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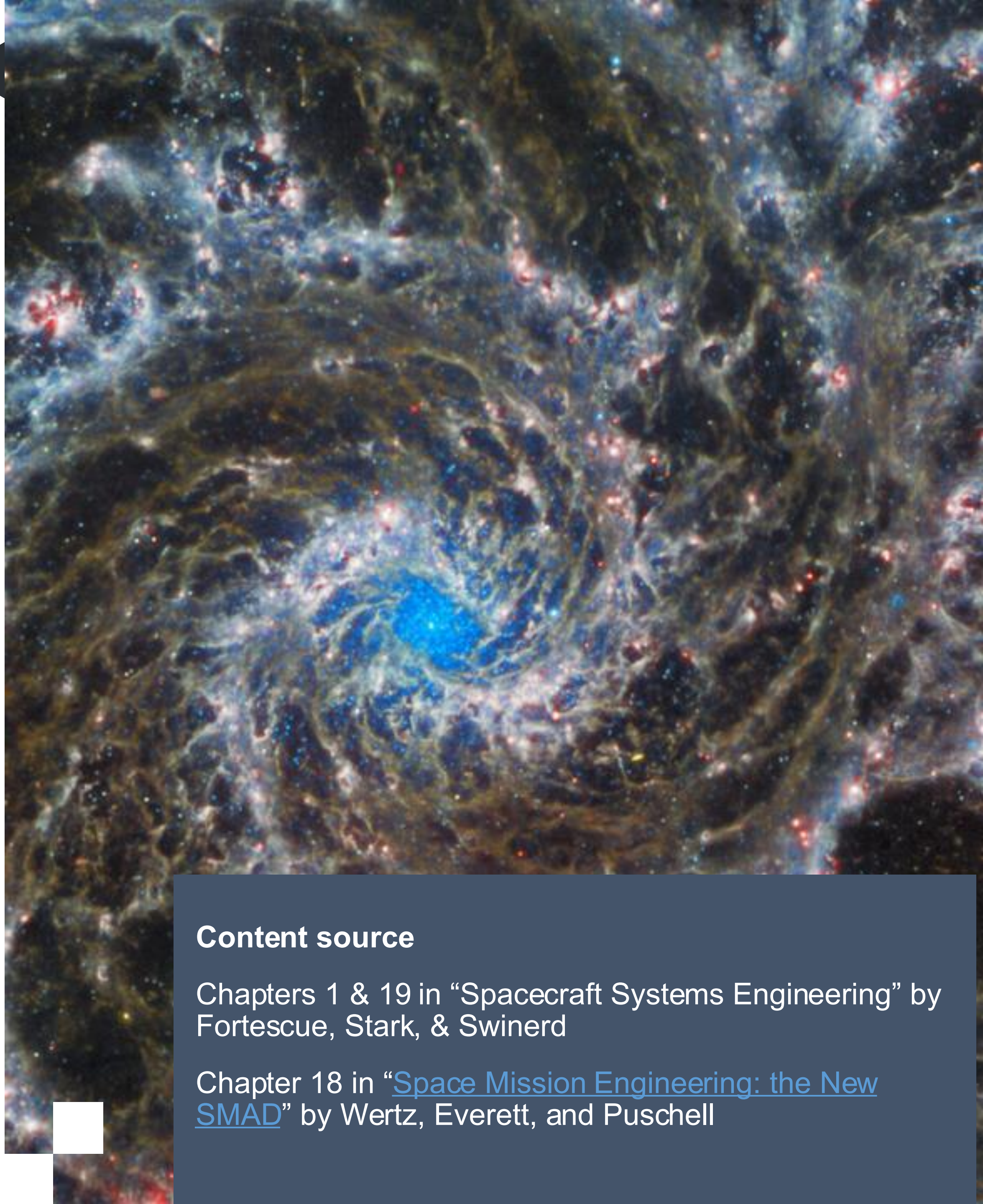
CONTENTS

Learning Outcomes

By the end of this lecture you should be familiar with…

- Know what ADCS means
- Understand the functions of the ADCS
- Identify the drivers for dimensionning
- Design you ADCS

The content is adapted from the slides from Muriel Richard teaching this class from 2010 to 2019



Content source

Chapters 1 & 19 in “Spacecraft Systems Engineering” by Fortescue, Stark, & Swinerd

Chapter 18 in “Space Mission Engineering: the New SMAD” by Wertz, Everett, and Puschell

Source: NASA/JWST

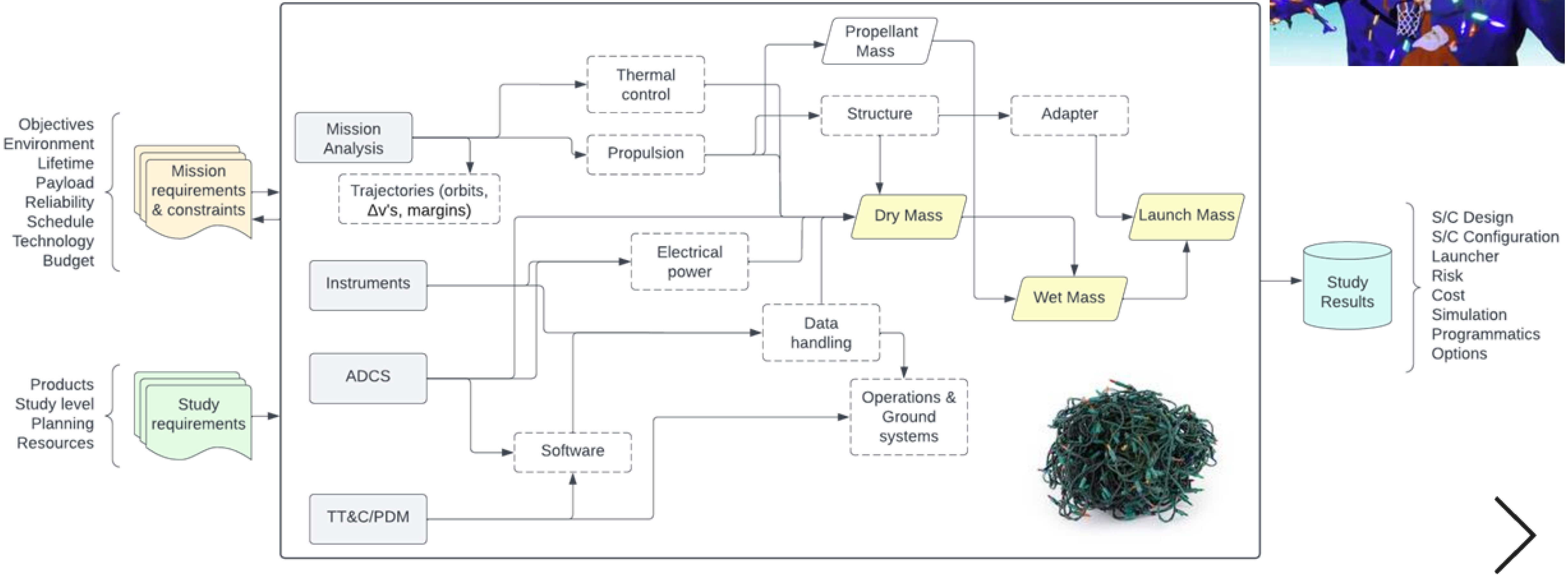
Introduction

How Does a Space Project Start?

EE584

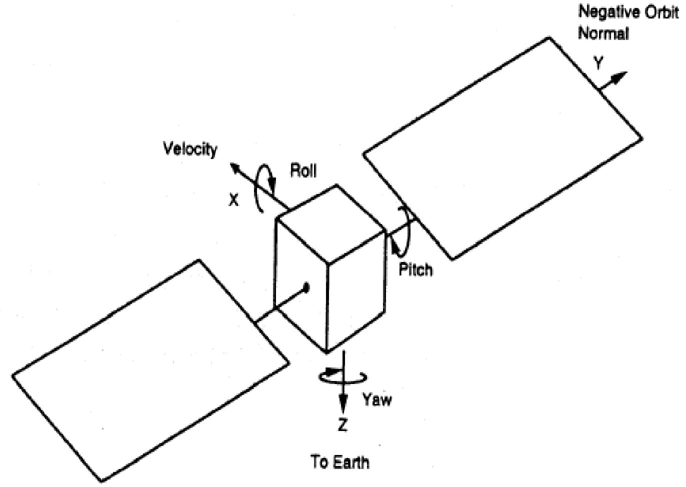
The Space Mission Engineering Process

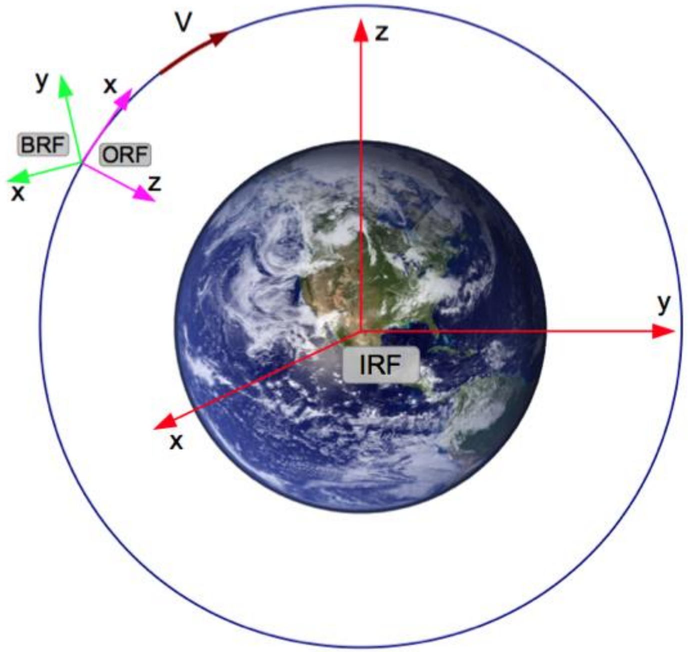
CONCEPTUAL MODEL OF MISSION & SPACECRAFT DESIGN PROCESS



Definitions

- Attitude: satellite's angular motion
- State: set of variables that completely describe the satellite's Attitude
  - Yaw/Pitch/Roll/angular speeds
  - Quaternions/angular speeds
  - The State is given in which Reference Frame?
- Determination (Navigation): Estimation of the Attitude (orbital position) from sensors → processed in real time or a posteriori
- Guidance: Command of the desired Attitude. Depends on requirements of the mission: science, and subsystems
- Control: Process to steer the system aiming at minimizing the difference between the actual state (navigation) and the desired state (guidance)





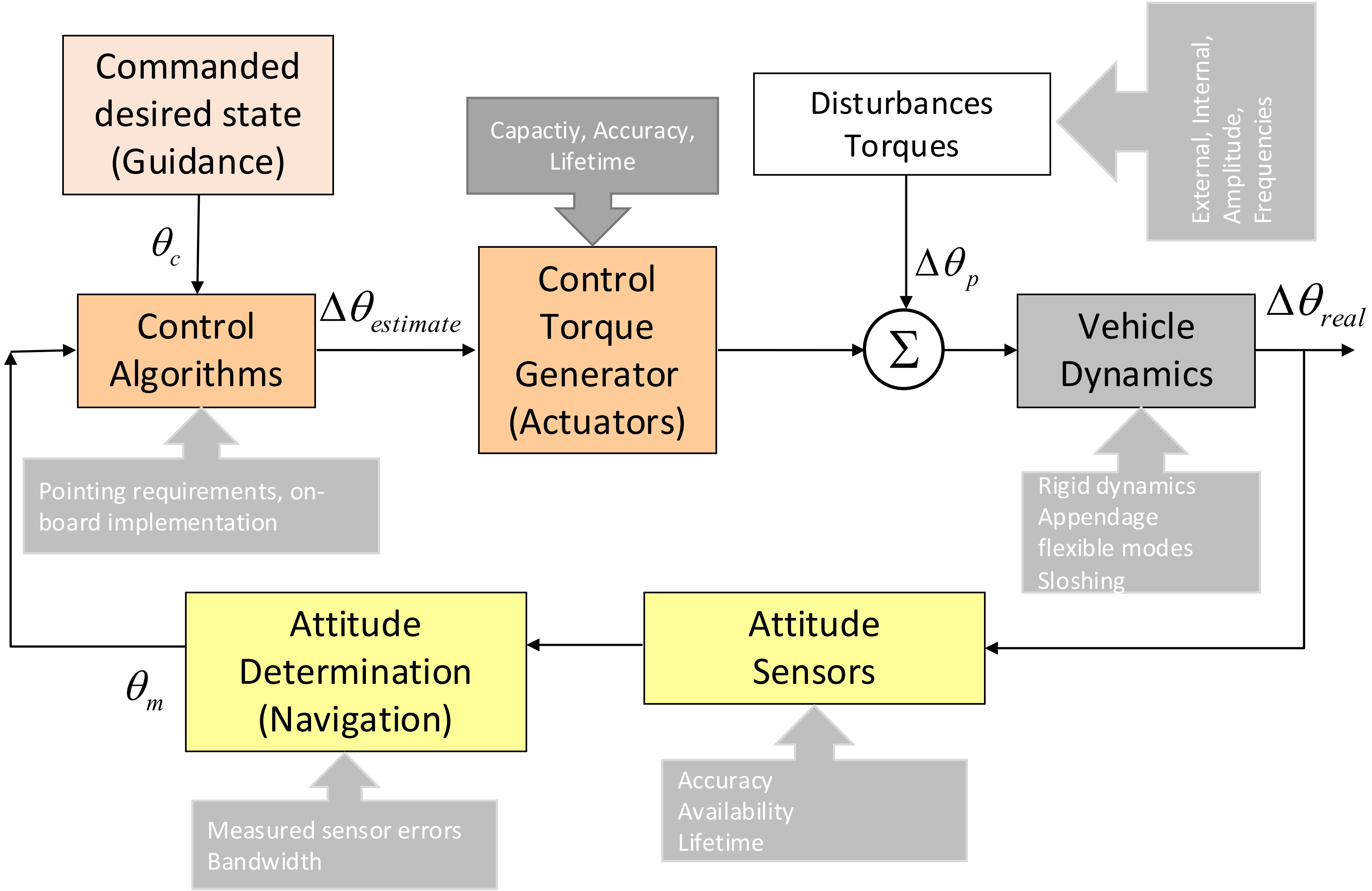
Definitions and Functions

- Attitude Determination and Control Subsystem (ADCS)
    - Attitude measurements and estimation, also called “determination”
    - Attitude guidance
    - Attitude control
    - Acquisition and maintenance of a safe attitude in emergency cases and return to nominal mission upon command

- Orbital Control Subsystem (OCS -> AOCS)
    - Orbital navigation (position & velocity estimation), also called orbit determination
    - Orbital guidance (done on-ground)
    - Orbital control (maneuvers)

- Guidance, Navigation and Control (GNC) – Rendezvous, formation flying, interplanetary vehicles…
    - Orbital guidance is done on-board
    - Real-time on-board trajectory guidance and control
    - Real-time on-board relative position estimation and control

ADCS Functional Block Diagram



Commanded desired state (Guidance)

θ_c

Control Algorithms

Pointing requirements, on-board implementation

$\Delta\theta_{estimate}$

Capactiy, Accuracy, Lifetime

Control Torque Generator (Actuators)

Disturbances Torques

External, Internal, Amplitude, Frequencies

$\Delta\theta_p$

Σ

Vehicle Dynamics

Rigid dynamics
Appendage flexible modes
Sloshing

$\Delta\theta_{real}$

Attitude Sensors

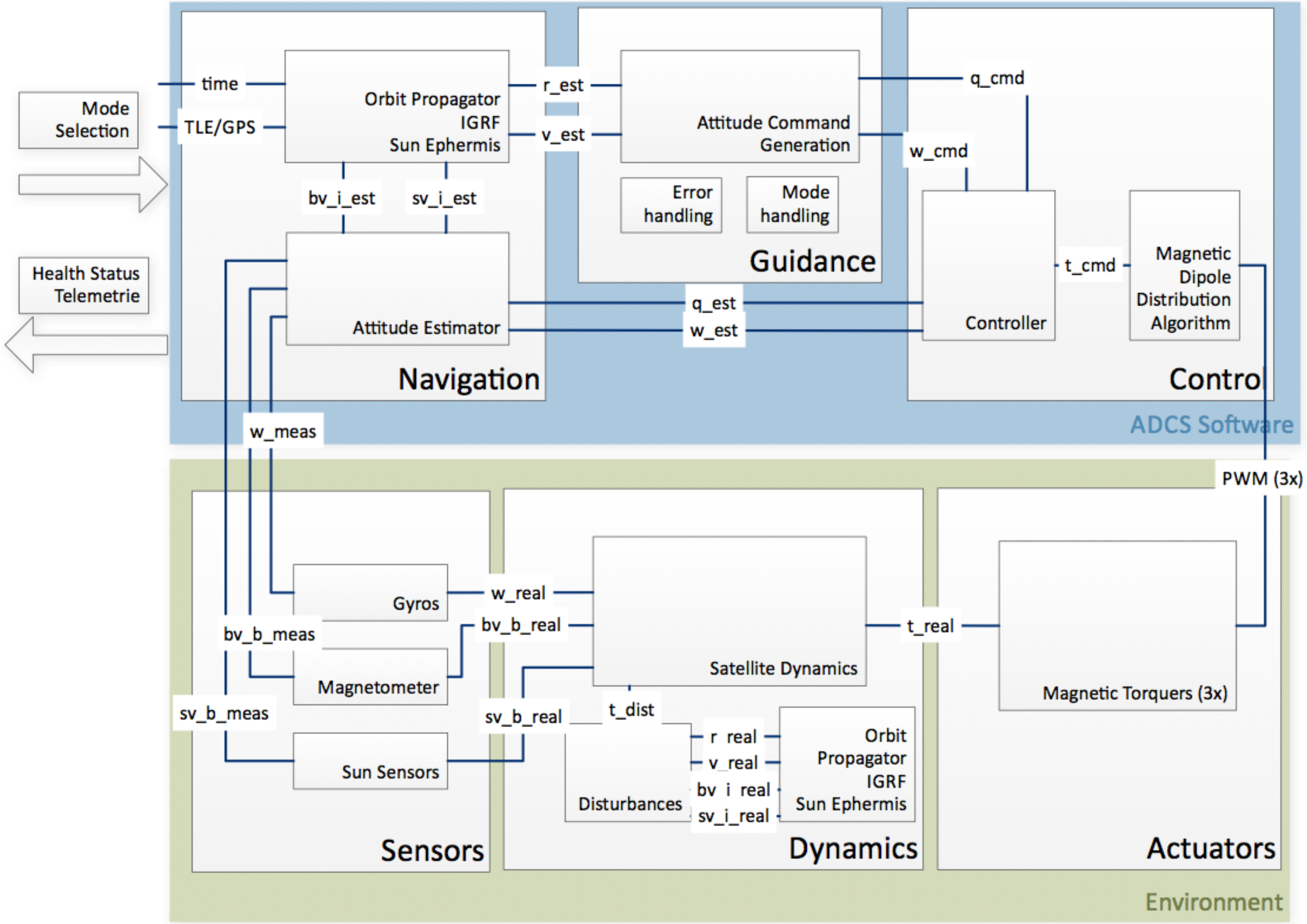
Accuracy
Availability
Lifetime

Attitude Determination (Navigation)

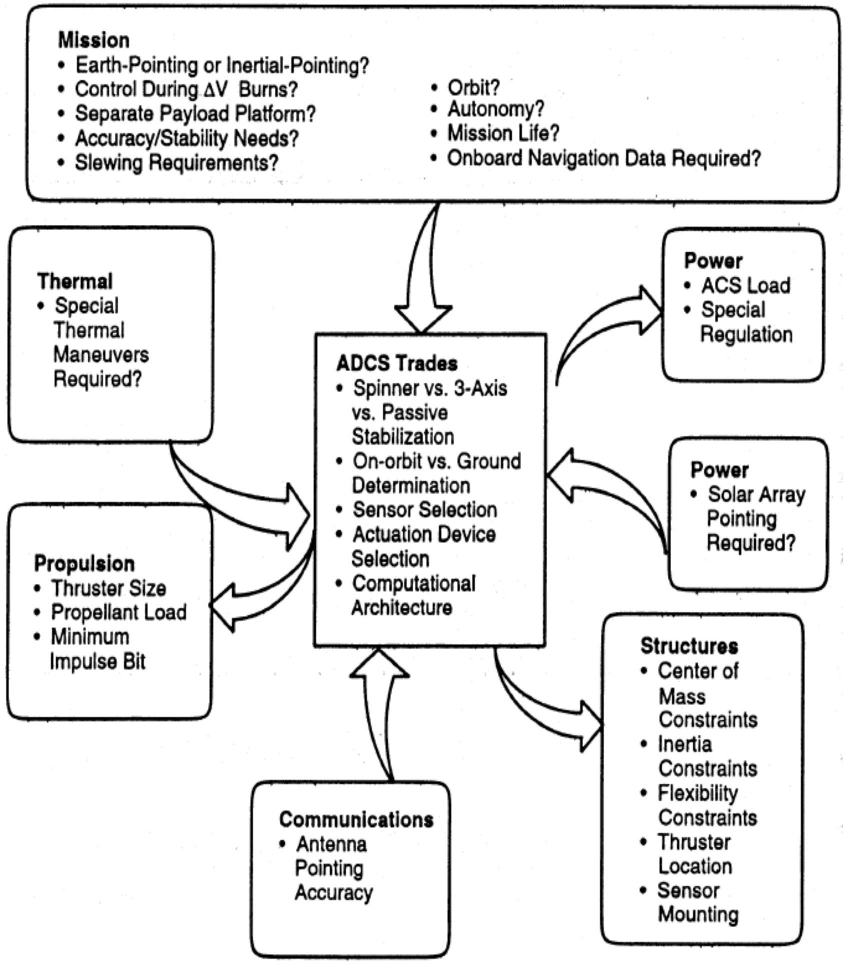
Measured sensor errors
Bandwidth

θ_m

Example on CubETH



Subsystems Interactions and ITERATIONS



Mission
- Earth-Pointing or Inertial-Pointing?
- Control During ΔV Burns?
- Separate Payload Platform?
- Accuracy/Stability Needs?
- Slewing Requirements?
- Orbit?
- Autonomy?
- Mission Life?
- Onboard Navigation Data Required?

ADCS Trades
- Spinner vs. 3-Axis vs. Passive Stabilization
- On-orbit vs. Ground Determination
- Sensor Selection
- Actuation Device Selection
- Computational Architecture

Thermal
- Special Thermal Maneuvers Required?

Propulsion
- Thruster Size
- Propellant Load
- Minimum Impulse Bit

Power
- ACS Load
- Special Regulation

Power
- Solar Array Pointing Required?

Structures
- Center of Mass Constraints
- Inertia Constraints
- Flexibility Constraints
- Thruster Location
- Sensor Mounting

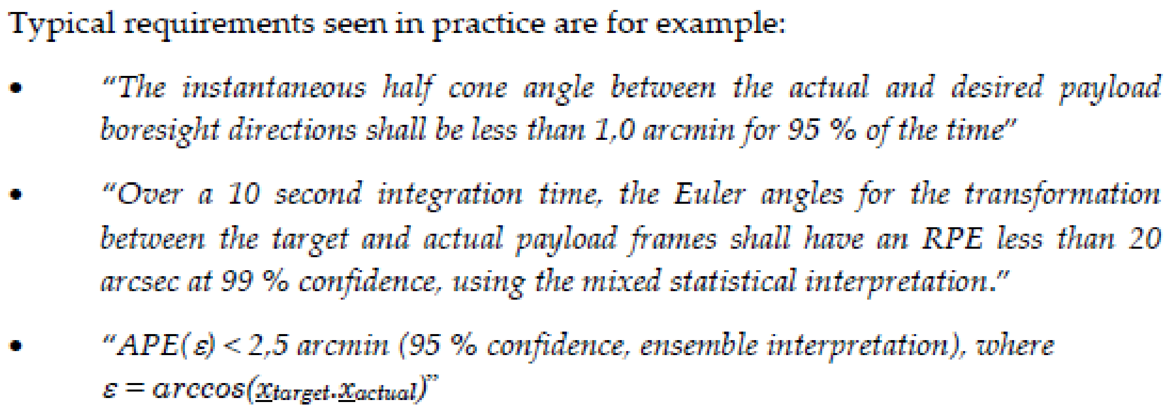
Communications
- Antenna Pointing Accuracy

Subsystem Functionality and Requirements

Requirements definitions

Pointing (angular position, deg or radians) and Stability requirement (angular rate, deg/s or radians/s) - Requirement typical attributes:

- A probability is associated to the requirement
- Statistical interpretation (temporal, ensemble or mixed) is defined
- The distinction between real-time and "a posteriori" knowledge should be done
    - The fact that the performance is reached in real time, or can be achieved "a posteriori" through dedicated processing, possibly in the ground control centre, is an important characteristics of the requirement
- The frequency content is sometimes important, especially to take into account that the AOCS cannot have any effect on some high frequency physical phenomena like micro-vibrations.
- Example ECSS-E-ST-60-10C: *"The ADCS shall ensure an absolute rate error of TBS microradians per second, at TBS % confidence level, using the TBS (temporal, ensemble or mixed) statistical interpretation, for all frequencies lower than TBS Hz"*



Typical requirements seen in practice are for example:

- *"The instantaneous half cone angle between the actual and desired payload boresight directions shall be less than 1,0 arcmin for 95 % of the time"*
- *"Over a 10 second integration time, the Euler angles for the transformation between the target and actual payload frames shall have an RPE less than 20 arcsec at 99 % confidence, using the mixed statistical interpretation."*
- *"APE(ε) < 2,5 arcmin (95 % confidence, ensemble interpretation), where $\varepsilon = \arccos(\underline{x}_{target}.\underline{x}_{actual})$"*

Requirements definitions

Agility requirement

- Example: *"The ADCS shall provide the capability to perform attitude manoeuvres in the following conditions:*
  - *1. TBS degrees on roll axis in less than TBS seconds, including the tranquilization phase.*
  - *2. TBS degrees on pitch axis in less than TBS seconds, including the tranquilization phase.*
  - *3. TBS degrees on yaw axis in less than TBS seconds, including the tranquilization phase."*

Orbit control requirement

- Example: *"The OCS shall perform the Delta-V commanded by the ground for the orbit control with an accuracy better than:*

  1. TBS % of the Delta-V magnitude along the commanded direction.

  2. TBS % of the Delta-V magnitude on the perpendicular directions (parasitic impulses)."

ADCS Requirements

BUS REQUIREMENTS

- **Telecom subsystem:** Antennas requirements. (function of the orbit and your GS)
- **Thermal Subsystem:** Do I need to cool down/heat some parts? (avoiding certain attitude for certain time)
- **Power Subsystem:** Solar panels and power requirements
- **Propulsion/docking:** necessary high precision to burn!
- Other issues from the BUS?

SCIENCE REQUIREMENTS: high pointing requirements! And not only….

Before the design of the subsystem → DESIGN of the REQUIREMENTS (put all together)

- Usually divided into "Operational Modes"
    - Ex: Acquisition, observation, Safe Mode, Manoeuvre, docking, etc..

For each mode often:

- **Pointing accuracy**: "*The AOCS shall ensure a pointing stability of 8 arcsec at 99.7% confidence level for 10 hours*"
- **Stability:** =resistance to the external torques [rad/s]
- **Attitude RANGE**: avoiding zones
- **Attitude knowledge**: *"The AOCS shall ensure […] an absolute attitude knowledge performance of TBS micro-radians, at TBS % confidence level, using the TBS (temporal, ensemble or mixed) statistical interpretation."*

ECSS standard CLASS of requirements: APE, RPE, AKE, RKE, […]

Error definitions

- Knowledge: difference between “known/estimated” and “achieved/true”
  - Absolute knowledge error (AKE)
  - Relative knowledge error (RKE) – relative to a specific duration of observation for instance
- Performance: difference between “target/desired” and “achieved/true”
  - Absolute performance error (APE)
  - Relative performance error (RPE)
- Examples: sensor noise, sensor bias, actuator noise, actuator bias, disturbance forces and torques (e.g. microvibrations, manoeuvres, external or internal subsystem motions), friction forces and torques, misalignments, thermal distortions, assembly distortions, digital quantization, control law performance (steady state error), jitter, etc.

Performance budgets

- The AOCS shall provide budgets for the following performances:
  1. absolute attitude pointing budgets,
  2. on-board absolute attitude knowledge budgets,
  3. relative attitude pointing budgets,
  4. contribution to propulsion related budgets,
  5. orbit correction performance budgets,
  6. duration budgets (mode transitions, agility, convergence, AOCS availability and outages).

ADCS Modes

- Nominal
  - May involve several guidance types:
    - Sun pointing
    - Nadir pointing
    - Local vertical/Local Horizontal…
  - May include acquisition mode, in between modes

- Safe mode

- End-of life disposal

- Mapping of the ADCS/OCS modes into satellites modes needs to be done to clarify all the possible configurations in which the satellite can be in relation with the AOCS

Disturbance torques

Disturbance Torques on Satellite

External torques	Sizing	Varies as
Aerodynamic drag	LEO	exp(-r)
Solar radiation pressure	LEO-GEO	Const.
Magnetic	LEO-GEO	$1/r^3$
Gravity-gradient	LEO-GEO	$1/r^3$

- Secular: mean not 0 over T(=1orbit usually) →Drift →Saturation of the actuators
- Cyclic: mean 0 over T
- Internal torques
    - Angular momentum exchange between moving parts (rotating machinery)
    - Antenna, solar array, boom deployments and actuation
    - Scanning motion of instruments
    - Liquid sloshing
    - Thermal shock on flexible structures
    - Dynamics of flexible bodies…
- Other: thruster misalignment, mismatch of thruster outputs, uncertainty in CG

Atmospheric Drag

- Force created by atmospheric drag:
  - Cd: drag coefficient
  - A: cross-sectional area (perpendicular to velocity vector)
  - ρ: atmospheric density
  - V_{rel}: velocity relative to the atmosphere
  - b: distance of the CoP from your center of RF

$$F_{drag} = \frac{C_d A \rho}{2} v_{rel}^2$$

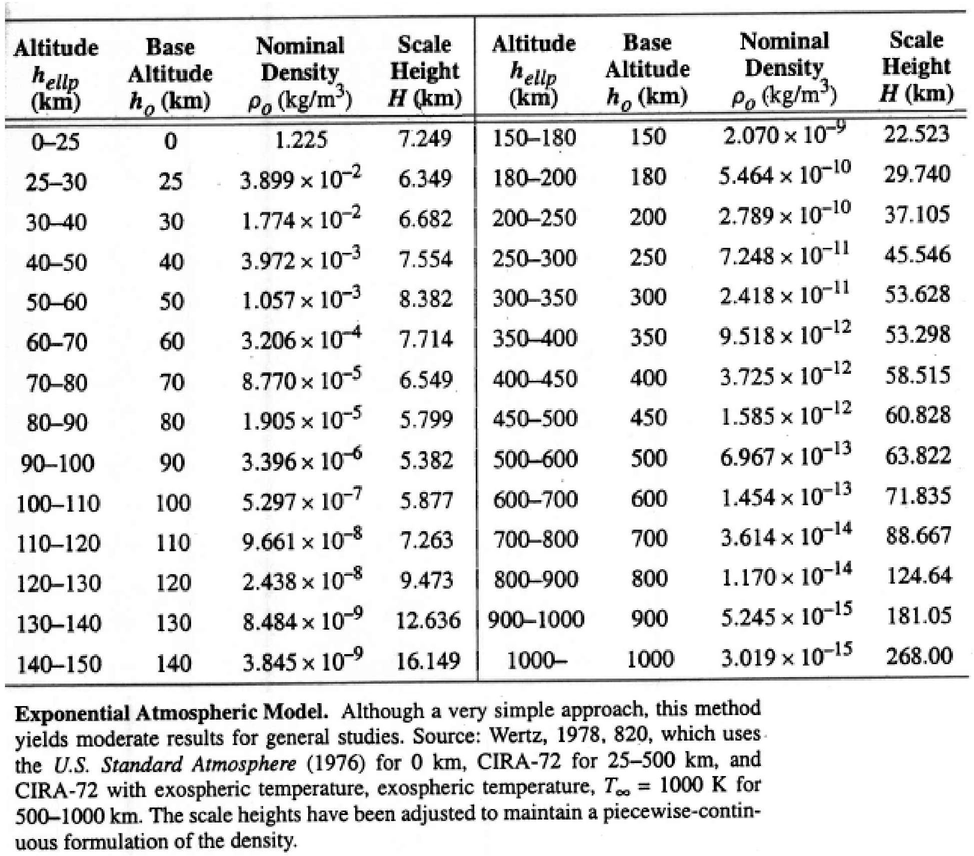
- Drag coefficient is Cd ~ 2 for spheres and 2.2 for flat plate in rarefied gas

- Atmospheric density
  - Varies with solar cycle and solar flares and geomagnetic activity
  - Can see an order of magnitude differences
  - Several models attempt to represent fluctuations (see next slide)

- Objectives:
  - calculate rate at which satellite is losing altitude (orbit decay rate);
  - Calculate aerodynamic torque on the satellite.

$$\vec{T}_{drag} = \vec{b} \times \vec{F}_{drag}$$

Atmospheric Drag



Altitude h_{ellp} (km)	Base Altitude h_o (km)	Nominal Density ρ_o (kg/m³)	Scale Height H (km)	Altitude h_{ellp} (km)	Base Altitude h_o (km)	Nominal Density ρ_o (kg/m³)	Scale Height H (km)
0–25	0	1.225	7.249	150–180	150	2.070×10^{-9}	22.523
25–30	25	3.899×10^{-2}	6.349	180–200	180	5.464×10^{-10}	29.740
30–40	30	1.774×10^{-2}	6.682	200–250	200	2.789×10^{-10}	37.105
40–50	40	3.972×10^{-3}	7.554	250–300	250	7.248×10^{-11}	45.546
50–60	50	1.057×10^{-3}	8.382	300–350	300	2.418×10^{-11}	53.628
60–70	60	3.206×10^{-4}	7.714	350–400	350	9.518×10^{-12}	53.298
70–80	70	8.770×10^{-5}	6.549	400–450	400	3.725×10^{-12}	58.515
80–90	80	1.905×10^{-5}	5.799	450–500	450	1.585×10^{-12}	60.828
90–100	90	3.396×10^{-6}	5.382	500–600	500	6.967×10^{-13}	63.822
100–110	100	5.297×10^{-7}	5.877	600–700	600	1.454×10^{-13}	71.835
110–120	110	9.661×10^{-8}	7.263	700–800	700	3.614×10^{-14}	88.667
120–130	120	2.438×10^{-8}	9.473	800–900	800	1.170×10^{-14}	124.64
130–140	130	8.484×10^{-9}	12.636	900–1000	900	5.245×10^{-15}	181.05
140–150	140	3.845×10^{-9}	16.149	1000–	1000	3.019×10^{-15}	268.00

Exponential Atmospheric Model. Although a very simple approach, this method yields moderate results for general studies. Source: Wertz, 1978, 820, which uses the *U.S. Standard Atmosphere* (1976) for 0 km, CIRA-72 for 25–500 km, and CIRA-72 with exospheric temperature, exospheric temperature, T_∞ = 1000 K for 500–1000 km. The scale heights have been adjusted to maintain a piecewise-continuous formulation of the density.

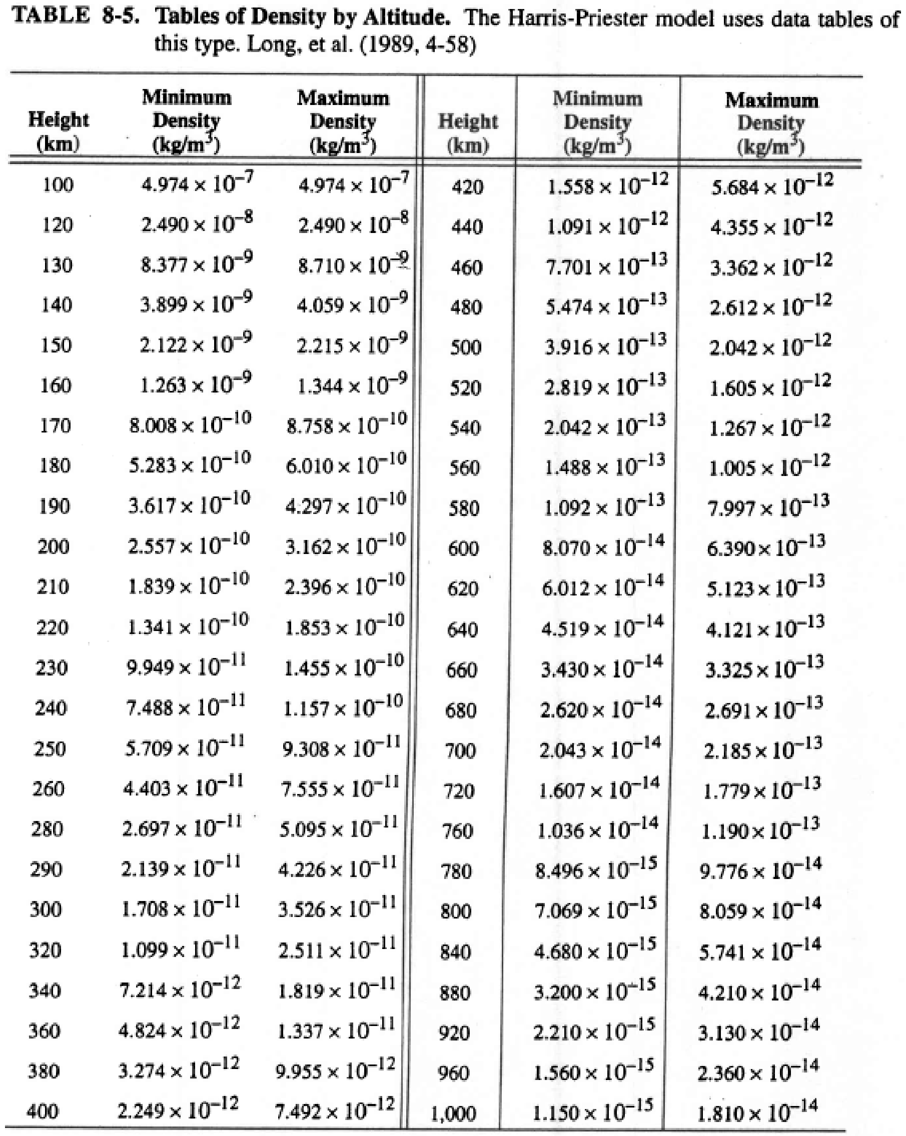


TABLE 8-5. Tables of Density by Altitude. The Harris-Priester model uses data tables of this type. Long, et al. (1989, 4-58)

Height (km)	Minimum Density (kg/m³)	Maximum Density (kg/m³)	Height (km)	Minimum Density (kg/m³)	Maximum Density (kg/m³)
100	4.974×10^{-7}	4.974×10^{-7}	420	1.558×10^{-12}	5.684×10^{-12}
120	2.490×10^{-8}	2.490×10^{-8}	440	1.091×10^{-12}	4.355×10^{-12}
130	8.377×10^{-9}	8.710×10^{-9}	460	7.701×10^{-13}	3.362×10^{-12}
140	3.899×10^{-9}	4.059×10^{-9}	480	5.474×10^{-13}	2.612×10^{-12}
150	2.122×10^{-9}	2.215×10^{-9}	500	3.916×10^{-13}	2.042×10^{-12}
160	1.263×10^{-9}	1.344×10^{-9}	520	2.819×10^{-13}	1.605×10^{-12}
170	8.008×10^{-10}	8.758×10^{-10}	540	2.042×10^{-13}	1.267×10^{-12}
180	5.283×10^{-10}	6.010×10^{-10}	560	1.488×10^{-13}	1.005×10^{-12}
190	3.617×10^{-10}	4.297×10^{-10}	580	1.092×10^{-13}	7.997×10^{-13}
200	2.557×10^{-10}	3.162×10^{-10}	600	8.070×10^{-14}	6.390×10^{-13}
210	1.839×10^{-10}	2.396×10^{-10}	620	6.012×10^{-14}	5.123×10^{-13}
220	1.341×10^{-10}	1.853×10^{-10}	640	4.519×10^{-14}	4.121×10^{-13}
230	9.949×10^{-11}	1.455×10^{-10}	660	3.430×10^{-14}	3.325×10^{-13}
240	7.488×10^{-11}	1.157×10^{-10}	680	2.620×10^{-14}	2.691×10^{-13}
250	5.709×10^{-11}	9.308×10^{-11}	700	2.043×10^{-14}	2.185×10^{-13}
260	4.403×10^{-11}	7.555×10^{-11}	720	1.607×10^{-14}	1.779×10^{-13}
280	2.697×10^{-11}	5.095×10^{-11}	760	1.036×10^{-14}	1.190×10^{-13}
290	2.139×10^{-11}	4.226×10^{-11}	780	8.496×10^{-15}	9.776×10^{-14}
300	1.708×10^{-11}	3.526×10^{-11}	800	7.069×10^{-15}	8.059×10^{-14}
320	1.099×10^{-11}	2.511×10^{-11}	840	4.680×10^{-15}	5.741×10^{-14}
340	7.214×10^{-12}	1.819×10^{-11}	880	3.200×10^{-15}	4.210×10^{-14}
360	4.824×10^{-12}	1.337×10^{-11}	920	2.210×10^{-15}	3.130×10^{-14}
380	3.274×10^{-12}	9.955×10^{-12}	960	1.560×10^{-15}	2.360×10^{-14}
400	2.249×10^{-12}	7.492×10^{-12}	1,000	1.150×10^{-15}	1.810×10^{-14}

Solar Radiation Pressure

- Like drag, solar radiation is a non-conservative perturbation, and is more pronounced at higher altitude
  - A: illuminated surface area, perpendicular to Sun-satellite incidence direction
  - P_{sr} : solar pressure, determined from the solar flux (=I/cR^2)
  - C_r: satellite reflectivity (1+k)
  - C_{sp}: solar pressure center
  - b: distance of CoP from your center of RF

$$F_{sr} = P_{sr} C_r A$$

$$\square \quad \square \quad \square$$

$$T_{sr} = b \square F_{sr}$$

- Variation depending on the solar cycle and solar flares
  - $P_{sr} \sim 4.51 \, 10^{-6}$ N/m^2

- Process of calculation involves:
  - Determination of shadows on the spacecraft itself
    - Pressure distribution creates a torque
  - Determination satellite-sun worst case line of sight (incidence from the Sun)
  - Determination of the satellite's reflectivity ($C_r \sim 1.4 – 1.8$)

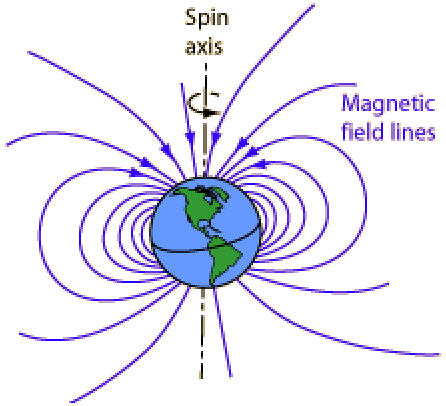
Magnetic Torque

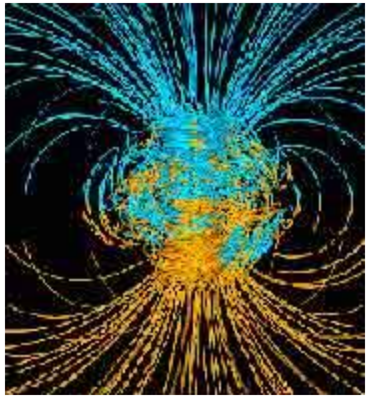
- Magnetic torque present when in orbit around a planet with substantial magnetic field, like Earth and Jupiter. The torque is given by:

$$T_{mag} = m_{satellite} \times B$$

- m is the satellite magnetic dipole due to current loops and residual magnetization in the spacecraft. It is also called residual dipole and is expressed in Am^2.
- B is the planet magnetic field vector expressed in spacecraft coordinates; it is proportional to 1/r^3, where r is the radius vector to the spacecraft. It is measured in Tesla (SI), or Gauss (CGS). 1 Tesla = 10^4 Gauss.

- Typical values for a small spacecraft in LEO:
  - B ~ 10^{-4} -10^{-5} Tesla
  - M = 1 Am^2 for sat>100kg, 1-0.1e-3Am^2 (Cubesat 3kg)
  - T_{mag} ~ 3.10^{-6} N m





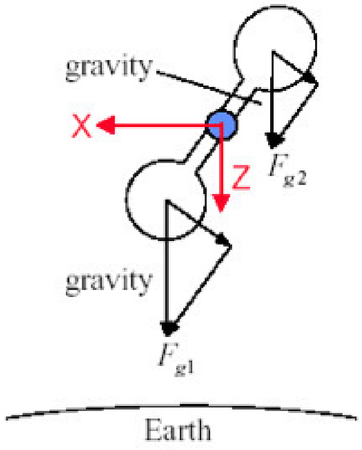
$$B_{PolarOrbit} \approx \frac{2M_{Earth}}{r^3}$$

$$B_{EquatorialOrbit} \approx \frac{M_{Earth}}{r^3}$$

$$M_{Earth} = 7.96 \times 10^{15}\, Tesla.m^3$$

Gravity-Gradient Torque

- Magnitude of the gravitational force of the Earth (or central body) varies as $1/r^3$
  - The gravitational force on one part of the satellite is different from another part (if typically separated by some relatively large distance), resulting in a net torque
  - Example: Moon, Mercury



- Gravitational force dF_i acting on a satellite mass element dm_i located at position r_i relative to geocenter is:

$$d\mathbf{F}_i = \frac{-\mu.\mathbf{r}_i}{r_i^3} dm_i$$

- Integrating over entire satellite:
  - I: moment of inertia tensor

$$T_{gg} = \int \mathbf{r}_i \times d\mathbf{F}_i = \frac{3\mu}{a^3} \mathbf{r} \times I.\mathbf{r}$$

$$I = \begin{bmatrix} I_{11} & I_{12} & I_{13} \\ I_{21} & I_{22} & I_{23} \\ I_{31} & I_{32} & I_{33} \end{bmatrix}$$

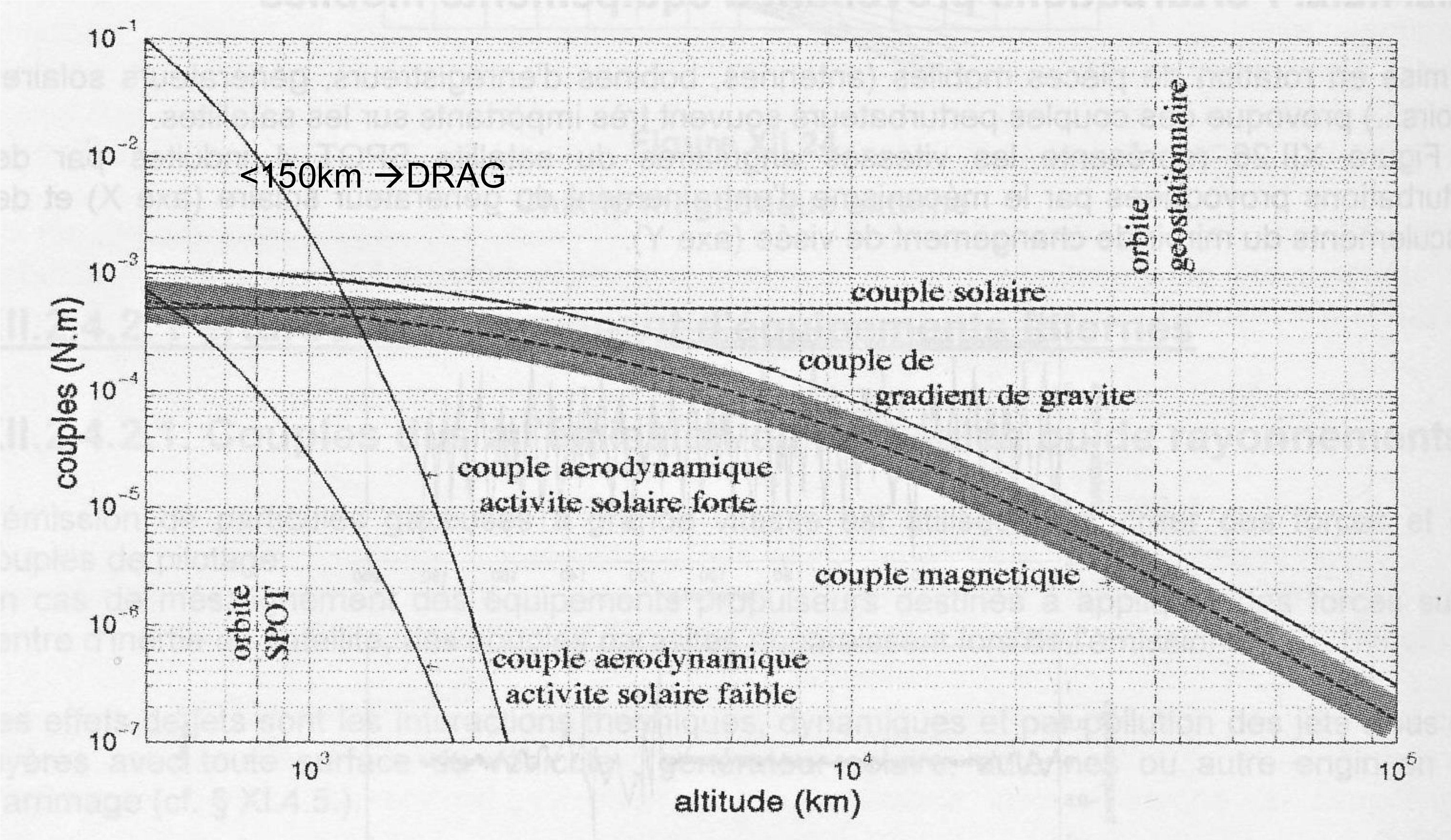
- For a circular orbit and an Earth-referenced spacecraft (Z to nadir, X along velocity vector), the torque is given by:
  - θ: deviation from Z axis

$$T_x = \frac{3\mu}{2r^3} |I_z - I_y| \sin(2\theta_y)$$

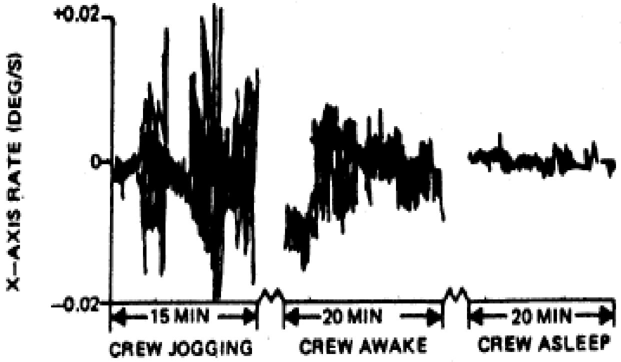
$$T_y = \frac{3\mu}{2r^3} |I_z - I_x| \sin(2\theta_x)$$

approximation, CG=CRF

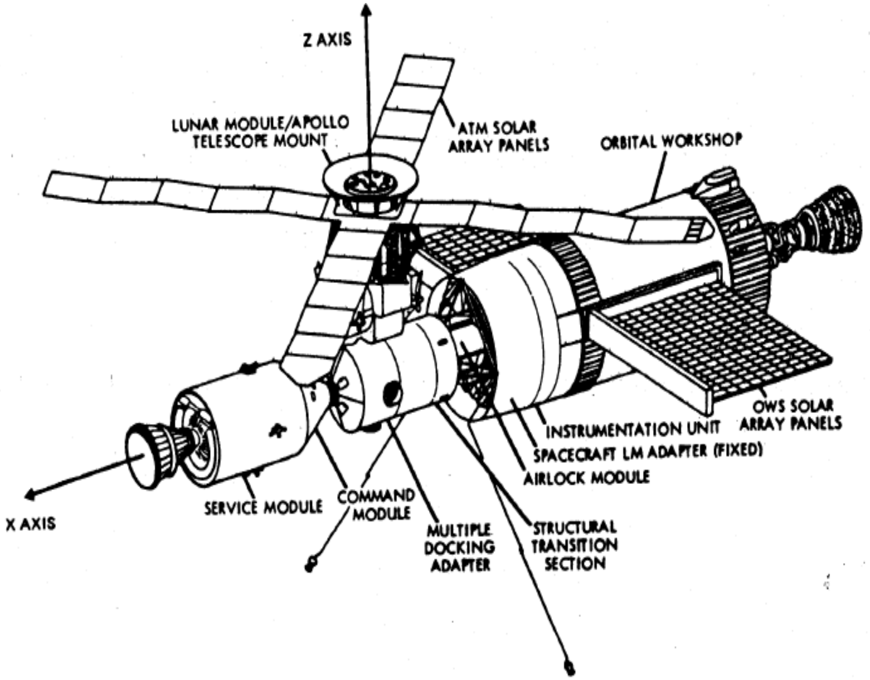
External Torques Summary



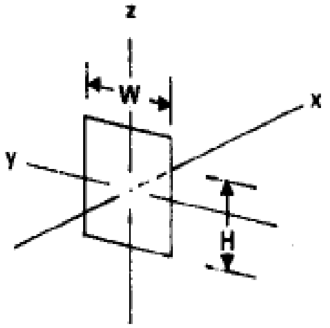
Internal Torques



Jitter Caused by Crew Motion Onboard Skylab. (Adapted from Chubb, *et al.*, [1975].)



Useful Formulas

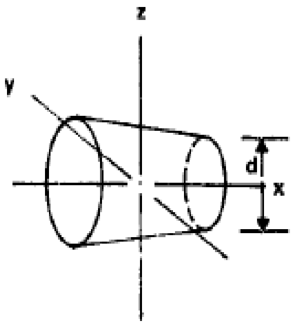


RECTANGULAR PLATE

$I_{xx} = \frac{m}{12}(H^2 + W^2)$

$I_{yy} = \frac{m}{12} H^2$

$I_{zz} = \frac{m}{12} W^2$



CYLINDRICAL SHELL

$I_{xx} = \frac{md^2}{4}$

$I_{yy} = m\left(\frac{d^2}{8} + \frac{L^2}{12}\right)$

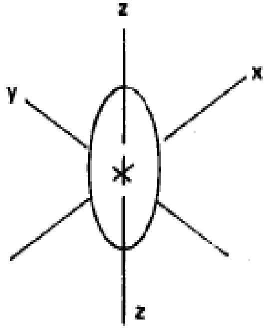
$I_{zz} = m\left(\frac{d^2}{8} + \frac{L^2}{12}\right)$

SOLID CYLINDER

$I_{xx} = \frac{md^2}{8}$

$I_{yy} = \frac{m}{12}\left(\frac{3d^2}{4} + L^2\right)$

$I_{zz} = \frac{m}{12}\left(\frac{3d^2}{4} + L^2\right)$

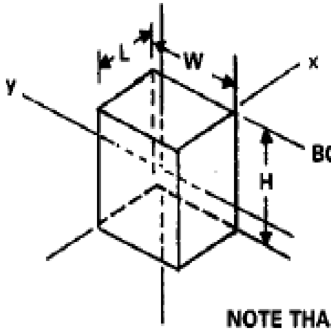


DISK

$I_{xx} = \frac{md^2}{8}$

$I_{yy} = \frac{md^2}{16}$

$I_{zz} = \frac{md^2}{16}$



BOX

$I_{xx} = \frac{m}{12}(H^2 + W^2)$

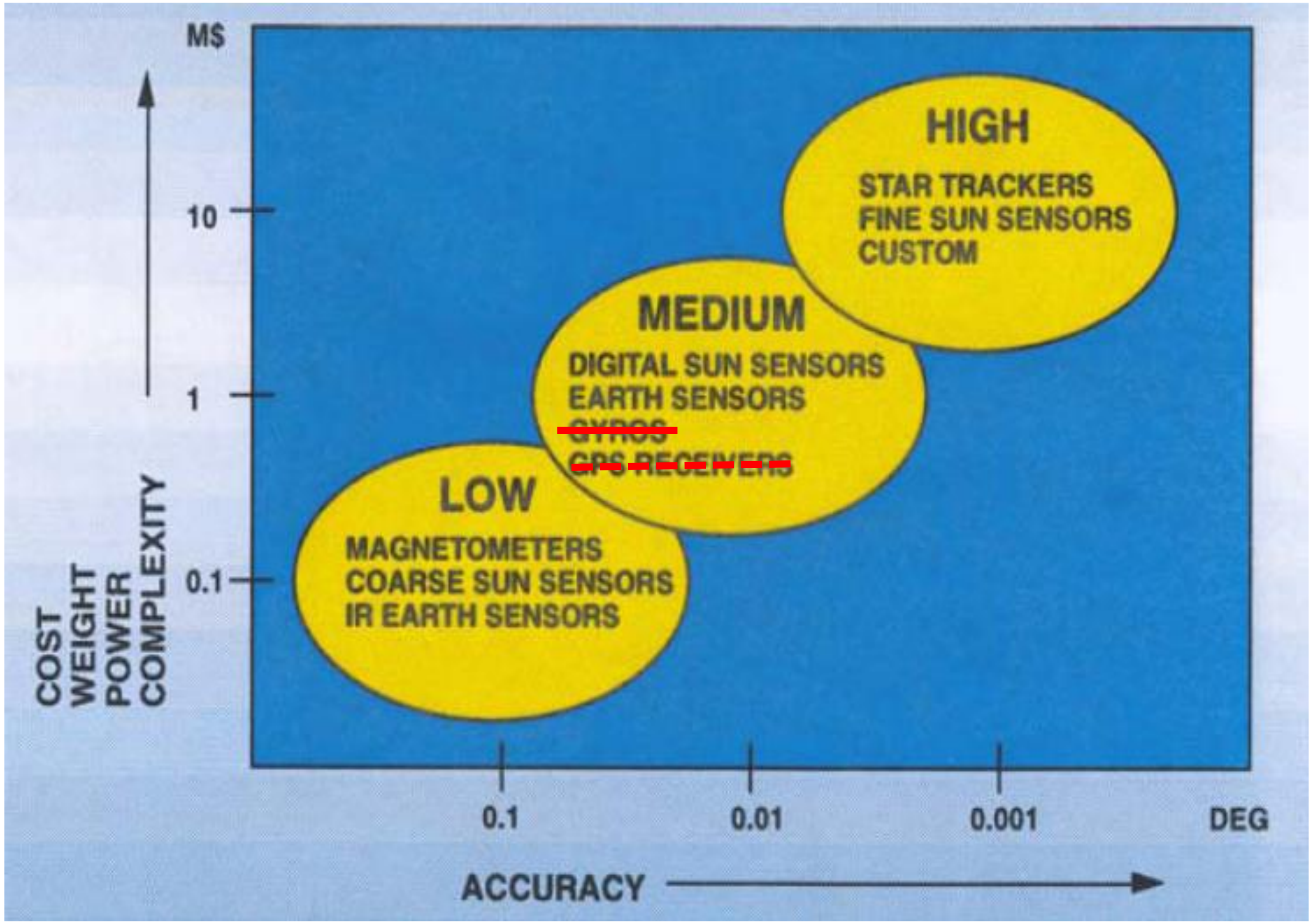
$I_{yy} = \frac{m}{12}(L^2 + H^2)$

$I_{zz} = \frac{m}{12}(L^2 + W^2)$

NOTE THAT FOR ANY PLANE FIGURE, IF THE X-AXIS IS ⊥ TO THE PLANE, $I_{xx} = I_{yy} + I_{zz}$

Attitude sensors

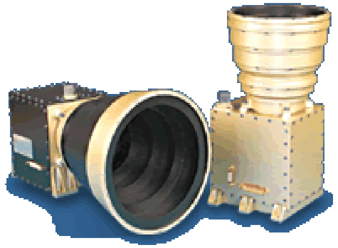
Attitude Sensors



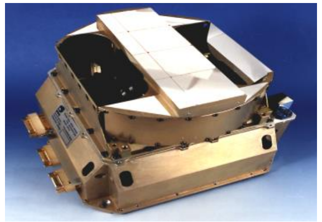
EPFL Space Center

Attitude Sensors

- Optical sensors:
  - Star tracker
    - Provides precise 3-axis inertial attitude 10” from Lost in Space (star pattern recognition)
    - Orbital position required for Earth pointing
    - New generation: APS (CMOS) instead of CCD
  - Earth sensor
    - Provides 2-axis attitude w.r.t. Earth
    - Third axis = sun sensor or gyroscopic stiffness
    - 0.03 deg GEO (radiance sensitivity)
    - Scanning (dynamic) or static
  - Sun sensor
    - Provides 2-axis attitude w.r.t. Sun
    - Either coarse analogue (acquisition) or fine digital
  - Navigation camera
    - Celestial body imaging and navigation algorithms



Autonomous CCD-Star Tracker



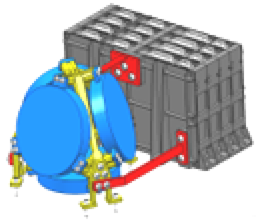
Scanning infra-red Earth sensor

2-axis Digital Sun sensor

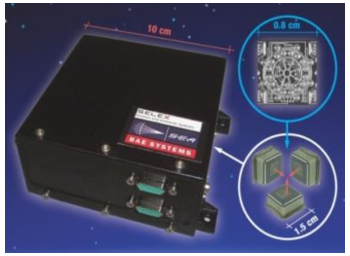
Attitude Sensors

- Magnetic and Inertial sensors:
  - Magnetometer
    - Provides (coarse) magnetic field measurement
    - Light and cheap sensor for acquisition in LEO
  - Integrating gyros
    - Provides integrated angular rate
    - High bandwidth and accuracy (but drift error)
    - Hybridisation with optical sensor (Kalman filter)
  - Accelerometer
    - Stand-alone or within IMU
    - No space qualified European sensor
  - Coarse rate sensors
    - Provides angular rate <10 deg/h
    - Light and cheap sensor for detumbling, acquisition, short term attitude propagation

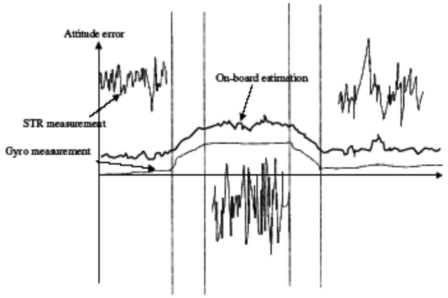
3-axis magnetometer

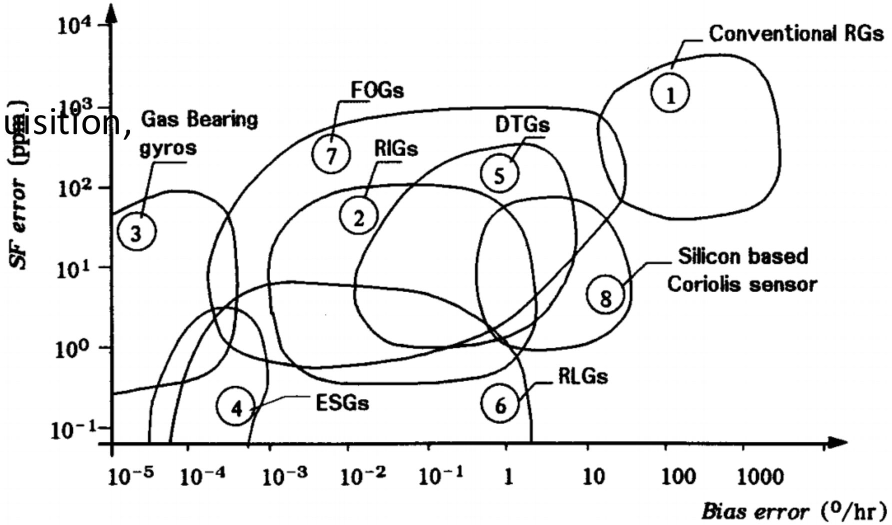


4-axis Fiber Optic Gyroscope



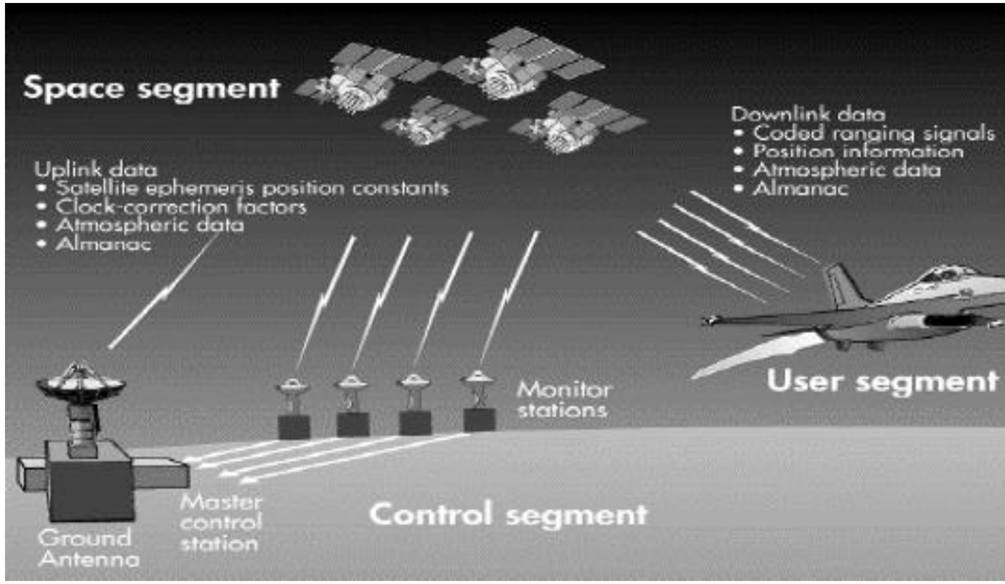
3-axis MEMS rate sensor





Attitude/Navigation Sensors

- Global Positioning System:
  - Although long tried, GPS never really made as useful attitude sensor
  - Cheap technique
  - Key issue is multi-path reflection of GPS signals
  - Requires multiple antennae (minimum 3 for a 3 axis determination)
  - GPS extensively used for navigation



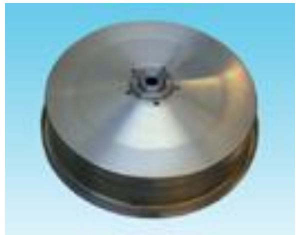
Attitude Sensors - Summary

Sensor Type	Accuracy (Degrees)	Remarks
Sun Sensor	0.01-0.1	Simple, reliable, cheap, intermittent
Earth Sensor	0.02-0.03	Expensive, limited application, no-yaw
Magnetometer	1	Cheap, LEO only
Star Tracker Narrow Modern (wide angle)	 0.001 0.01	 Expensive, heavy complex Cheap, light, simple
Gyroscope Mechanical Tactical	 0.01 */hr* 0.1 */hr*	 Costly, massive Cheap, light, simple
GPS	0.1	Cheap, simple

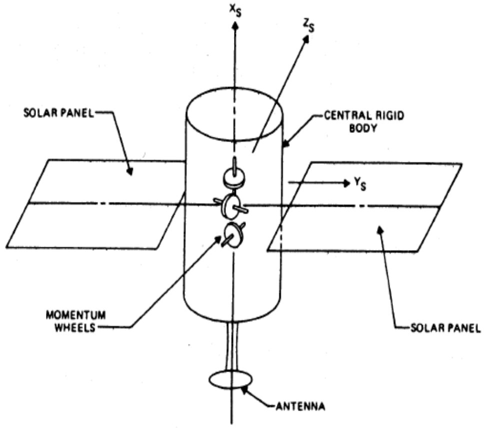
DYN→0.02˚ in GEO
ST →0.03˚

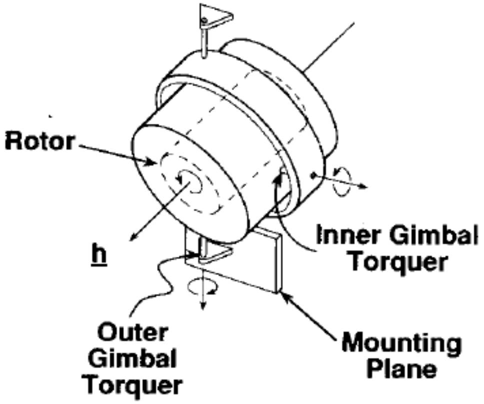
Attitude Actuators

- Wheels
    - Reaction Wheels
        - Electric motor spins wheel, provide one axis of control
        - Typical arrangement is 4 wheel in a tetrahedron for redundancy
        - Momentum capacity 10-40 Nms
        - Torque up to 0.1Nm (momentum exchange)
        - Desaturation necessary, microvibration issues
    - Momentum Wheels
        - Reaction wheel operating at non-zero momentum (non-zero nominal spin rate) to provide gyroscopic stiffness
        - Same arrangement as reaction wheels
        - Momentum dumping is required to keep the speed at a set constant value
    - Control Moment Gyros (CMGs)
        - CMG is a gimballed momentum wheel
        - Torque applied to the gimbal produces a change in the angular momentum perpendicular to the existing angular momentum vector (h), and thus a reaction torque on the body
        - Heavy, need lots of power, noisy but very high control authority (ISS)



12 Nms Reaction wheel

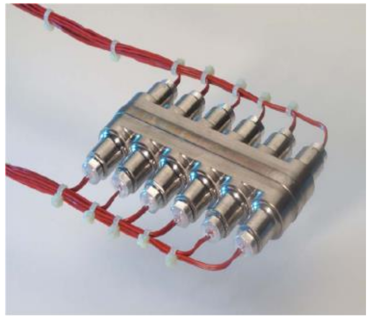




Attitude Actuators

- Others
  - Propulsion
    - High to low external torque capacity
    - Use for orbit control and initial acquisition
    - Efficiency Isp(s): $\Delta m.g\ Isp = F.\Delta t = M_{sat}.\Delta V$
    - Cold gas, hydrazine, bi-liquid
    - Electric propulsion (high Isp, low thrust)
    - Residual net force on the system (hence also changes the orbit)
  - Magnetic torquers
    - Interaction with Earth magnetic field
      $T = m \times B$
    - m = nIA, n number of rounds, I current, A area
    - LEO: acquisition/safe mode and RW desaturation

Cold Gas Thruster



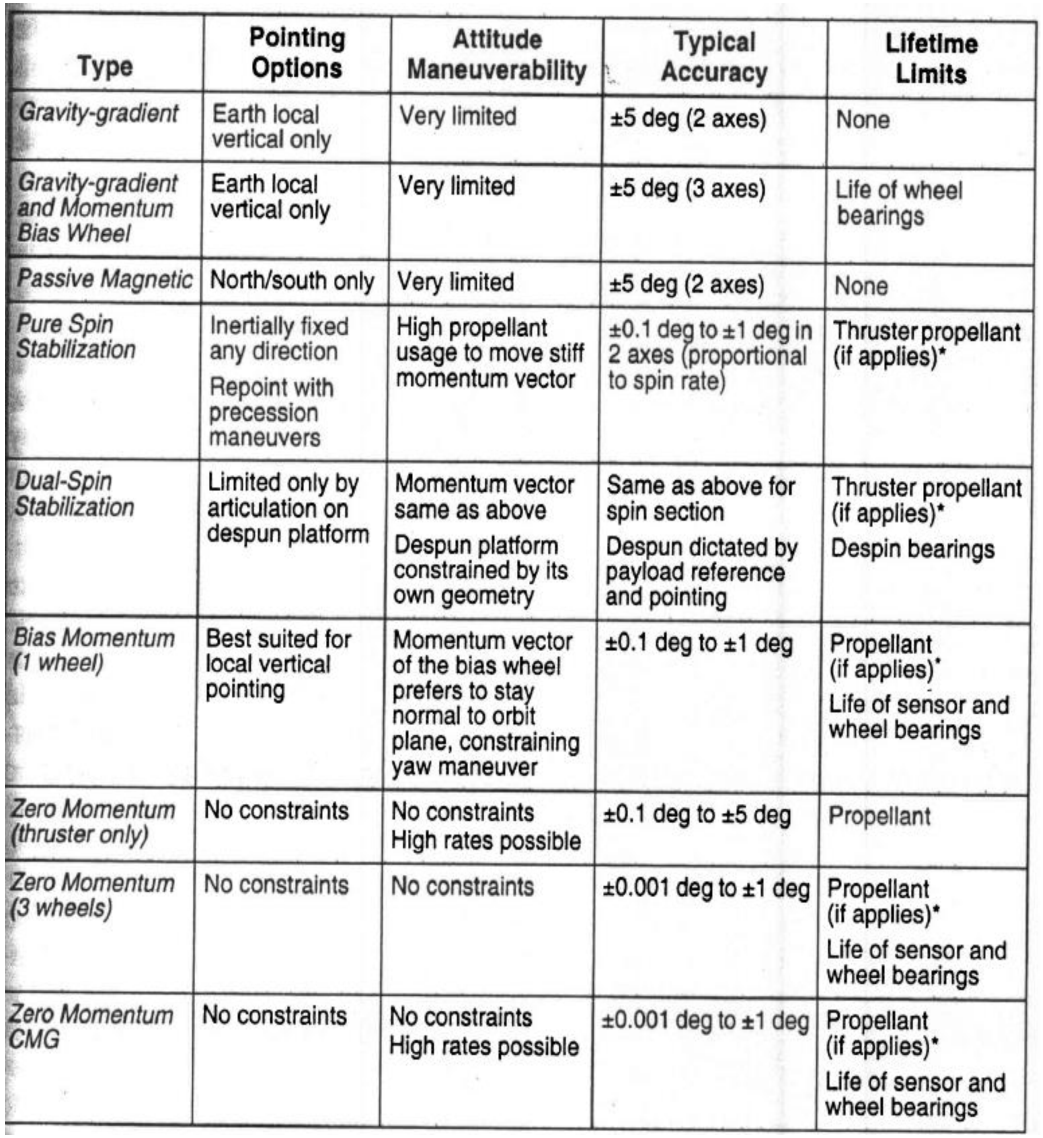
Solid Cold Gas Generator

Magnetic torquer

Attitude Control strategies

Attitude Control Strategies & Capabilities

- Passive
  - Gravity gradient
  - Aerodynamic
  - Spin (&dual spin)
  - *Magnetic*
- Active
  - Momentum Bias (MW)
  - Zero Momentum (THR, RW,CMG)
- To get full attitude determination, 2 reference directions are required (e.g Sun, magnetic field, stars, Earth horizon…)



Type	Pointing Options	Attitude Maneuverability	Typical Accuracy	Lifetime Limits
Gravity-gradient	Earth local vertical only	Very limited	±5 deg (2 axes)	None
Gravity-gradient and Momentum Bias Wheel	Earth local vertical only	Very limited	±5 deg (3 axes)	Life of wheel bearings
Passive Magnetic	North/south only	Very limited	±5 deg (2 axes)	None
Pure Spin Stabilization	Inertially fixed any direction Repoint with precession maneuvers	High propellant usage to move stiff momentum vector	±0.1 deg to ±1 deg in 2 axes (proportional to spin rate)	Thruster propellant (if applies)*
Dual-Spin Stabilization	Limited only by articulation on despun platform	Momentum vector same as above Despun platform constrained by its own geometry	Same as above for spin section Despun dictated by payload reference and pointing	Thruster propellant (if applies)* Despin bearings
Bias Momentum (1 wheel)	Best suited for local vertical pointing	Momentum vector of the bias wheel prefers to stay normal to orbit plane, constraining yaw maneuver	±0.1 deg to ±1 deg	Propellant (if applies)* Life of sensor and wheel bearings
Zero Momentum (thruster only)	No constraints	No constraints High rates possible	±0.1 deg to ±5 deg	Propellant
Zero Momentum (3 wheels)	No constraints	No constraints	±0.001 deg to ±1 deg	Propellant (if applies)* Life of sensor and wheel bearings
Zero Momentum CMG	No constraints	No constraints High rates possible	±0.001 deg to ±1 deg	Propellant (if applies)* Life of sensor and wheel bearings

Attitude Control Strategies - Passive

- Gravity gradient
  - Interact with gravitational field to maintain attitude (10^{-5}Nm)
  - Effective near Earth
  - Gravity-gradient torque must be greater than all other torques
    - Principal moment of inertia must be smaller than the others, causing the minor axis to align along the nadir vector
    - Ix+Iy>Iy>Ix>Iz CONSTRAINT
    - Booms are often deployed along the minor axis
  - Gravity-gradient torque causes the satellite to oscillate
    - passive damper is generally used

- Aerodynamic and solar pressure
  - Has been used in emergency or by design
  - Solar sails may use flaps for attitude control of the sail

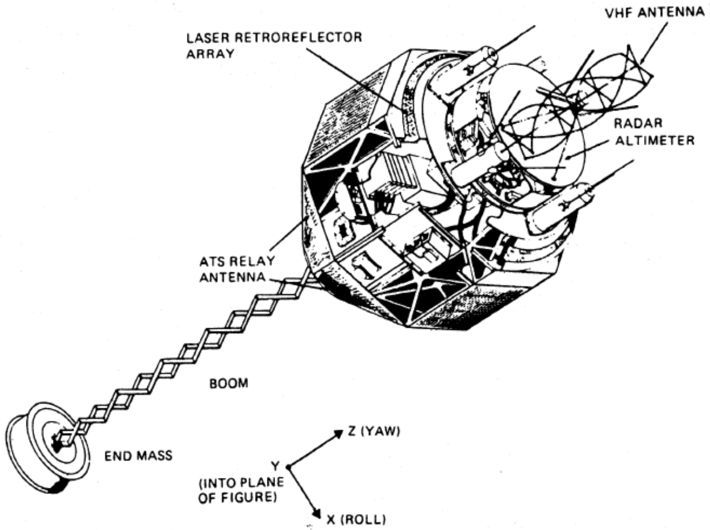
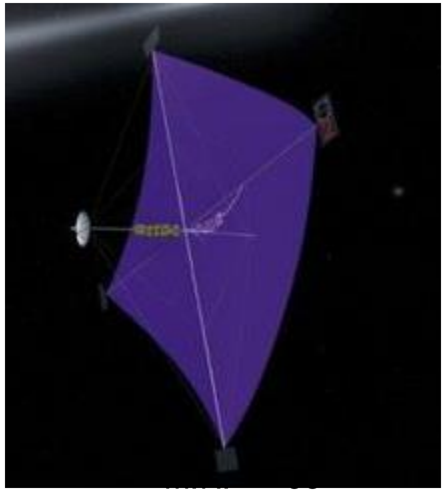
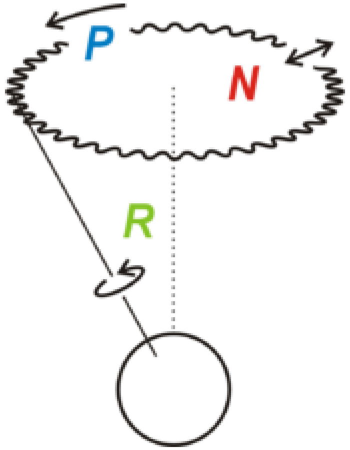


Fig. 19-17. GEOS-3 Spacecraft

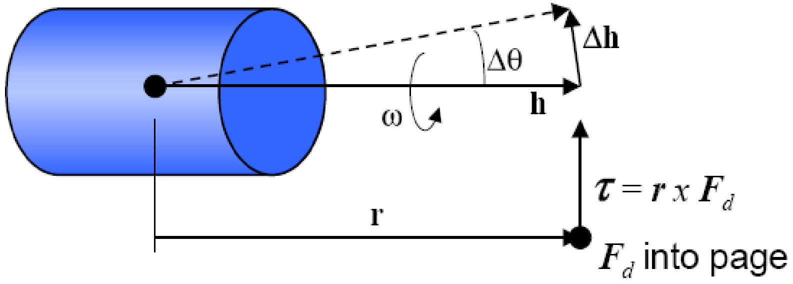


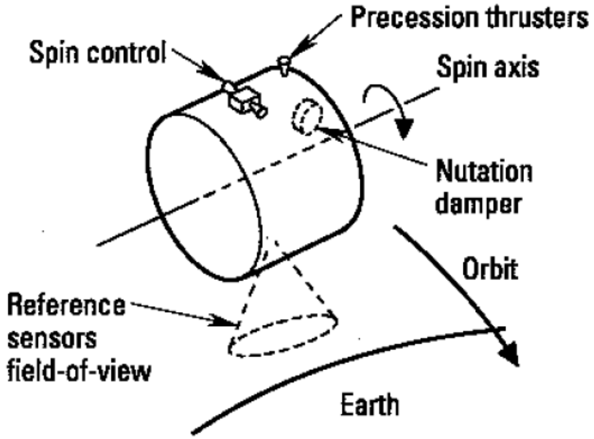
Attitude Control Strategies – Spin Control



- Spin stabilization
  - Gyroscopic stiffness of a spinning body maintains orientation in inertial space
  - Disturbance torques cause precession and nutation
    - May require a nutation damper
    - Requires torquers to control nutation (spin axis drift)
  - Usually requires an axis of maximum inertia so that **Iz >> Ix, Iy (Disk)**
    - Note that high Iz and/or large ω give gyroscopic stiffness

$$\Delta\theta = \frac{rF_d}{I\omega}\Delta t$$



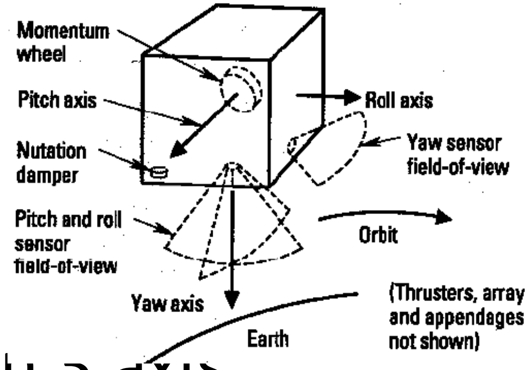


- Dual spin-stabilization
  - Two satellite components spin at different rates (one could be the satellite and the other a wheel)
  - A dual spin system provides platforms for both scanning and inertially fixed pointing instruments

Attitude Control Strategies - Active

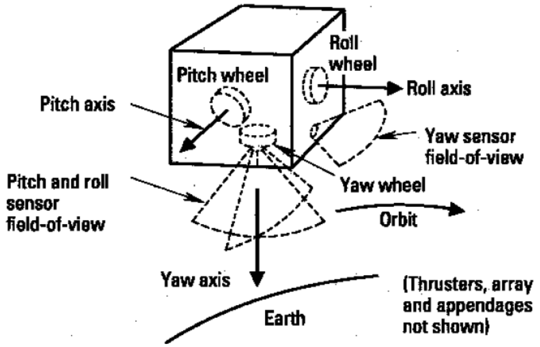
- Active 3-axis stabilization is more common but more complex and more expensive
    - Use combination of momentum wheels, reaction wheels, CMGs

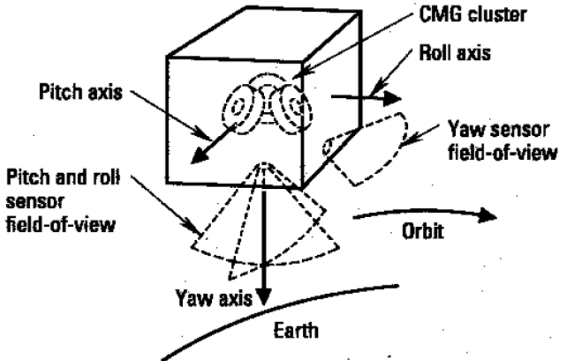
- Momentum bias system:
    - Use momentum wheel along pitch axis



- Zero-momentum bias system: wheels on 3 axis

Reaction Wheels	CMGs
Low maneuver rates	High maneuver rates
Low propellant needed for desaturation (unloading)	Low propellant use
3or4RWs? Different configuration	
Redundancy	



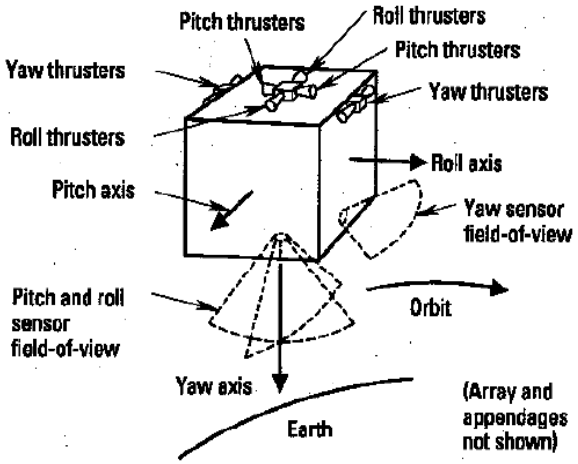


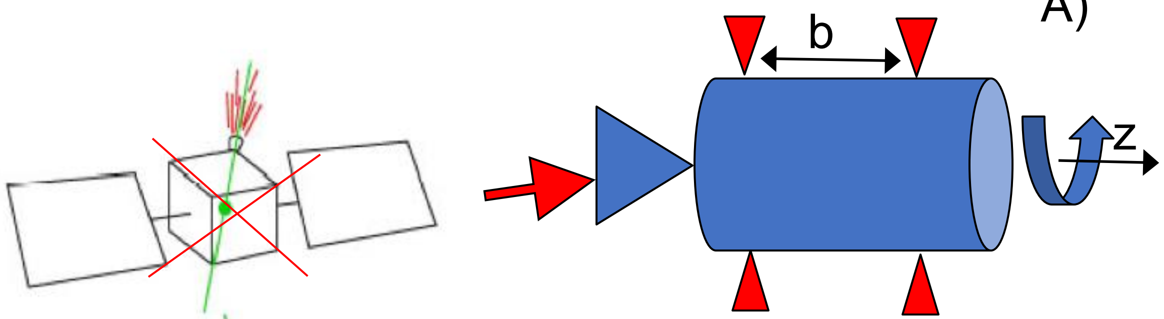
Attitude Control Strategies - Active

- Reaction Control System
    - High Maneuver Rates
    - Moderate Propellant Use
    - Shuttle, Voyager

A. Typical control of the Nutation at kick-stage (due to THR misalignment)

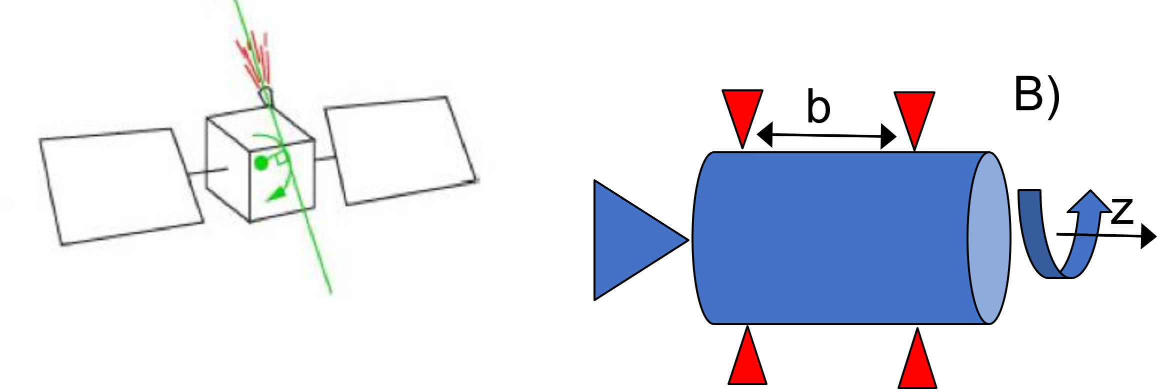
B. Typical DENUTATION (bang bang) (no THR-residual nutation)





$$F = \frac{2 I_z I_x T}{b H (I_z - I_x) \sin(2\theta)}$$

How much propellant?



$$F = \frac{\pi I_x \omega_{xy}}{4 t_{denut} b}$$

Attitude Determination and Control Algorithms

Dynamics fundamental principle:

- In an inertial frame (fixed wrt stars) Ri = (Xi, Yi, Zi)
- In satellite frame (attached to the satellite body):

$$T_{ext} = \left.\frac{dh}{dt}\right|_{Ri}$$

Euler Equations:

$$\vec{T}_{ext} = \left.\frac{\partial \vec{h}}{\partial t}\right|_{Rsat} + \vec{\omega} \times \vec{h}$$

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

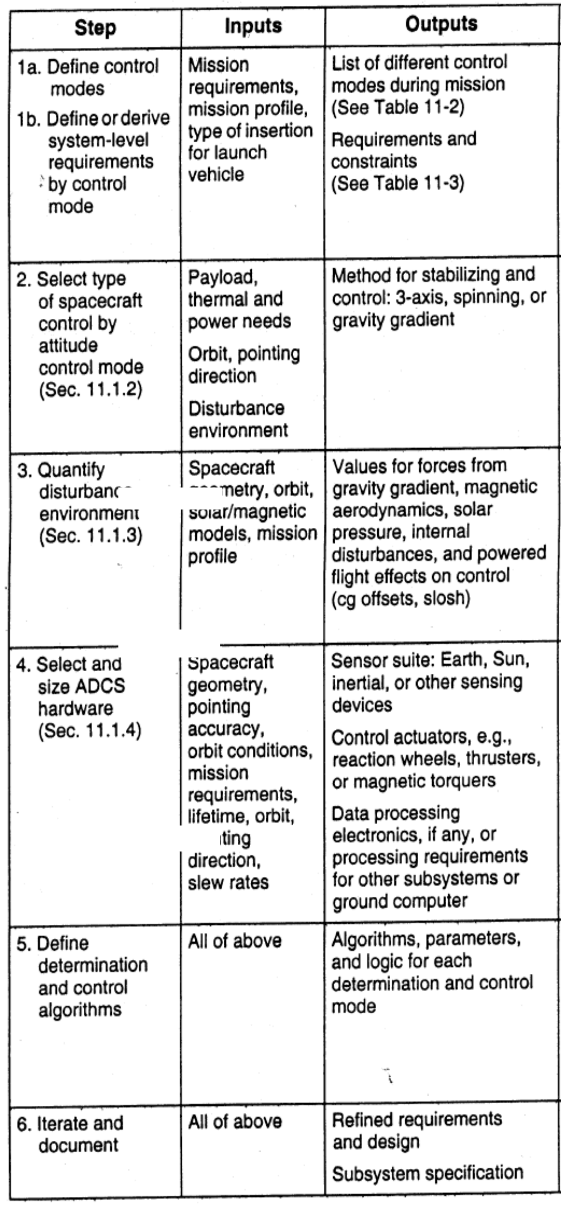
- The basic algorithms for attitude determination depend on the coordinate frames of interest and the geometry of the measurements
  - Use either Euler angles (roll, pitch, yaw)
  - Or Quaternions (scaled vectors for Eigen-axis rotations of coordinate frames)

- Sensor readings may be use some form of averaging, smoothing or Kalman filtering to increase accuracy of measurements

- Control requires good mathematical simulations of the entire system
  - Apply linear theory for preliminary analysis and design, then use non-linear effects

ADCS Design processes

ADCS Design Process



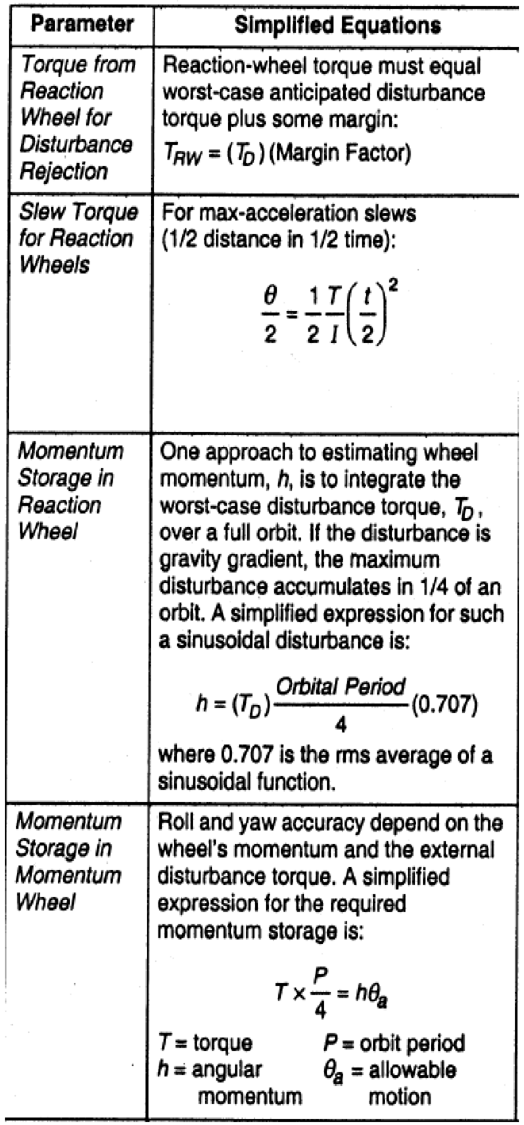
Step	Inputs	Outputs
1a. Define control modes 1b. Define or derive system-level requirements by control mode	Mission requirements, mission profile, type of insertion for launch vehicle	List of different control modes during mission (See Table 11-2) Requirements and constraints (See Table 11-3)
2. Select type of spacecraft control by attitude control mode (Sec. 11.1.2)	Payload, thermal and power needs Orbit, pointing direction Disturbance environment	Method for stabilizing and control: 3-axis, spinning, or gravity gradient
3. Quantify disturbanc environment (Sec. 11.1.3)	Spacecraft metry, orbit, solar/magnetic models, mission profile	Values for forces from gravity gradient, magnetic aerodynamics, solar pressure, internal disturbances, and powered flight effects on control (cg offsets, slosh)
4. Select and size ADCS hardware (Sec. 11.1.4)	Spacecraft geometry, pointing accuracy, orbit conditions, mission requirements, lifetime, orbit, ting direction, slew rates	Sensor suite: Earth, Sun, inertial, or other sensing devices Control actuators, e.g., reaction wheels, thrusters, or magnetic torquers Data processing electronics, if any, or processing requirements for other subsystems or ground computer
5. Define determination and control algorithms	All of above	Algorithms, parameters, and logic for each determination and control mode
6. Iterate and document	All of above	Refined requirements and design Subsystem specification

- Steps:
  1. Define control modes and requirements
  2. Define control strategy
  3. Quantify disturbances
  4. Select and size hardware
  5. Define determination and control algorithms
  6. Iterate and document

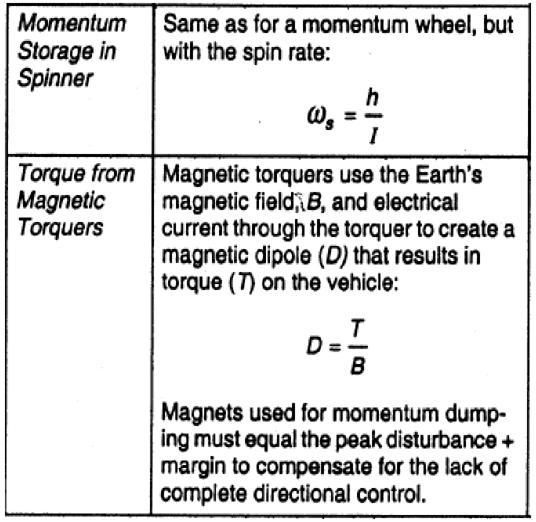
- ADCS performance to rarely driven by external torques. Those are often predictable to a large extent and compensated.

- Sensor and actuator (including internal disturbances , flexible/slosh) are ultimately limiting the system performance.

ADCS Design Process

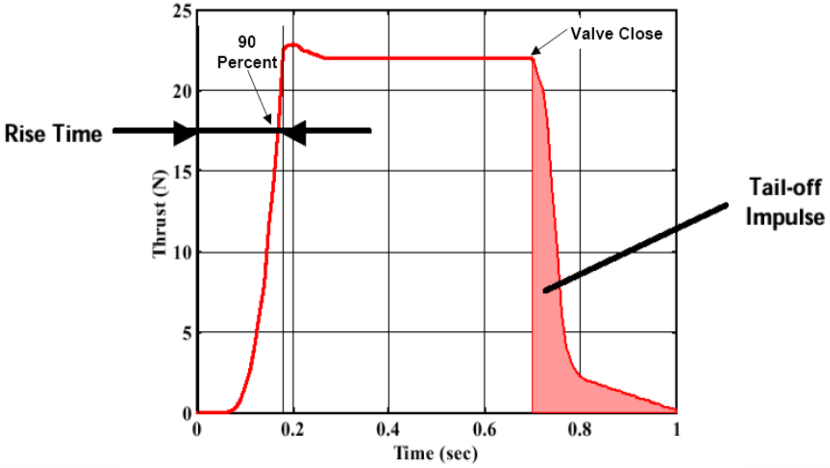


Parameter	Simplified Equations
Torque from Reaction Wheel for Disturbance Rejection	Reaction-wheel torque must equal worst-case anticipated disturbance torque plus some margin: $T_{RW} = (T_D)$ (Margin Factor)
Slew Torque for Reaction Wheels	For max-acceleration slews (1/2 distance in 1/2 time): $\frac{\theta}{2} = \frac{1}{2}\frac{T}{I}\left(\frac{t}{2}\right)^2$
Momentum Storage in Reaction Wheel	One approach to estimating wheel momentum, *h*, is to integrate the worst-case disturbance torque, T_D, over a full orbit. If the disturbance is gravity gradient, the maximum disturbance accumulates in 1/4 of an orbit. A simplified expression for such a sinusoidal disturbance is: $h = (T_D)\frac{\text{Orbital Period}}{4}(0.707)$ where 0.707 is the rms average of a sinusoidal function.
Momentum Storage in Momentum Wheel	Roll and yaw accuracy depend on the wheel's momentum and the external disturbance torque. A simplified expression for the required momentum storage is: $T \times \frac{P}{4} = h\theta_a$ T = torque h = angular momentum P = orbit period θ_a = allowable motion



Momentum Storage in Spinner	Same as for a momentum wheel, but with the spin rate: $\omega_s = \frac{h}{I}$
Torque from Magnetic Torquers	Magnetic torquers use the Earth's magnetic field, *B*, and electrical current through the torquer to create a magnetic dipole (*D*) that results in torque (*T*) on the vehicle: $D = \frac{T}{B}$ Magnets used for momentum dumping must equal the peak disturbance + margin to compensate for the lack of complete directional control.

- Actuator sizing simplified equations
  - When sizing wheel, it is important to distinguish between cyclic and secular disturbances, and between angular momentum storage and torque authority
    - Size the angular momentum capacity of a reaction wheel to handle the cyclic storage (for ¼ or ½ of the orbit)
    - Secular torque and storage capacity determine frequency of wheel desaturation
    - Pointing accuracy or slew requirements determine needed torque capability of the wheels
  - Size thrusters for external disturbances (secular), desaturation of the wheels, or slewing (bang-bang system)
    - Slew rate defines thrust level given a moment arm
    - Calculate minimum impulse bit to determine smallest repeatable impulse that the device can provide
    - Depending on mission needs, calculate number of pulses (thrust on/thrust off), and propellant mass required



Typical thruster operation

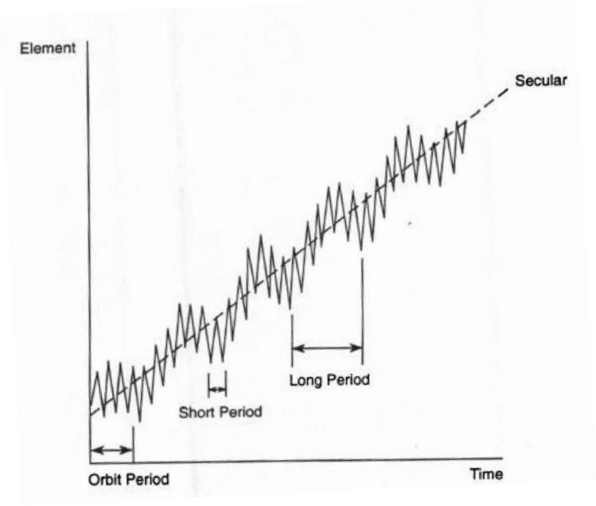
Orbital Control

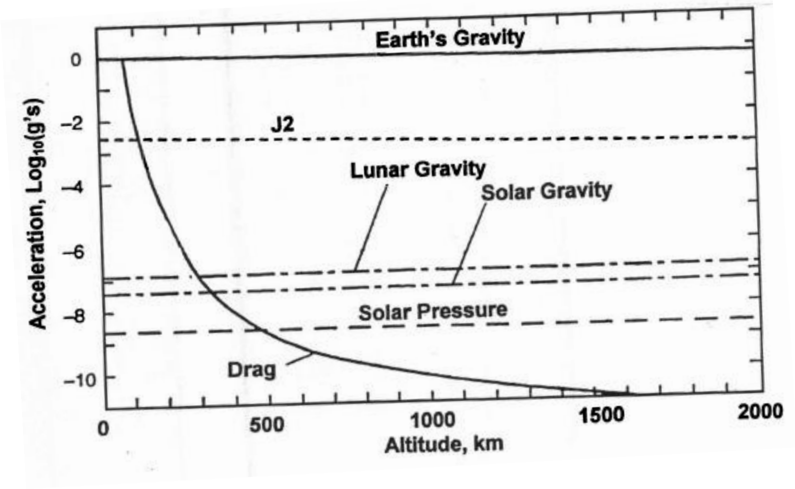
Orbit Perturbations and Maintenance

- Previous analysis of two-body motion made simplifying assumptions. These assumptions need to be revisited, as non-negligible perturbations exist.

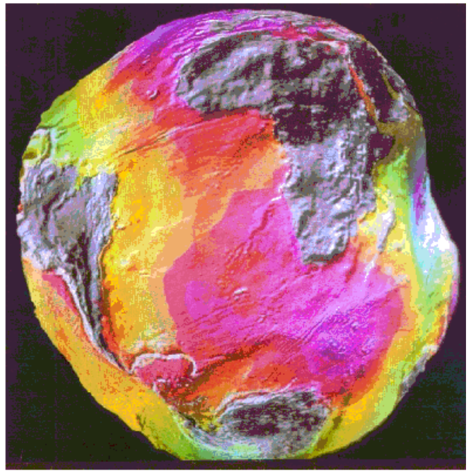
- Orbital perturbations include:
    - Oblateness of the Earth (non perfect symmetrical body, non-spherical gravitational field)
    - Atmospheric drag (additional force)
    - Attraction of the Sun and Moon (third body effects)
    - Solar radiation pressure (additional force)

- To overcome these perturbations, determination and control techniques must be applied
    - Techniques call for periodic readjustment of the attitude of the satellite and of the orbital elements





Earth's Gravitational Field Orbital Perturbations



- Earth is not a sphere
- Non-uniform distribution of mass
- Gravitational potential for a perfect sphere:

$$\Phi = -\frac{\mu}{r}$$

- For an oblate sphere:

$$\Phi = -\frac{\mu}{r}\left[1 - \sum_{n=2}^{\infty} J_n \left(\frac{R_E}{r}\right)^n P_n(\sin L)\right]$$

P_n: Legendre polynomials

- Most important terms:

$$J_2 = 0.00108263$$

$$J_3 = -2.54 \cdot 10^{-6}$$

- Impact: Regression of nodes:

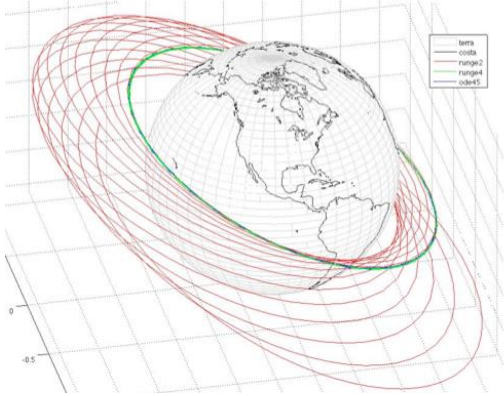
$$\frac{d\Omega}{dt} = \frac{-3nJ_2R_E^2\cos(i)}{2a^2(1-e^2)^2}$$

Rotation of apsides:

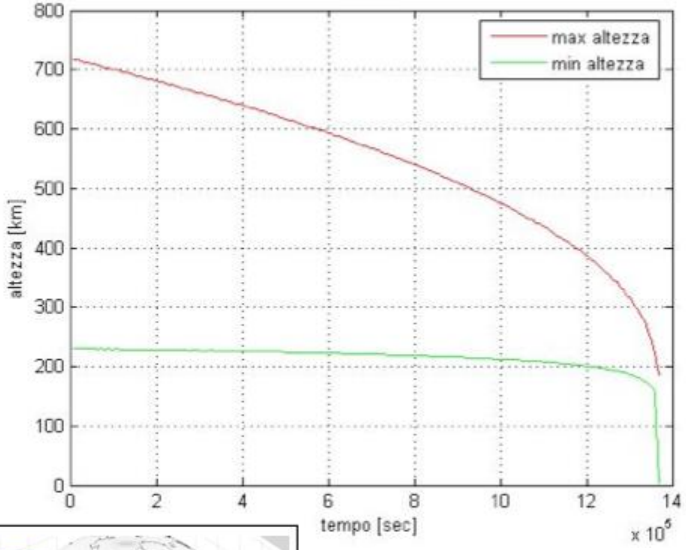
$$\frac{d\omega}{dt} = \frac{3nJ_2R_E^2(4-5\sin^2(i))}{4a^2(1-e^2)^2}$$

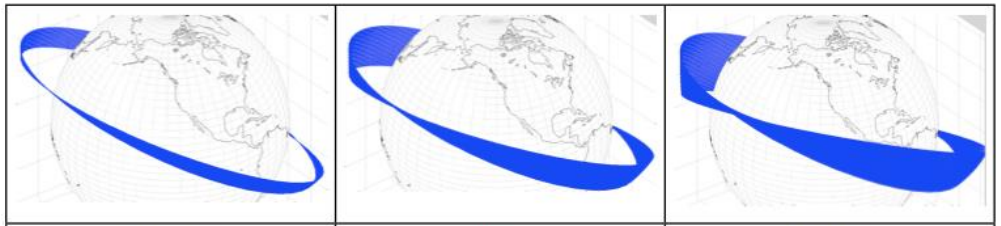
n: mean motion

Orbital perturbations - example



Precision of orbit propagation…





50 orbite *100 orbite* *150 orbite*

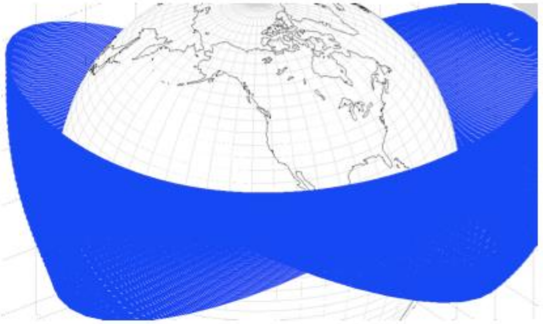
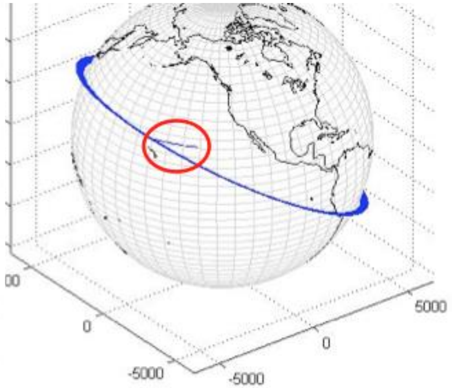
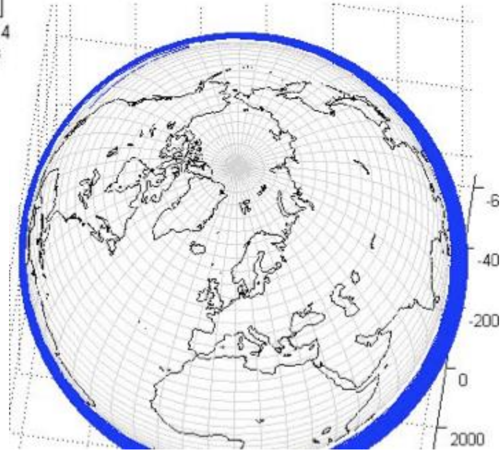


Figura.6.5: 500 orbite (47 giorni ca)

J2 influence on orbit





Atmospheric drag influence…

Conclusion and next steps

- Quizz what did we learn today?
- How you can apply what you have learned into your projects?

For your projects

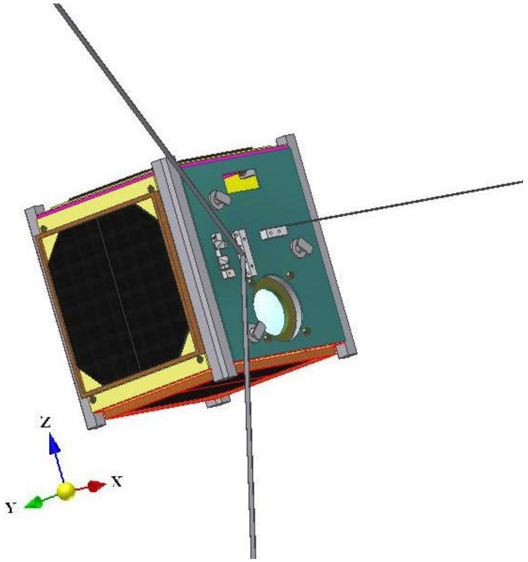
Design of ADCS subsystem

Taking into account a simple cubic structure and basic appendages (solar arrays or other), design and size the ADCS hardware using a design margin of 2 on the worst case torques.

You may have to define better the pointing requirements for your case (driven mostly by your science instruments and telecom). If too much uncertainty comes in, make the following assumptions:

Pointing accuracy < 0.1 deg.

Pointing stability < 0.01 deg/s



Secondary Propulsion (ADCS)

To save time, assume that the ΔV needed for control purposes is 10% of the total primary mission ΔV. Choose and size your secondary propulsion system (if you haven't done so during Propulsion HW), check Isp and calculate propellant mass.

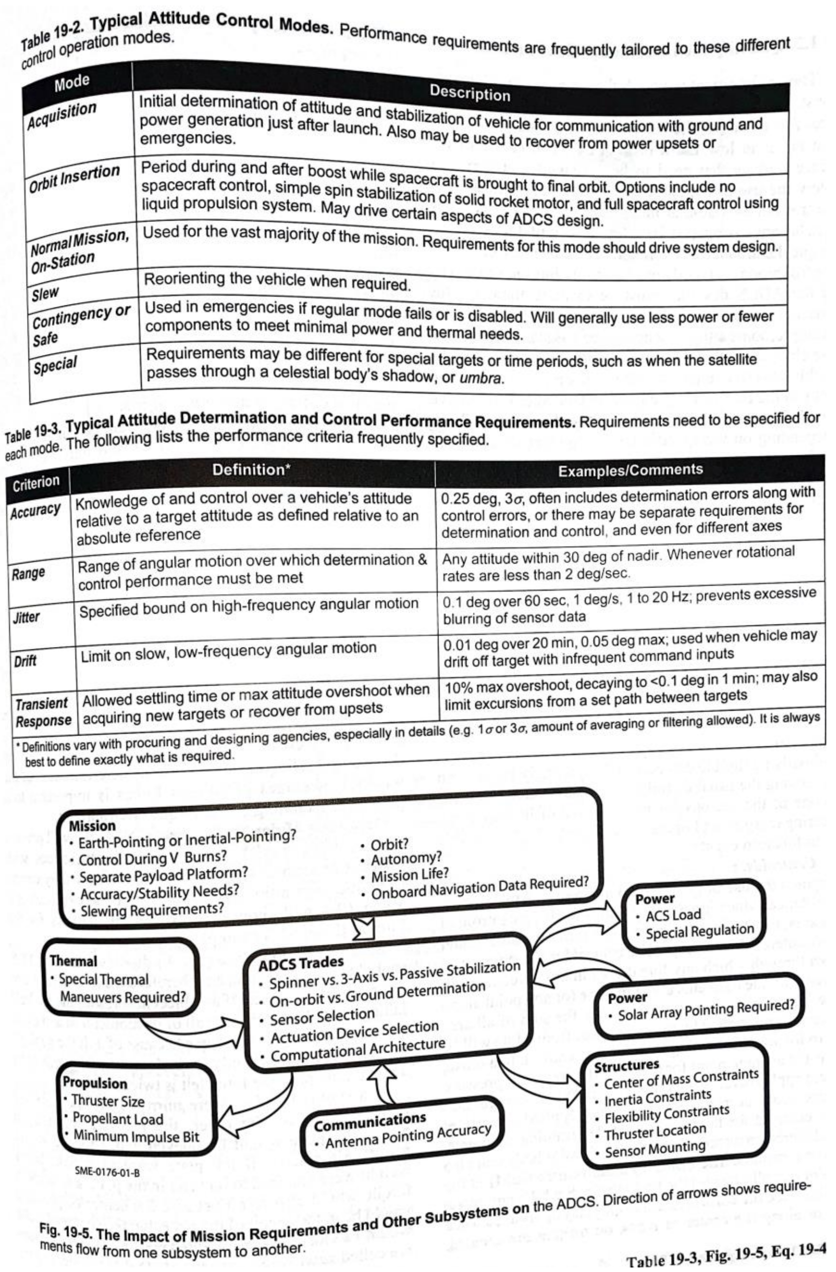


Table 19-2. Typical Attitude Control Modes. Performance requirements are frequently tailored to these different control operation modes.

Mode	Description
Acquisition	Initial determination of attitude and stabilization of vehicle for communication with ground and power generation just after launch. Also may be used to recover from power upsets or emergencies.
Orbit Insertion	Period during and after boost while spacecraft is brought to final orbit. Options include no spacecraft control, simple spin stabilization of solid rocket motor, and full spacecraft control using liquid propulsion system. May drive certain aspects of ADCS design.
Normal Mission, On-Station	Used for the vast majority of the mission. Requirements for this mode should drive system design.
Slew	Reorienting the vehicle when required.
Contingency or Safe	Used in emergencies if regular mode fails or is disabled. Will generally use less power or fewer components to meet minimal power and thermal needs.
Special	Requirements may be different for special targets or time periods, such as when the satellite passes through a celestial body's shadow, or *umbra*.

Table 19-3. Typical Attitude Determination and Control Performance Requirements. Requirements need to be specified for each mode. The following lists the performance criteria frequently specified.

Criterion	Definition*	Examples/Comments
Accuracy	Knowledge of and control over a vehicle's attitude relative to a target attitude as defined relative to an absolute reference	0.25 deg, 3σ, often includes determination errors along with control errors, or there may be separate requirements for determination and control, and even for different axes
Range	Range of angular motion over which determination & control performance must be met	Any attitude within 30 deg of nadir. Whenever rotational rates are less than 2 deg/sec.
Jitter	Specified bound on high-frequency angular motion	0.1 deg over 60 sec, 1 deg/s, 1 to 20 Hz; prevents excessive blurring of sensor data
Drift	Limit on slow, low-frequency angular motion	0.01 deg over 20 min, 0.05 deg max; used when vehicle may drift off target with infrequent command inputs
Transient Response	Allowed settling time or max attitude overshoot when acquiring new targets or recover from upsets	10% max overshoot, decaying to <0.1 deg in 1 min; may also limit excursions from a set path between targets

* Definitions vary with procuring and designing agencies, especially in details (e.g. 1σ or 3σ, amount of averaging or filtering allowed). It is always best to define exactly what is required.

Mission
- Earth-Pointing or Inertial-Pointing?
- Control During V Burns?
- Separate Payload Platform?
- Accuracy/Stability Needs?
- Slewing Requirements?
- Orbit?
- Autonomy?
- Mission Life?
- Onboard Navigation Data Required?

Thermal
- Special Thermal Maneuvers Required?

ADCS Trades
- Spinner vs. 3-Axis vs. Passive Stabilization
- On-orbit vs. Ground Determination
- Sensor Selection
- Actuation Device Selection
- Computational Architecture

Power
- ACS Load
- Special Regulation

Power
- Solar Array Pointing Required?

Propulsion
- Thruster Size
- Propellant Load
- Minimum Impulse Bit

Communications
- Antenna Pointing Accuracy

Structures
- Center of Mass Constraints
- Inertia Constraints
- Flexibility Constraints
- Thruster Location
- Sensor Mounting

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Fig. 19-5. The Impact of Mission Requirements and Other Subsystems on the ADCS. Direction of arrows shows requirements flow from one subsystem to another.

Table 19-3, Fig. 19-5, Eq. 19-4

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