Spacecraft Dynamics

Lesson 1: Introduction to Attitude Dynamics and Control and to ADCS (Attitude Determination and Control System)

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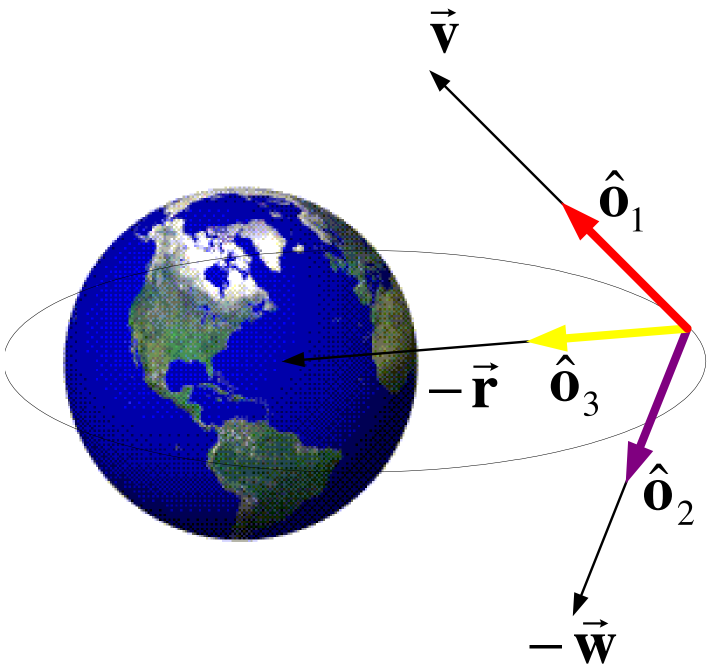
Introduction I

- The great majority of spacecraft have instruments or antennas which must point to one direction. For example:
  - Space telescopes (Hubble).
  - Communications satellites must point their antennas.
  - Solar panels must maximize their solar exposition.
  - Photography cameras must point to one location.
  - Radiators must be pointed to deep space.
  - The thrusters of a spacecraft must be correctly aligned.
  - Other scientific instruments and sensors.
- In addition there are other kinds of requirements:
  - Space telescopes (Hubble).
  - Target tracking.
  - Forbidden directions (e.g. the direction to the Sun for sensitive optics).
- A spacecraft's orientation (with respect to another frame of reference of interest, e.g. inertial or the orbit axes) is called attitude.

Introduction II

- The subsystem responsible for estimating and controlling the attitude is the ADCS (Attitude Determination and Control System) whose basic functions are:
  - Determine the current or instantaneous attitude, from the measurements of the sensors and the knowledge of the previous attitude (estimation problem).
  - Use the available actuators in order to stabilize the attitude and correct possible deviations with respect to a desired attitude (control problem).
- Other possible functions:
  - Generate attitude maneuvers (slew maneuvers), for example, in order to go from an initial attitude to a desired final one (attitude transfer problem)
  - Track a target (tracking problem).

Attitude Representation and Kinematics

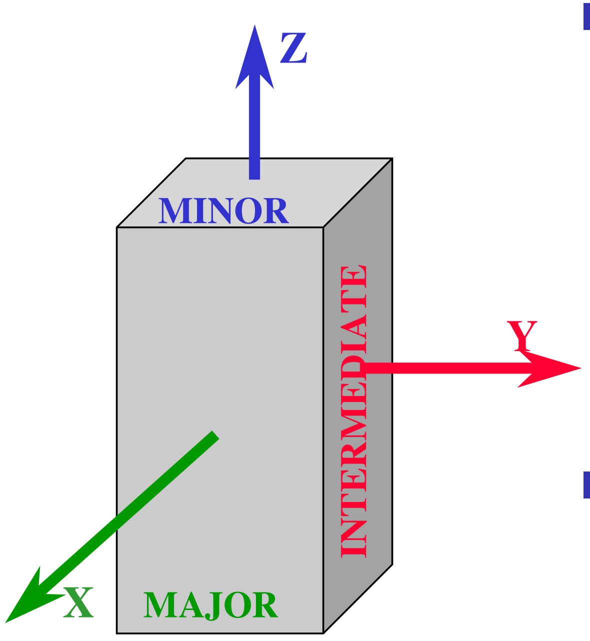


- Under the assumption of a rigid body, attitude is established by specifying the orientation of the body axes with respect to other axes of interest.
- For example, the orbit axes as shown in the figure, whose definition depends on the specific orbit.
- The relationship between two frames of reference can be represented in several ways: using matrices, Euler angles or other mathematical objects.
- Attitude kinematics is a combination of relationships (in the form of differential equations) between the spacecraft's angular velocity, $\vec{\omega}$, and its attitude, represented by any of the mathematical objects previously mentioned.

Attitude Dynamics

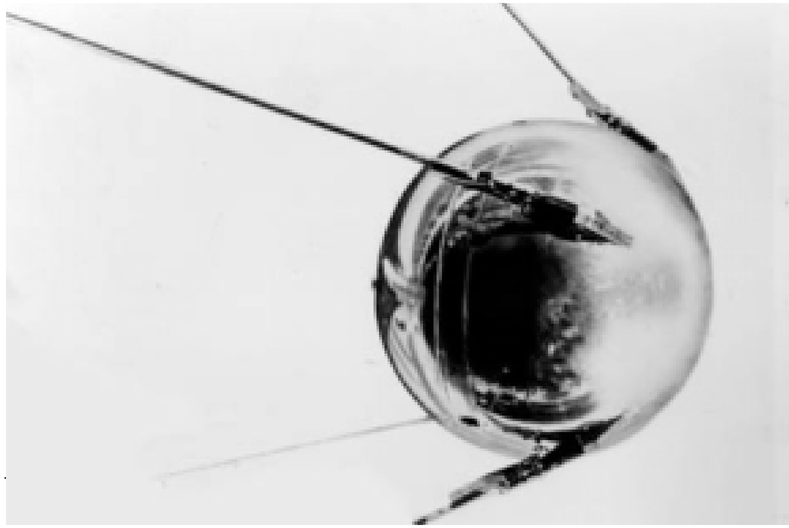
- Attitude dynamics relates the spacecraft's angular velocity with the moment of forces acting on it, and is based on the Angular Momentum Theorem; the resulting differential equations are known as Euler's Equations.
- The movement of a body in torque-free precession (moments equal to zero) is the most simple solution of these equations, and even explicit in the axisymmetric case; it is a precession of the rotation axes around another fixed axis.
- A body in rotation that is subject to a constant moment does not react "intuitively" but rather suffers perturbations in its initial rotation, causing precession and nutation movements.
- This resistance to perturbing moments is named gyroscopic effect. It is the basis of the spinning top's behavior.

Rotational Stability



- For the body in the figure, $I_1 = I_x$, $I_2 = I_y$, $I_3 = I_x$ are the principal moments of inertia (given the shape of the body). In addition $I_1 > I_2 > I_3$ because of the apparent dimensions in the figure, so the x axis is the major axis of inertia, the y axis is the intermediate one, and the z axis is the minor axis of inertia.
- It can be shown that if a rigid body rotates around the major or the minor axes, these rotations are stable (they are actually neutrally stable: when the rotation is disturbed, the perturbation does not increase).
- However if the rotation is around the intermediate axis, this rotation is unstable (an initial perturbation would increase and the instantaneous axis of rotation would get away from the intermediate axis).
- These results change in the presence of dissipation of energy (which always exists in real life): The minor axis is unstable if there is dissipation of energy (Major Axis Rule).

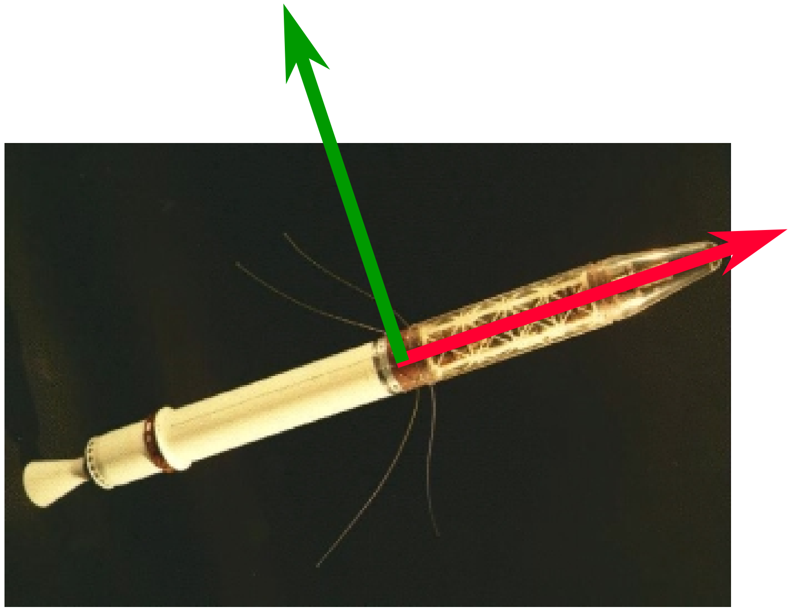
Sputnik vs. Explorer I

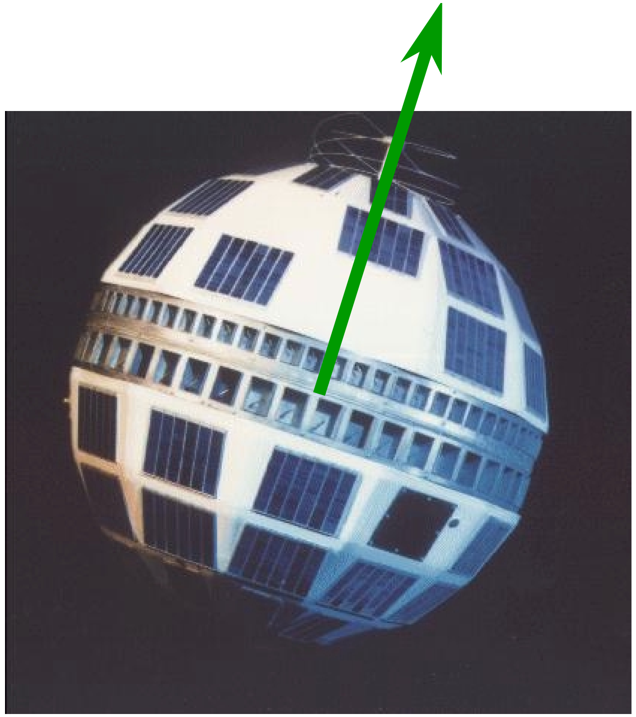


- Sputnik was launched in 1957
- The satellite was stabilized by rotation around its major axis.
- NASA engineers were not conscious of this fact, neither of the major axis rule (which cannot be deduced from a rigid body model).

- Explorer I was launched in 1958, "stabilized" by rotation around its minor axis.

Sputnik vs. Explorer II

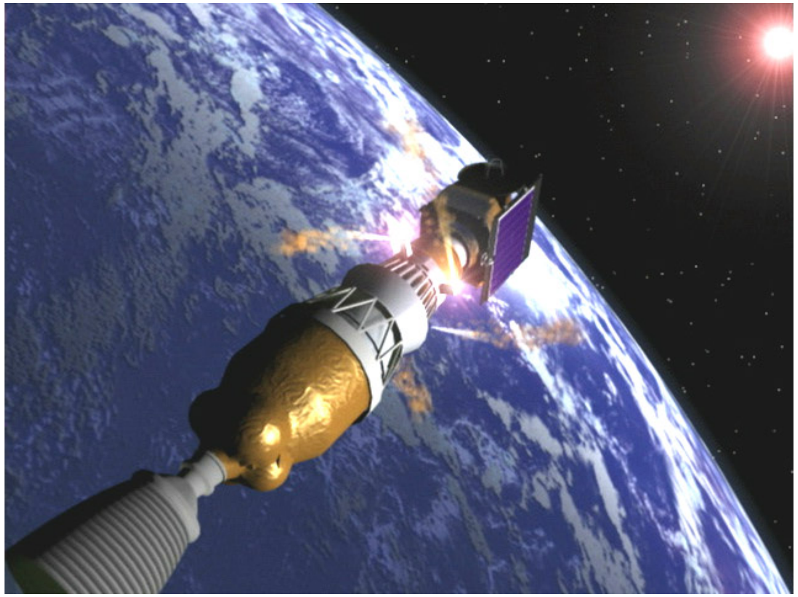




- Stabilization around the minor axis (red) did not work.
- In a few hours Explorer 1 started to spin around its major axis (green) with a quite chaotic movement, making communication with Earth difficult.

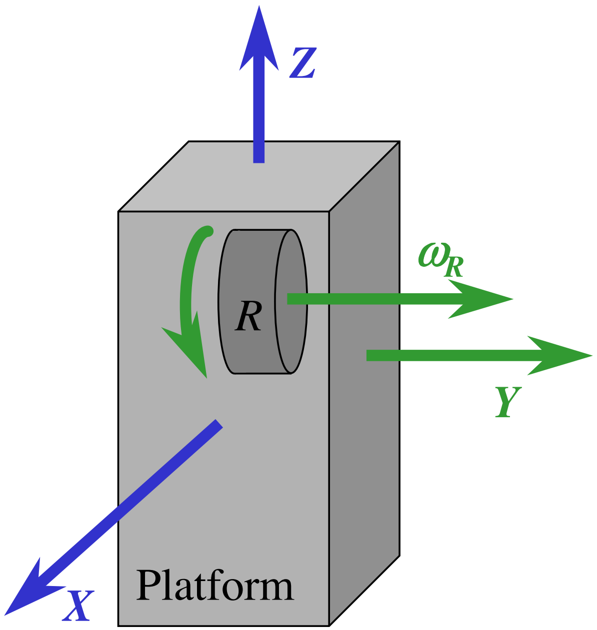
- Telstar I (the first communications satellite) was launched in 1962.
- It was stabilized by rotation around its major axis, spinning at 200 RPM.

Major Axis Rule: Exceptions



- The minor axis is unstable, but the characteristic time of the instability is slow (hours).
- Stabilization is typically achieved by rotation around the minor axis in the launch vehicles' later stages, before firing these stages.
- The gyroscopic effect induced by the rotations considerably reduces errors due to misalignment between the real and ideal axis of thrust.
- After ejecting the final stage, this rotation is typically stopped, for example with a yo-yo mechanism, or waiting long enough so that the dynamics transform the rotation to a major axis spin.
- Example: Mars Odissey.

Effect of a wheel in rotational dynamics



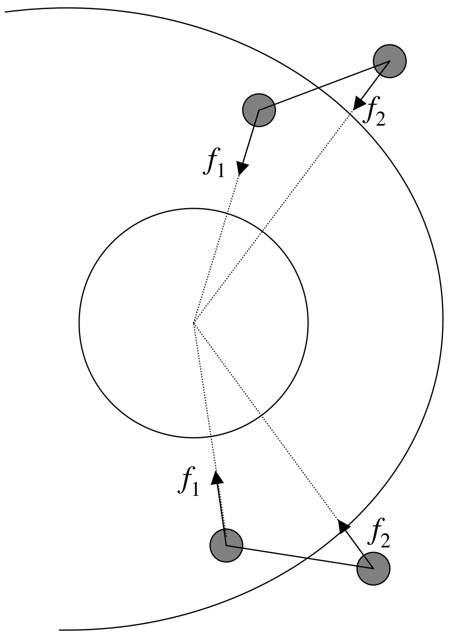
- A wheel, flywheel or rotor placed inside or outside the vehicle, and which is in rotation, produces a stabilization effect due to the gyroscopic effect it provides to the ensemble.
- In addition, the intermediate axis, or even the minor axis in presence of dissipation of energy, can be stabilized with a wheel.
- Moreover, rotations (maneuvers) can be performed as follows: if the wheel is accelerated in one direction, in the absence of (significant) external moments, the vehicle would rotate in the opposite direction due to the fact that the total angular momentum cannot change.
- The most extreme example of this principle is a CMG (control moment gyroscope); it consists of a wheel with high inertia and large fixed velocity but with moving axes.

Examples of Spacecraft with flywheels

- Navstar satellite (GPS).
- 4 flywheels spinning at several thousands of RPM.
- Auxiliary system: RCS (hydrazine).

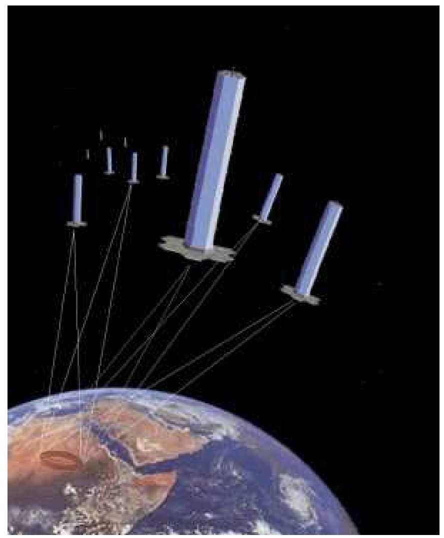
- DSP (Defense Support Program) satellites are part of the USA early warning system. They have infrared sensors.
- Stabilized by rotation with a flywheel.

Gravity gradient (G^2)



- The non spherical shape and mass distribution of a spacecraft produces the so-called gravitational torque, while it travels in its orbit, since $F = \mu m/r^2$.
- It can be seen as a "restorative force" which makes the spacecraft rotate as a pendulum, around its equilibrium position.

- "G^2" can be used for stabilization; however, it barely provides stability in yaw.
- The Moon is "stabilized" by G^2.
- The Polar BEAR satellite, stabilized by gravity, inverted its equilibrium position.



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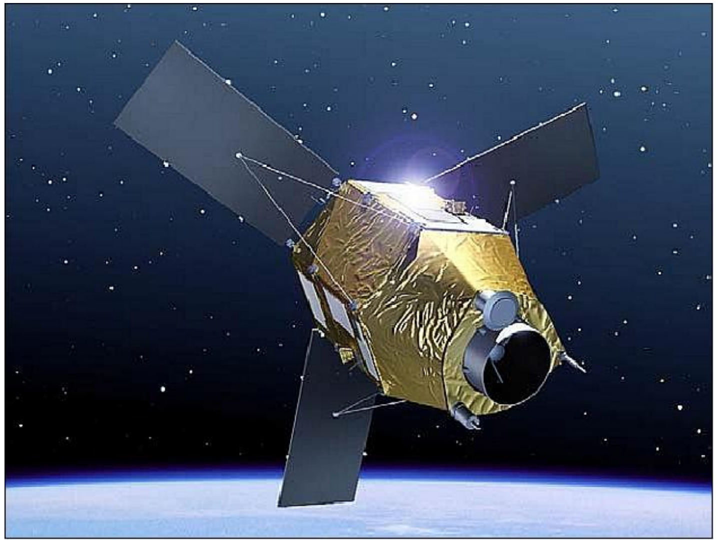
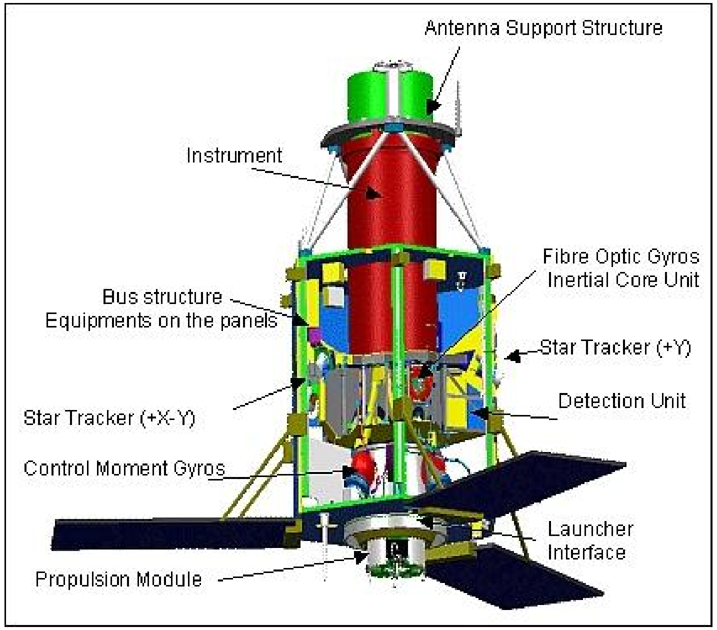
Three-axis stabilized systems

- Stellites with an ADCS system that totally controls their attitude are known as three-axis stabilized satellites.

- For example, the Hubble telescope's attitude control system is one of the most accurate systems ever built by man.
- The principal telescope has to be able of maintaining its position respect to a target with an accuracy of 0.007 arc seconds (a human hair width seen from a distance of 1.5 km).
- A golfer with that accuracy (and the required strength) would be able to achieve a "hole in one" in a golf course in Malaga executing the exit from Moscow, 19 out of 20 times!
- The Hubble performs its three-axis attitude control using flywheels.

Agile satellites





- Earth observation satellites have considerable attitude control requirements.
- The so-called "agile satellites" are prepared to obtain multiple images or even 3D images (taken twice from different angles).
- For example, the Pleiades constellation (2 CNES—French space agency—satellites) has the capacity to obtain images with a resolution < 1 m. from any point of the Earth!
- In order to take advantage of the optical capabilities, a large accuracy in the attitude control/determination is required, but also speed in the maneuvers; this is achieved with CMG (control moment gyros), star trackers and FOG (fiber optic gyros) of high resolution.