Attitude and Orbit Control Systems (AOCS)

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Outline & Learning Outcomes

- **What is AOCS?**
- **Know your system & operating environment**

AOCS affecting factors

  - **Orbit Assumptions**
  - **External**: Body masses & Space Environment
  - **Internal**: Satellite inertia & operation mechanism

- **Know your design "tools"**

AOCS goal & usage

  - Measurements
  - Actuators
  - AOCS Strategies
  - Complexity

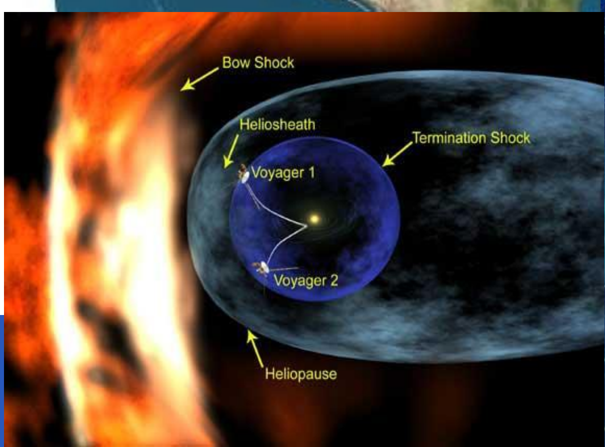
What is AOCS?

The Attitude and Orbit Control System (AOCS) provides attitude information <u>and</u> maintains the required spacecraft attitude and orbit during all phases of the mission

http://goes.gsfc.nasa.gov/text/databook/section11.pdf

In order to design an AOCS you need to:

1. Know your system & operating environment



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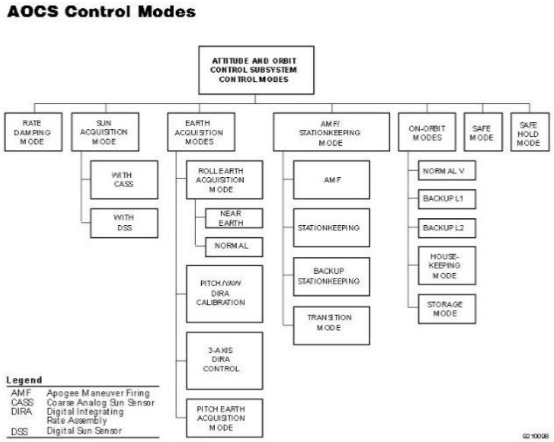
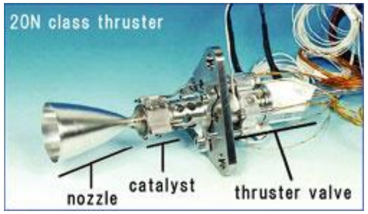
2. Know your design "tools"

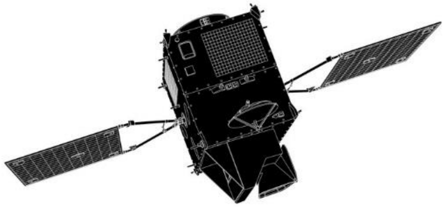
Control System Architecture & Strategy



Actuators



Dynamics



Sensors

AOCS affecting factors

1. Orbit Assumptions
2. External (Body masses)
3. External (Space environment)
4. Internal

Keplerian orbit theory under Newtonian attraction rests on several assumptions:

- Newtonian gravitation
- Point masses, or equivalently, spherically symmetric mass distributions
- Two bodies
- No other forces apart from gravitation

But in real world need to account for **non-Keplerian forces**, which are treated as:

- Small perturbations to the Keplerian motion
  ➔ leading to orbital elements which change slowly with time
- Instantaneous impulsive transfers
  ➔ analysis is treated in a similar way to the orbit transfers considered earlier

This breaks down when non-Keplerian forces are:

- *Similar to Newtonian gravity (e.g. in re-entry)*
- *Periodic with period comparable to the natural motion*

We will not consider these cases further here.

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

External (body masses)
- Non-sphericity of the earth (or other attracting body)
- The Moon and Sun
- Other Solar System bodies

External (space effects)
- Interaction with magnetic field
- Aerodynamic drag of residual atmosphere
- Solar radiation pressure

Internal
- Satellite inertia
- Operation of mechanisms

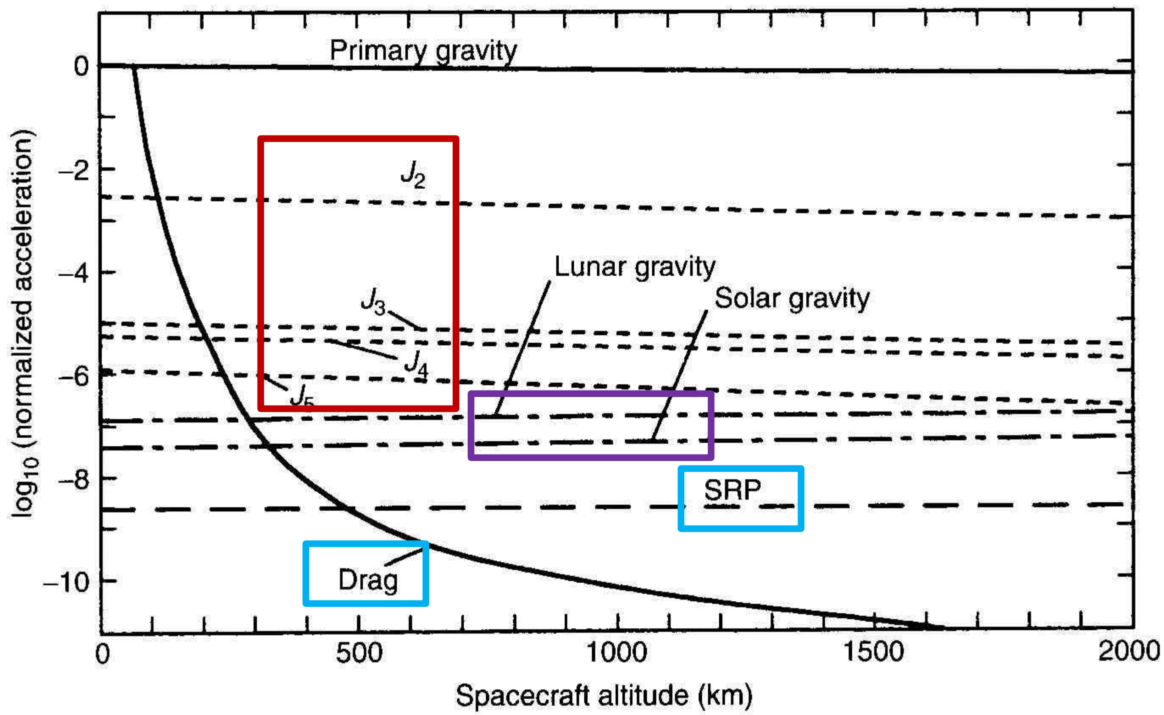
Affecting Factors – External

The main factors we have to take into account are:

- Non-Sphericity of the Earth
- Lunar-Solar Perturbations

Consequent Station Keeping requirements

- Aerodynamic Drag
- Solar Radiation Pressure



Affecting Factors – Non-Sphericity of Earth

Recall assumption: **Newtonian theory** is valid for finite size bodies (outside their radii), which possess spherically symmetric mass distributions.

However, we **need to consider effects of non-sphericity**, particularly for low orbits.

We have used for the PE of a body in the Earth's gravitational field:

$$-V(r) = -\frac{\mu}{r}, \text{ giving } \mathbf{F} = -\frac{\mu \mathbf{r}}{r^3}, F = -\frac{\mu}{r^2}$$

μ=GM
G=gravitational constant
M=total mass
r=planet radius

It can be shown that the full expression is :

$$\boxed{V(r) = \frac{\mu}{r}}\left[1 - \sum_{n=1}^{\infty}\left(\frac{\mathrm{R_e}}{\mathrm{r}}\right)^n \boxed{J_n} P_n(\sin\phi) + \sum_{n=1}^{\infty}\sum_{q}^{n}\left(\frac{\mathrm{R_e}}{\mathrm{r}}\right)^n \boxed{J_n} P_n(\sin\lambda)\cos q\left(\Lambda - \Lambda_{nq}\right)\right]$$

Λ is longitude of satellite from Greenwich, positive toward the East.

Λ_{nq} (-15°) is a constant describing the longitudes (-15°, 165°) of the minima in the Earth's potential

λ is latitude of satellite, positive toward the North.

$\mathbf{R_e}$ is mean Earth radius, 6378.16 km

Affecting Factors – Non-Sphericity of Earth

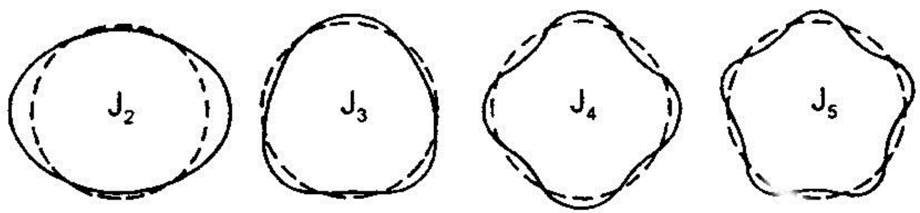
J_n, J_{nq} represent the deviations of the geopotential from perfect sphericity.

J_n are the coefficients multiplying P_n

P_n are the functions of increasing "frequency of waviness" from equator to poles of the Earth, which describe the deviation from a spherical figure, e.g. Polar Flattening.

The values from J_2 to J_5 obtained for the Earth and the qualitatively sketched deformations resulting from them are as follows:

$$J_2 = 1083.9 \cdot 10^{-6} \quad J_3 = -2.4 \cdot 10^{-6} \quad J_4 = -1.3 \cdot 10^{-6} \quad J_5 = -0.2 \cdot 10^{-6}$$



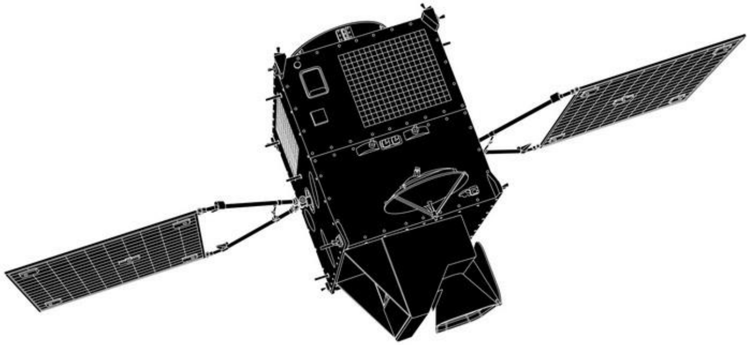
Real "shape" of the geopotential is obtained by linear weighted sum of spherical harmonics, from the first order term (the "point mass") to higher harmonics representing increasing spatial detail of the earth's mass distribution up to an infinite number of terms.

In practice, it is unnecessary to take into account more than the first few terms.

Dynamic Properties

Main effects are the **spacecraft mass properties & dynamic behaviour**:

- Satellite Structure
- Moments of Inertia
- Sloshing / Wheels

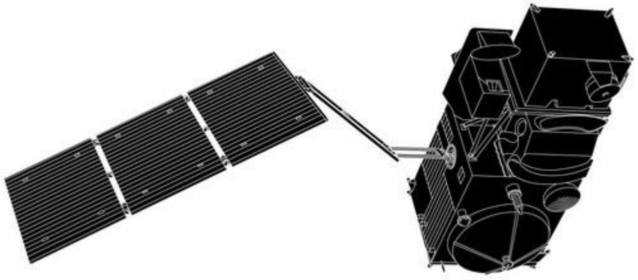


Dynamic Properties

Particular set of problems arises from **large components deployed in Space**, possibly non-linear: solar panels, antennas ...

These will exert an influence on the AOCS operation out of all proportion, due to their dynamics being dominant, or worse, unknown.

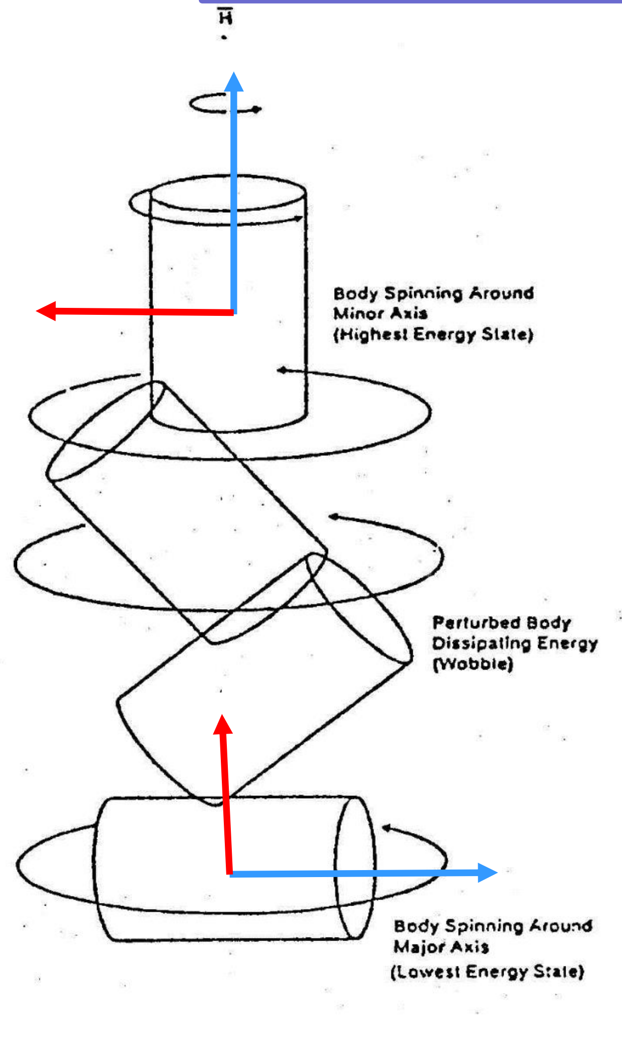
This is the case of "tail wagging the dog"".



Dynamic Properties

Ratio of principal moments of inertia is very important, because spacecraft will preferentially rotate about axis with highest moment of inertia, ➔the lowest energy state of the total system.

If rotation is initially about some other axis, and there is some energy loss mechanism, e.g. sloshing fuel or loose structure, then it will tumble into its lower energy mode eventually.



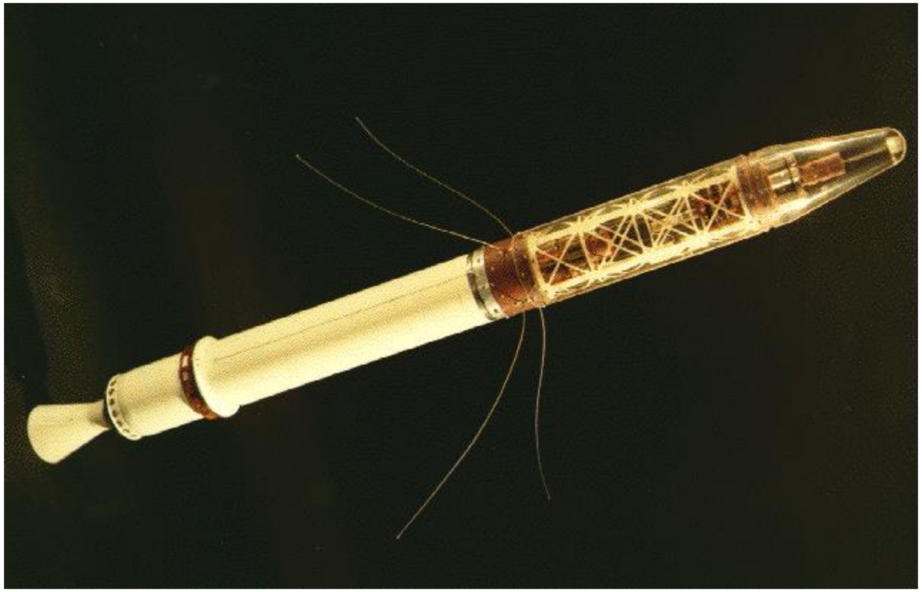
∴ Spinning Body is stable only about Major Axis

Affecting Factors – Moments of Inertia

This problem occurred on the first **US satellite, Explorer 1**

It was a slim cylinder, intended to be spin-stabilised about its long axis.

After a relatively short time it was tumbling uncontrollably due to loose structure.



AOCS goal & usage

Previous effects must be countered by the AOCS:

Translation ➔ by sensing deviation from desired orbit
and controlling with thrusters

Rotation ➔ by sensing deviation from desired attitude
and controlling with torque actuators

In both cases, forces & torques required are extremely small, and generally no attempt is made to directly counter them, AOCS merely tries to sense & minimize the deviations.

Translation Measurement

of instantaneous orbital elements of SC orbit are generally done externally

(with radar or optically, although limited GPS possible for some orbits)

*Accelerometers on board will **not** give us its motion as in a terrestrial airborne INS,*

since gravity acts equally on spacecraft and accelerometer test mass.

Translation Actuators

are generally monopropellant thrusters, although cold gas are still in limited use, and electric (ion) thrusters are being used for the first time.

All, singly or in combination, are **operated through the SC center of gravity.**

Most reaction devices operate on a **minimum control impulse**, or “impulse bit”, basis, which makes true linear proportional control impossible.

Also, the **thrust available is deliberately very limited** (a few N maximum)

Translation Control Strategy

Rarely done fully autonomously, or in real-time, but rather from a manned dedicated ground control station.

Do not directly adjust 3-dimensional motion of spacecraft, rather change its orbit by the transfer maneuvers already discussed (or variants)

Orbit correction strategy is counterintuitive:

Changes in perigee are made by corrections at apogee (and vice versa)

Apogee maneuvers are preferable from a fuel budget point of view, since changes are made to a smaller velocity vector.

In a few cases, orbit requirement can be satisfied using non-sphericity of Earth
➔passive orbit controller: e.g. sun-synchronous polar orbits or Molniya orbits

Attitude Measurement

generally done internally with optical instruments

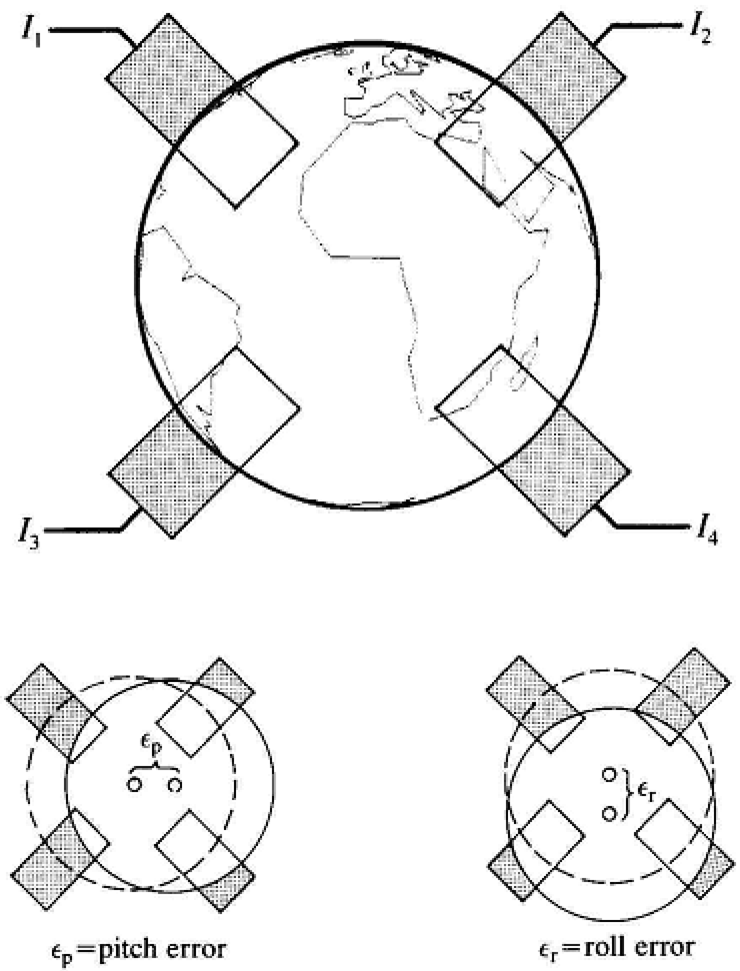
measuring SC attitude with respect to Earth horizon or terminator (sunset/sunrise), Moon, Sun or other stars

For very accurate attitude control, start-trackers with internal maps are used

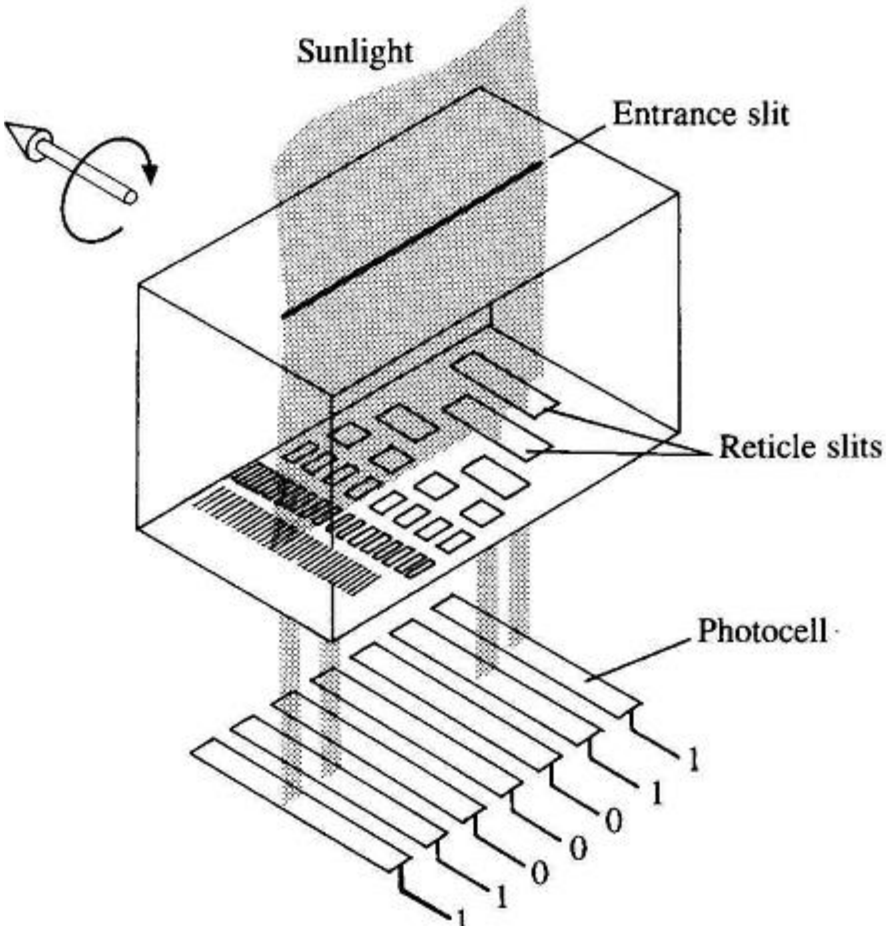
Attitude Control in Rotation

Examples of Earth and Sun Sensors

Static earth sensor for three-axis-stabilized spacecraft.



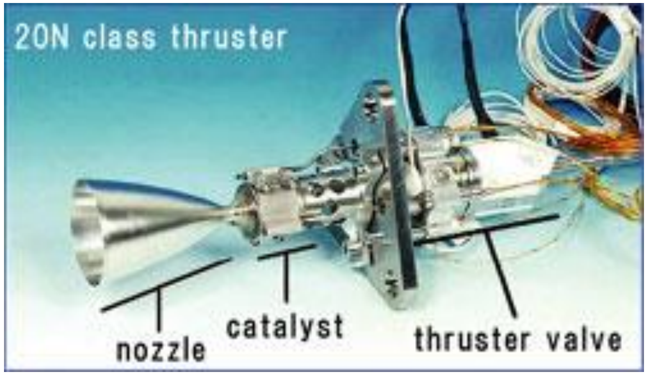
Digital sun sensor, type Adcole.

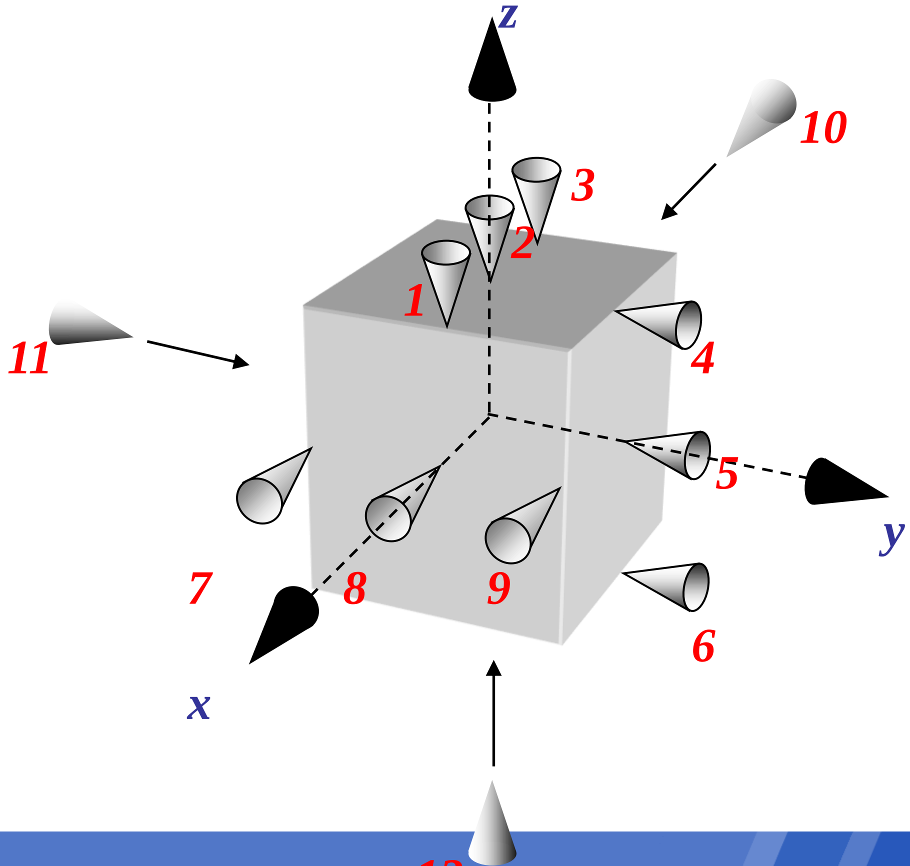


Attitude Actuators

Reaction thrusters

Control torques are provided by thrusters, usually the same devices used for translation, operated in equal and opposed pairs to provide torque but no net force.





Attitude Actuators

Gyroscopic devices

Reaction wheels- flywheels which can be rotated in one direction or the other, the reaction changing the spacecraft attitude - the nominal rotation rate being zero. Requires mechanisms which start and stop.

Momentum wheels - flywheels which rotate at a nominal fixed rate, which can be speeded up or slowed down within an operational r.pm band , the reaction to the speed change changing the spacecraft attitude. Do not require mechanisms which start and stop, but possess gyroscopic stiffness which introduces cross-coupling into multi axis control systems.

Attitude Actuators

Gyroscopic devices

Momentum wheel with cover removed showing integrated drive electronics. The wheel illustrated is the RDI 68 (Reproduced by permission of TELDIX GmbH)

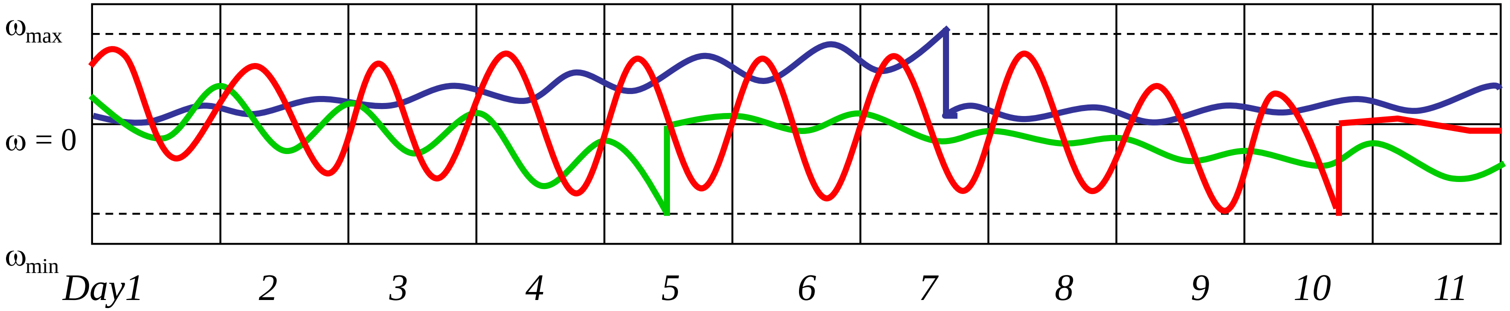
Attitude Actuators

Goals & Usage – Rotation Attitude Control

Gyroscopic devices

In both cases, reaction thrusters are also necessary.

Disturbing torques are often in one predominant direction,
thus reaction control must be used to rebias the reaction wheels back to zero,
or momentum wheels back to nominal r.p.m.



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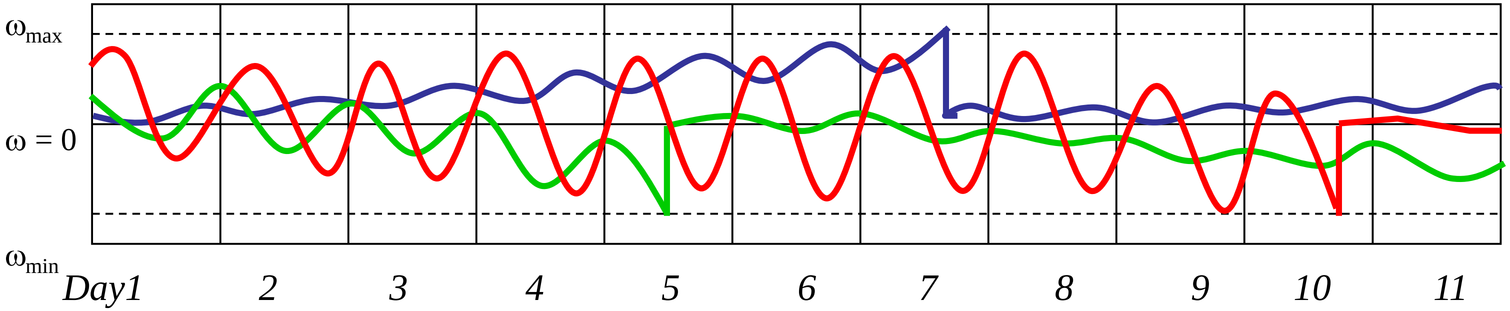
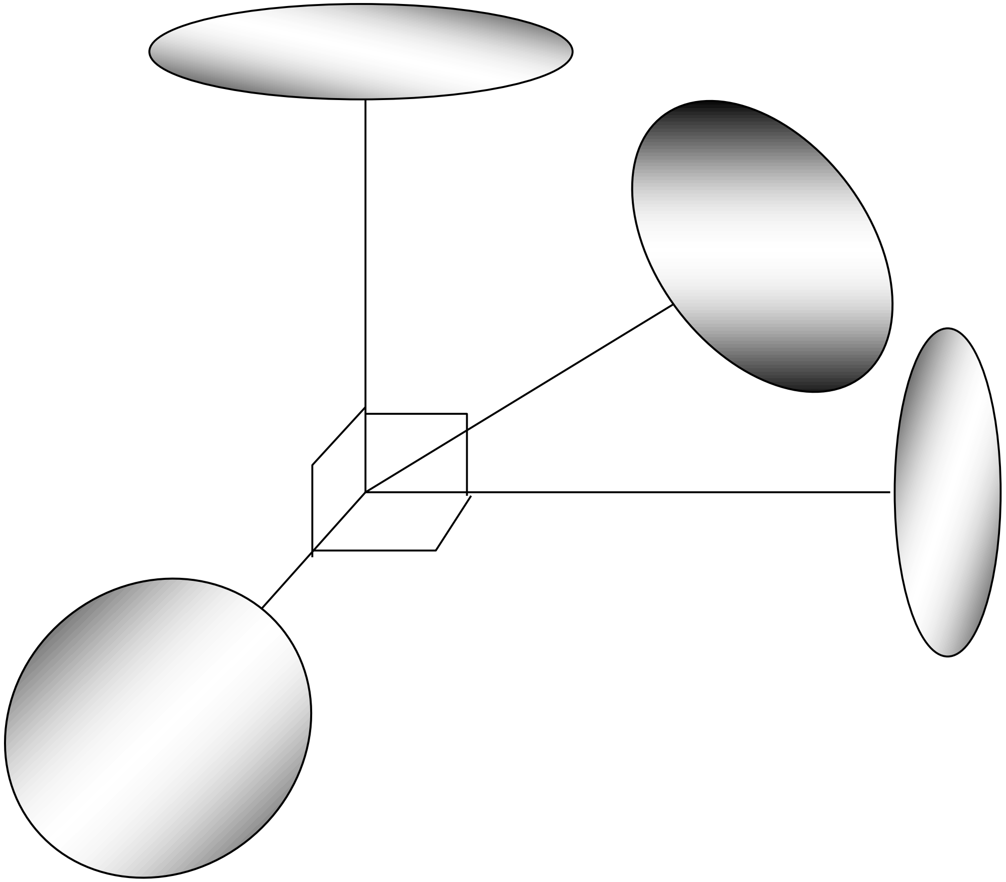


This enables overcoming disadvantage of thrusters “minimum impulse bit", with linear control through gyro-devices relatively simple.

In all cases there must be enough devices to provide 3-axis control - this means 3 perpendicular reaction or momentum wheels, with a fourth with angular velocity components in all 3 principal axes for redundancy

Goals & Usage – Rotation Attitude Control



Attitude Actuators

Magnetorquers

The spacecraft, usually axisymmetric, is provided with a multi-turn coil, through which the electrical supply can be switched in either sense, to provide a switchable magnetic dipole moment **μ** which interacts with the planetary magnetic field **B** to provide an attitude changing torque **μxB**.
This has the very great advantage of being free on the fuel budget, but at the cost of complexity and hence unreliability in the electrical system. It also requires an accurate magnetic field model to exist for precise control, which is not easy in periods of solar activity.

Magnetic torquers. The three torque rods shown are those used on the EURECA spacecraft, and are each in excess of a metre in length (Reproduced by permission of Fokker Space bv)

Spacecraft ACS classes

Spin-Stabilised

We can use the whole spacecraft as a gyroscope, which will then resist attitude changing torques by gyroscopic stiffness - the resulting precession may be tolerable for the particular application.

The attitude must then be changed by first inducing controlled precession, and then negating it, by opposed thrusters producing perturbation torques, first in one direction then the other.

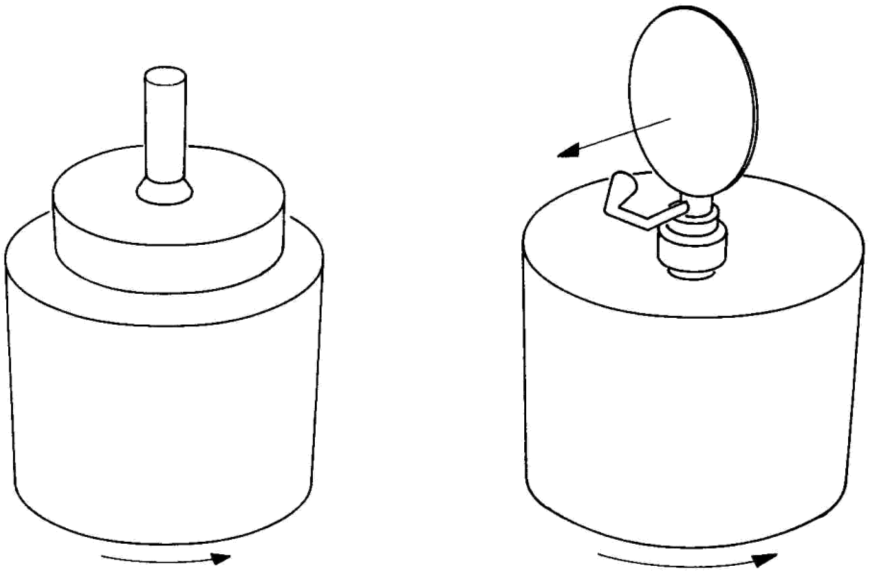
It is the precession that produces the attitude change, not the thrusters; they merely turn the precession on and off.

Spacecraft ACS classes

Spin-Stabilised

The spin stabilised configuration, with payload sensors boresighted on the spin axis, or looking out sideways and using the spacecraft rotation to scan the outside world, may be well suited to a particular application.

(Left). Satellite spin stabilization concept. (Right). Satellite dual spin stabilization concept.



If it is not, but still is attractive from an ACS point of view, the Dual Spin or Despun Platform configuration may be used. This retains the advantages of the Spin-Stabilised configuration at some cost in extra complexity, and possible dynamics problems.

3-Axis

Spacecraft is treated as an aircraft ➔ separate control /actuation per principle axis

If it is asymmetric or there are momentum wheels (or any other gyro machinery) then there may be some cross-couplings between axes.

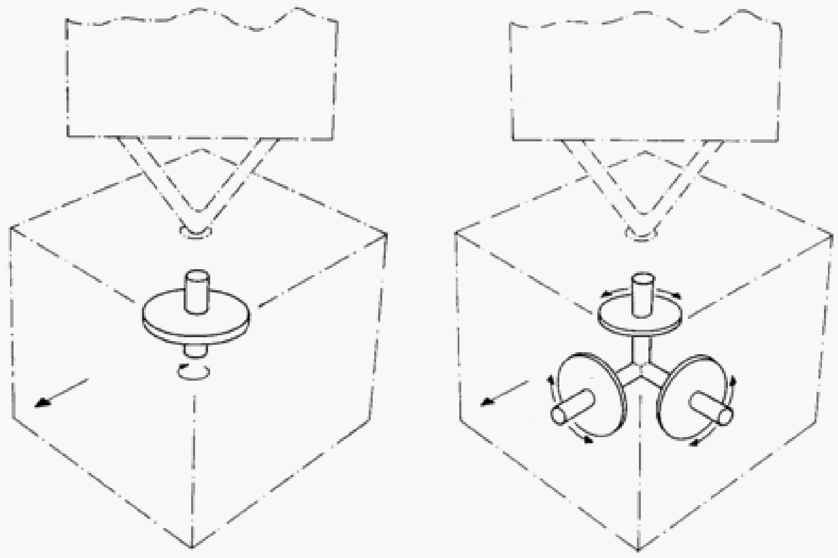
In general, multi-axis control schemes are not used since everything happens very slowly, and cross-coupling torques are just treated as independent perturbations

Most spacecraft are of this type today:

conceptually simple but require more actuators

yielding larger flexibility during operation

(Left). Satellite three-axis stabilization concept using a bias momentum wheel. (Right). Satellite three-axis stabilization concept using reaction wheels.



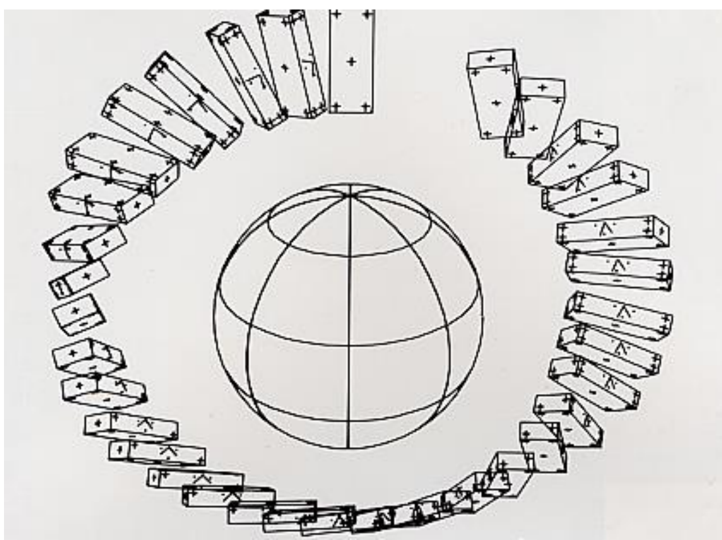
Gravity Gradient Stabilization

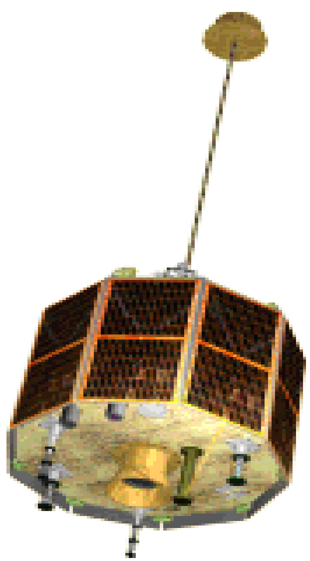
Any spacecraft in an inverse square gravity field will experience a restoring torque when its long axis deviates from the local vertical.

This is effectively the tidal force raised by the gradient of the gravity field across it.

It can be used as an effective ACS strategy in 2-axes if:
the “long-thin” configuration & the plane-pointing fit well with the application.

The third axis is usually dealt with by a single reaction wheel.





Situation may be further complicated by:

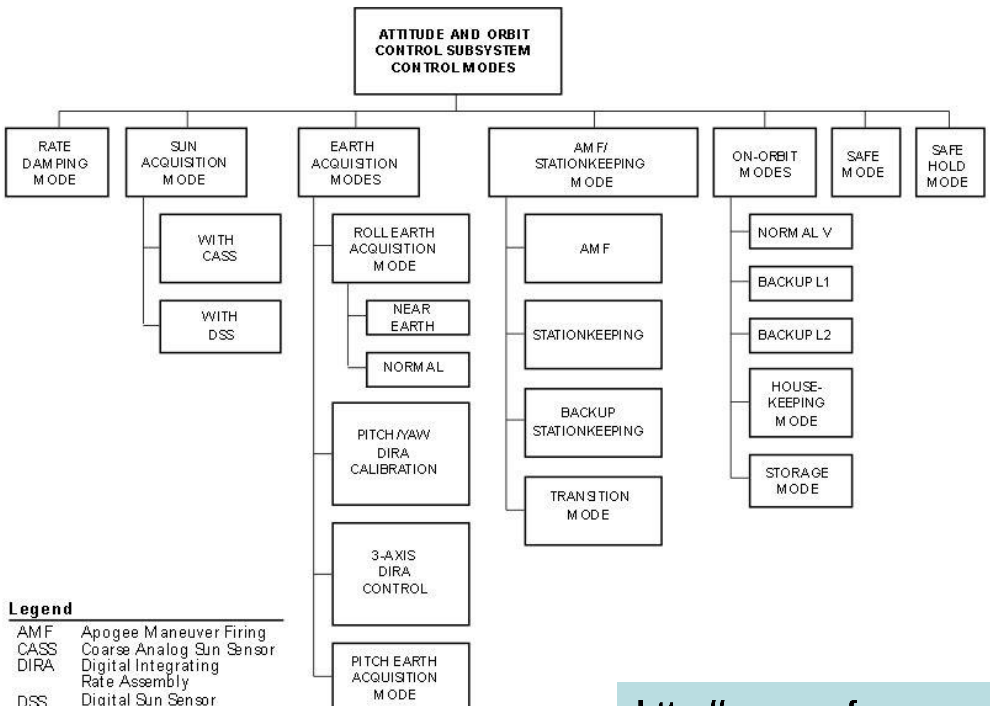
- **Requirements for independent operations**:

  e.g. pointing solar array at Sun (to guarantee power supply) or payload fine pointing

- **Different mission phases**

  which may result in independent sets of sensors and control laws.

AOCS Control Modes



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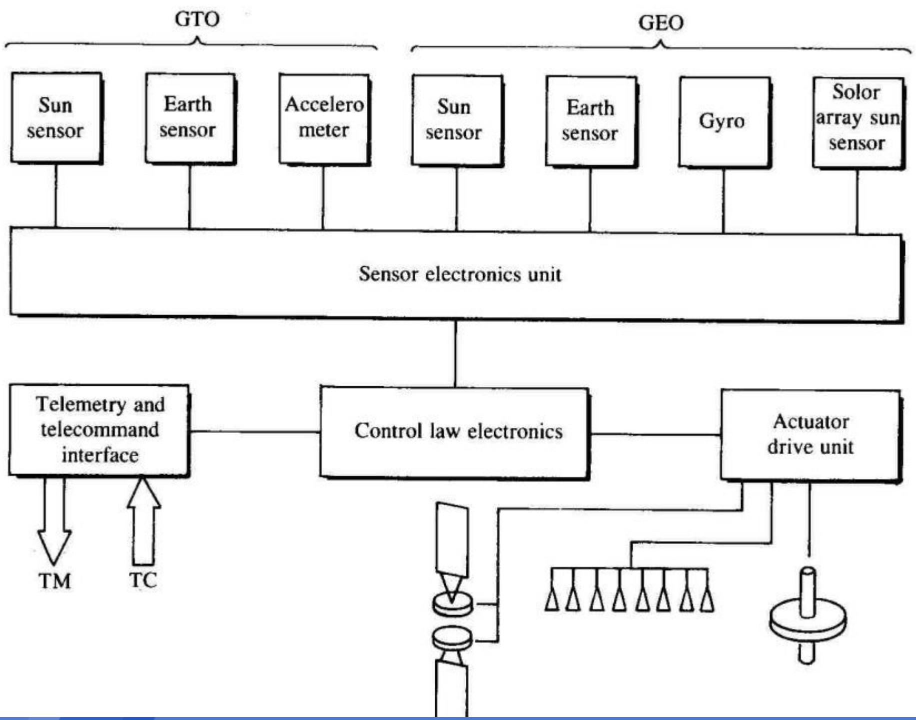
Goals & Usage – AOCS Complexity

Geostationary (GEO) spacecraft have fairly simple AOCS with requirements on pointing of:

- Solar array to the Sun
- Payload antennas to Earth
- In a slowly changing geometry (1°/day)

But in the geostationary transfer orbit (**GTO**), things happen much more rapidly, and the geometric relationships change requiring an independent control strategy.

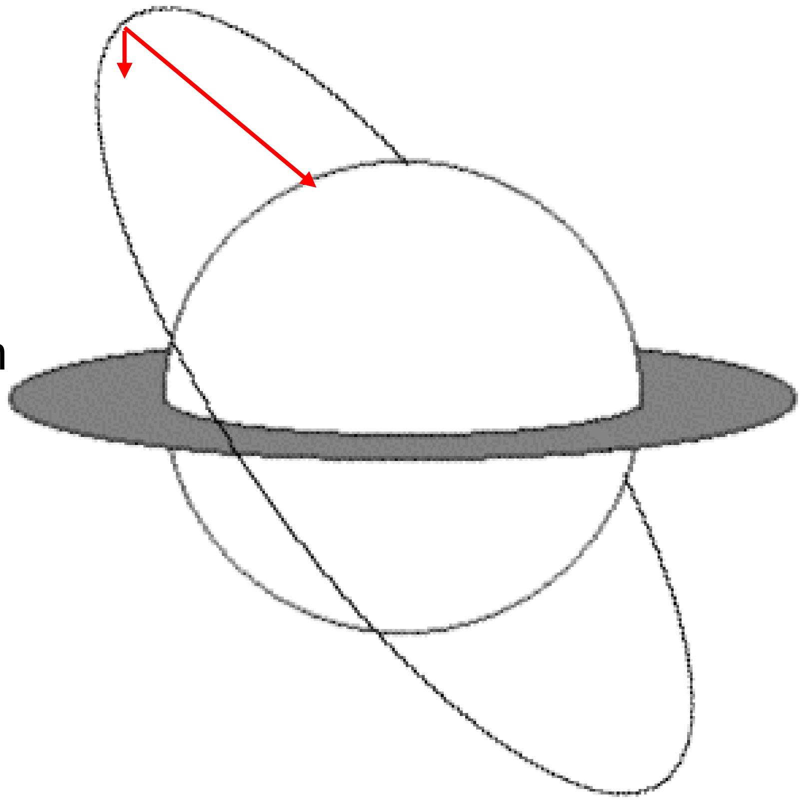
Attitude control subsystem architecture for a three-axis-stabilized spacecraft.



Extra

Polar Flattening

(Simplified Physical Explanation of NS-effect)



Positive J_2 ➔ flattened sphere
which may be modelled by a:

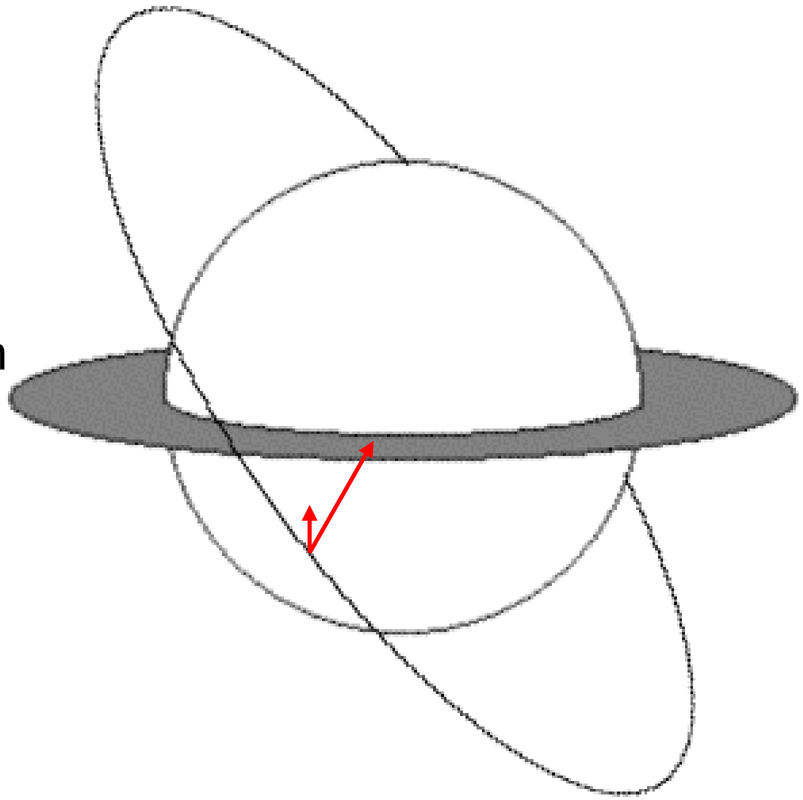
- spherically symmetric mass distribution
- with an added equatorial disc

This results in an extra restoring force toward the equatorial plane in the z-direction.

Affecting Factors – Non-Sphericity Effects

Polar Flattening

(Simplified Physical Explanation of NS-effect)



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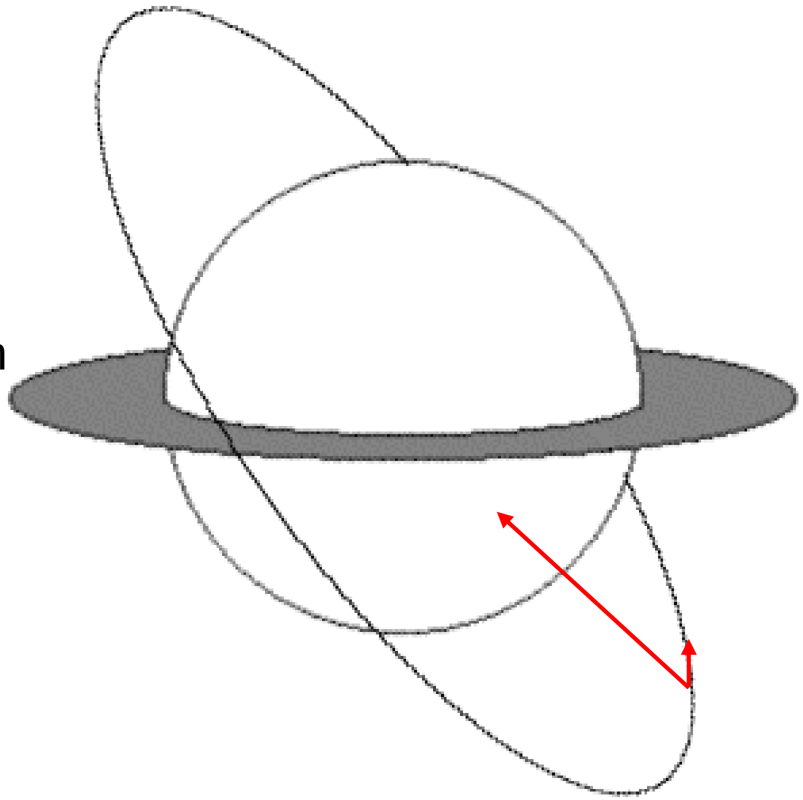

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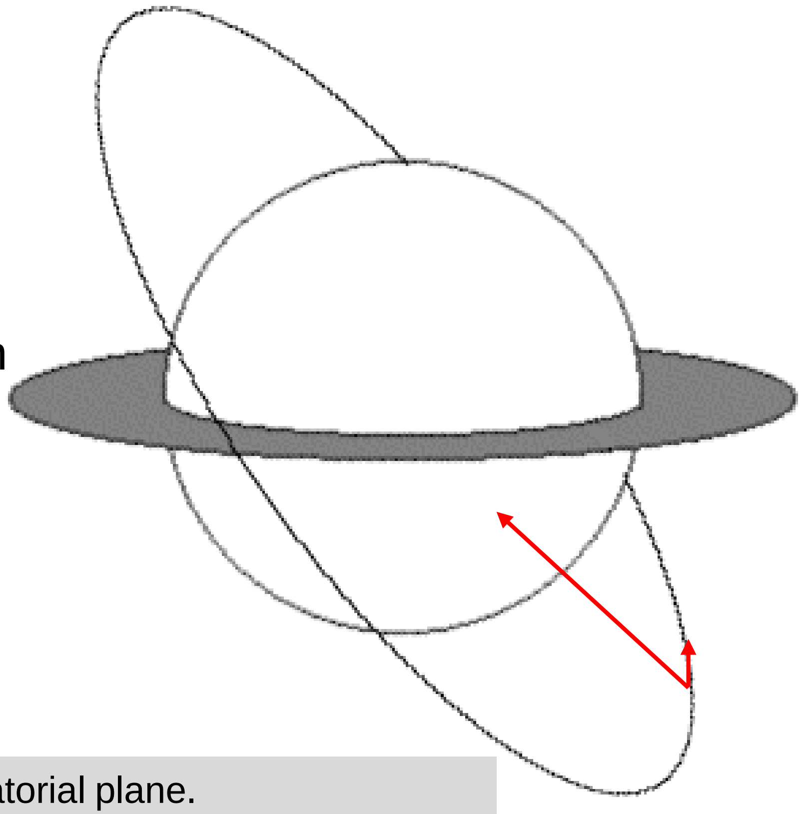

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- with an added equatorial disc

This results in an extra restoring force toward the equatorial plane in the z-direction.

In Z-DIRECTION ➔ motion perpendicular to the equatorial plane.

a. Period is decreased slightly, since restoring z-axis acceleration is increased
b. Times of traversal of equatorial plane are earlier than should be.
Thus the line of nodes is no longer fixed, but regresses backwards.