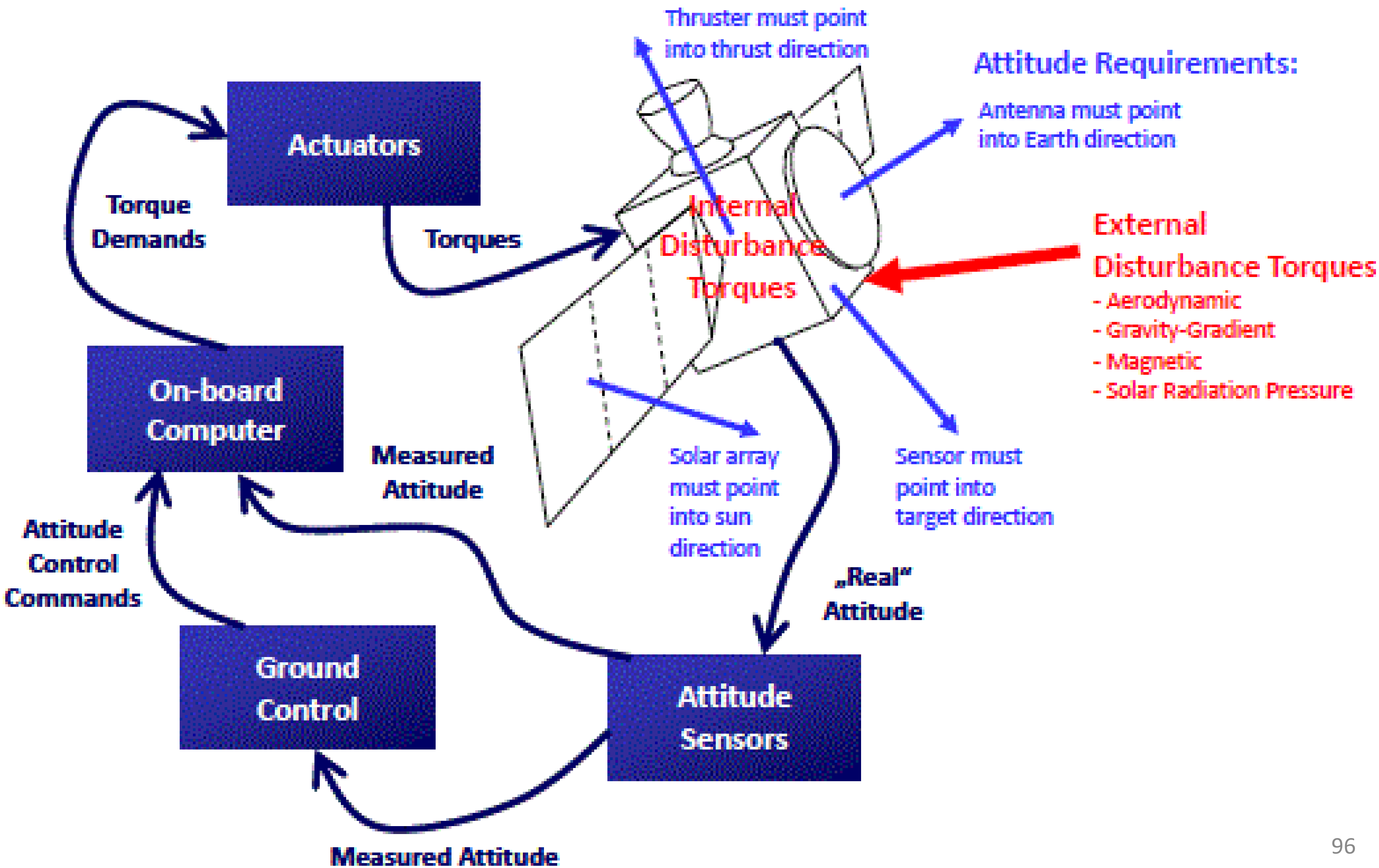
Below 1000 km altitude
Different torques must be considered

Between 250 - 400 km torque
Aerodynamic torque is dominant

Aerodynamic torque
Depends on atmospheric density and
density can change up to factor 10
Take into account day and night variation

Solar pressure
Strong dependence on solar activity
Take into account eclipse

Summary of attitude determination and control process



Summary

Objective and description of attitude

Hardware

- Sensors (determination)
  Sun-, Earth- and Star-Sensor, Magnetometers, Gyroscope
- Actuators (control)
  Thruster, Reaction wheel, Momentum wheel,
  Control momentum gyroscope, Magnetic torque

Attitude control methods

- Passive and active

Introduction to attitude concepts

- Conservation of angular momentum, inertia matrix
- Attitude kinematics and dynamics → Euler equation

Environmental torques

- Aerodynamic, Gravity-gradient, Magnetic, Solar pressure