Introduction to Attitude Dynamics and Control

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What is spacecraft attitude?
And why should we care about it?

- Most spacecraft have instruments or antennas that must be pointed in specific directions
  - Hubble must point its main telescope
  - Communications satellites must point their antennas
- The orientation of the spacecraft in space is called its attitude
- To control the attitude, the spacecraft operators (which could be the spacecraft's computer in the case of an autonomous "ADCS") must have the ability to
  - Determine the current attitude
  - Determine the error between the current and desired attitudes
  - Apply torques to remove the error

Spacecraft Attitude Determination and Control

- So, the spacecraft needs an Attitude Determination and Control System (ADCS)
- To do the determination function requires knowledge of kinematics
- Attitude is determined using sensors
- To do the control function requires knowledge of kinetics and kinematics (dynamics)
- Attitude is controlled using actuators

Attitude Determination

Determine the attitude, or orientation, or pointing direction of a reference frame fixed in the body, with respect to a known reference frame, usually an inertial frame. That is, *where is the spacecraft pointing?*

- Generally involves finding a rotation matrix, or its equivalent
- Requires two or more attitude sensors
  - Sun sensor, Earth horizon sensor, Moon sensor, star tracker, magnetometer
- Requires an algorithm

The Differential Equation

- Every good dynamics course must begin with a differential equation
- For attitude dynamics and control, the equation of choice is

$$\dot{\vec{\mathbf{h}}} = \vec{\mathbf{g}}$$

Euler (1707-1783)

- This is the rotational equivalent of

$$m\vec{\mathbf{a}} = \vec{\mathbf{f}} \quad or \quad m\ddot{\vec{\mathbf{r}}} = \vec{\mathbf{f}}$$

Newton (1643-1727)

- Other notation used in other books and papers:

$$\dot{\vec{\mathbf{L}}} = \vec{\mathbf{N}} \qquad \dot{\vec{\mathbf{H}}} = \vec{\mathbf{M}}$$

- *Why doesn't everybody get together and agree on a specific notation?*

Euler’s Equations

- Euler’s vector differential equation

$$\dot{\vec{\mathbf{h}}} = \vec{\mathbf{g}}$$

h is angular momentum
g is torque

- Becomes a matrix differential equation when expressed in a body-fixed reference frame

$$\mathbf{I}\dot{\boldsymbol{\omega}} \quad = \quad -\boldsymbol{\omega}^{\times}\mathbf{I}\boldsymbol{\omega} + \mathbf{g}$$

I is inertia matrix
ω is angular velocity

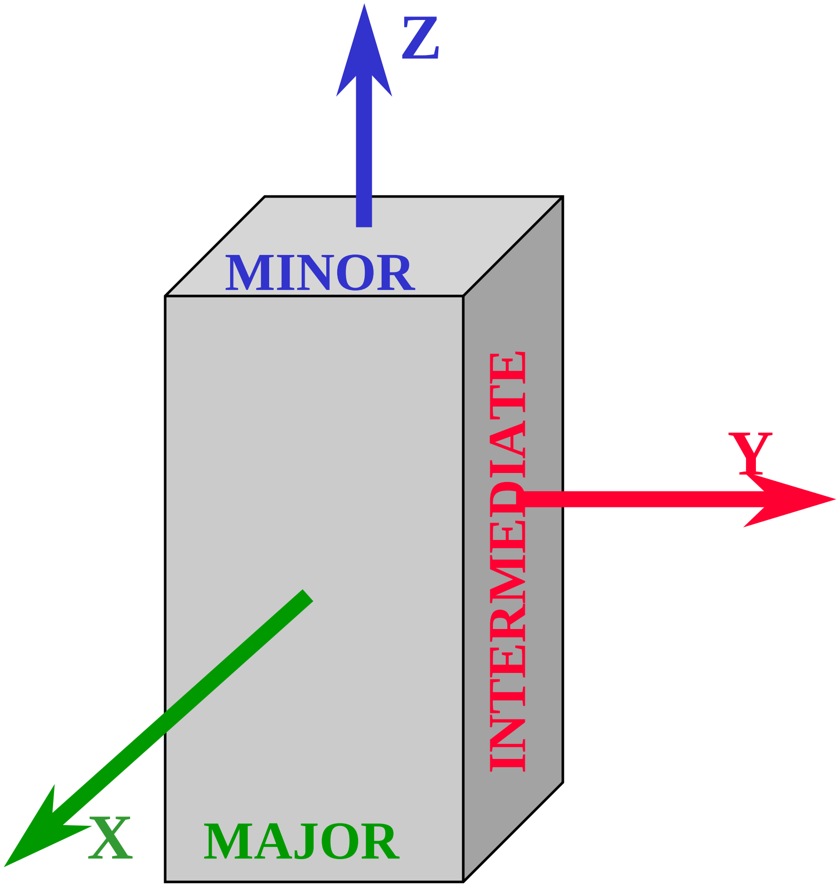
- And when expressed in a principal reference frame, it becomes

$$\dot{\omega}_1 = \frac{I_2 - I_3}{I_1}\omega_2\omega_3 + \frac{g_1}{I_1}$$

$$\dot{\omega}_2 = \frac{I_3 - I_1}{I_2}\omega_1\omega_3 + \frac{g_2}{I_2}$$

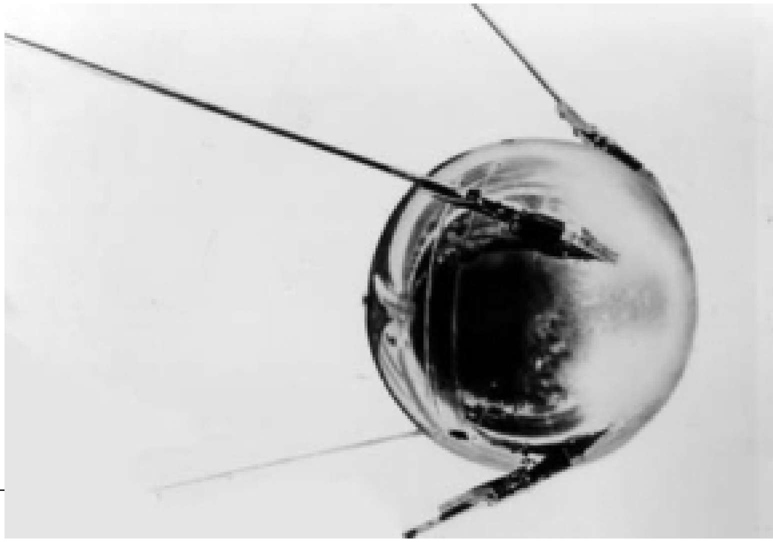
$$\dot{\omega}_3 = \frac{I_1 - I_2}{I_3}\omega_1\omega_2 + \frac{g_3}{I_3}$$

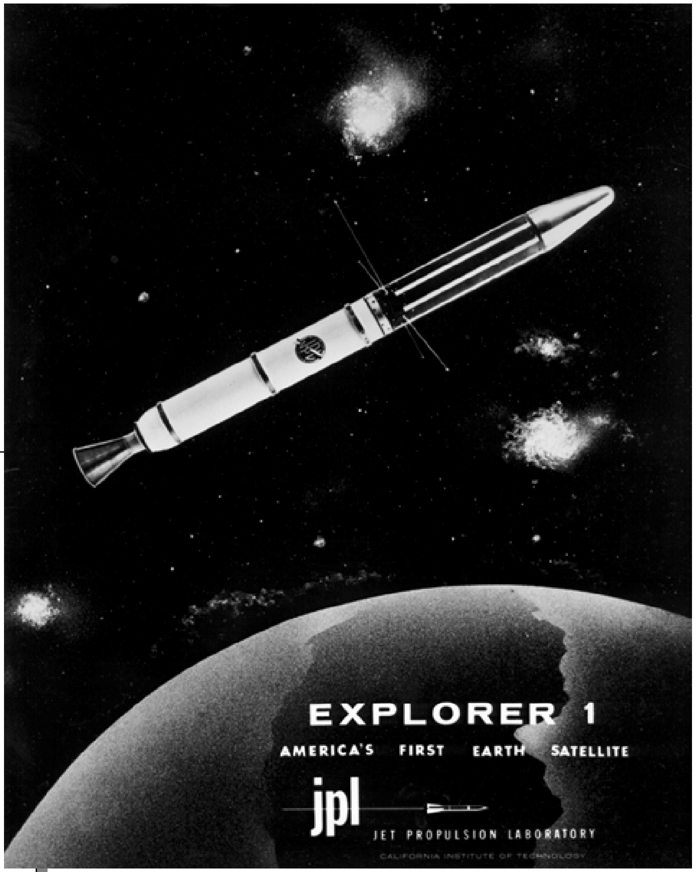
Rigid Body Spin Stability



- $I_{xx} > I_{yy} > I_{zz}$
- Major axis spin is stable
- Minor axis spin is stable
- Intermediate axis spin is unstable
- Energy dissipation changes these results
  → Minor axis spin becomes unstable
- This is called the Major-Axis Rule

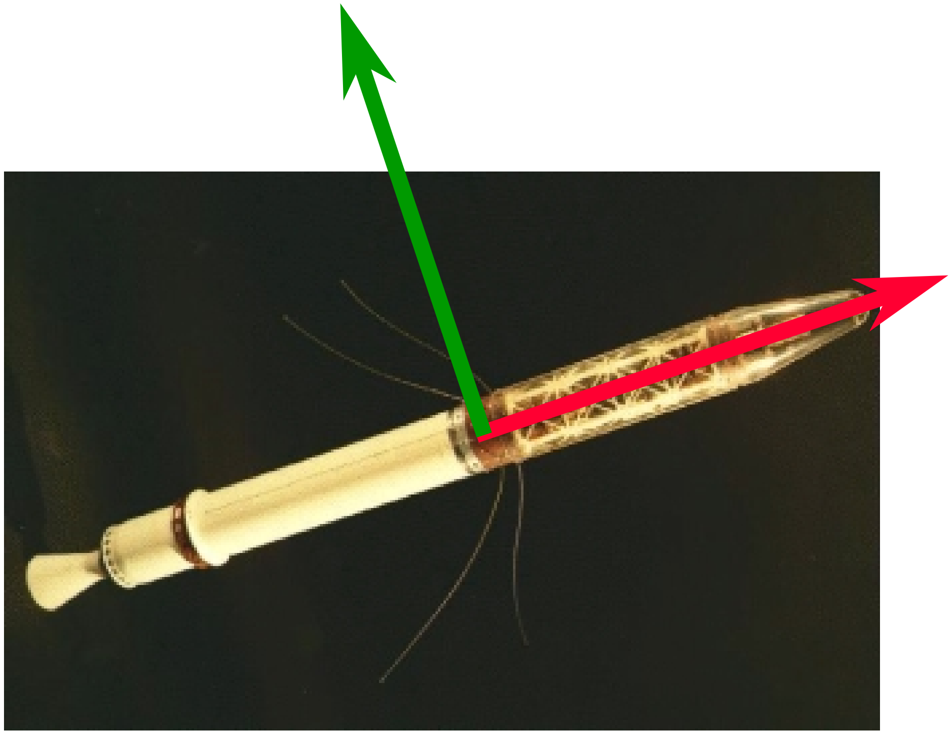
Sputnik & Explorer I



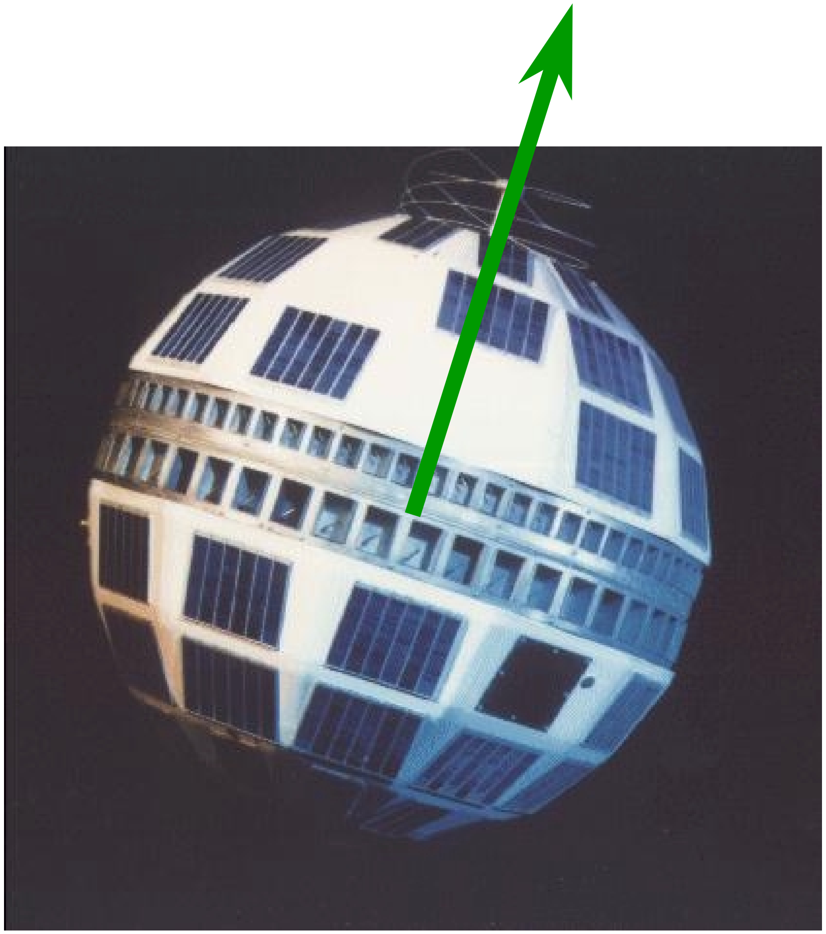


- Sputnik was launched in 1957
- Professor Ronald Bracewell, a radio astronomer at Stanford, deduced that Sputnik was spinning about a symmetry axis, and that it must be the major axis
- He called JPL to make sure that the Explorer I design was taking this into account, but security prevented him from getting through
- Explorer I was designed as a minor axis spinner, launched in 1958

Spin-Stabilized Satellites



Explorer I (1958) was supposed to be spin-stabilized about its minor axis. It went into a flat spin due to energy dissipation.



Telstar I (1962) was spin-stabilized about its major axis, spinning at about 200 RPM.

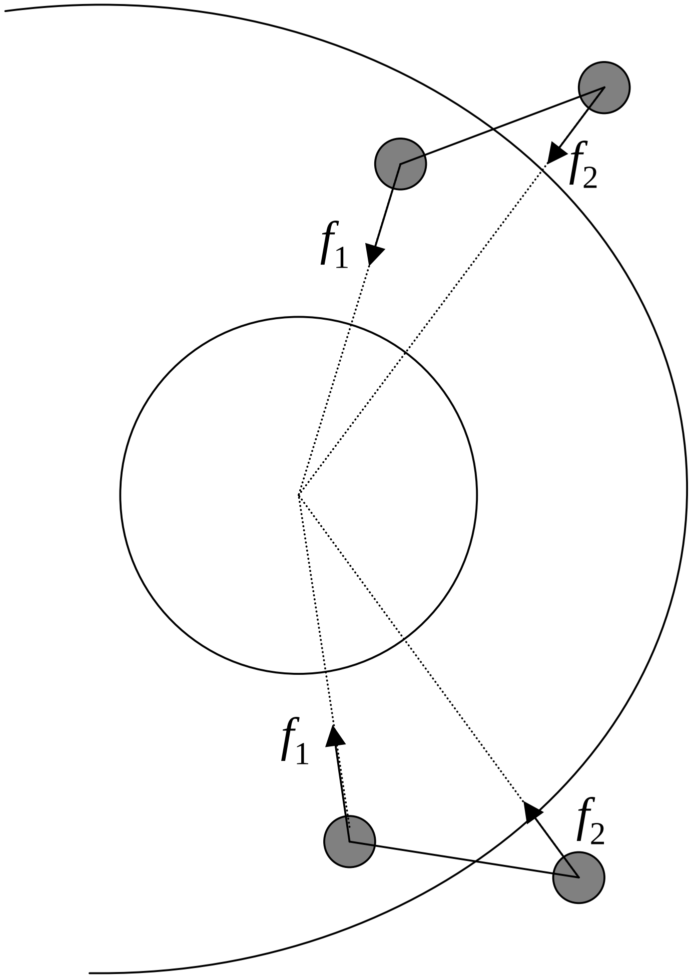
Gravity-Gradient Stabilization

- Gravitational attraction:

  $f = \mu m / r^2$

- Top: $f_1 > f_2 \Rightarrow$ torque is out of the page
- Bottom: $f_1 > f_2 \Rightarrow$ torque is into the page

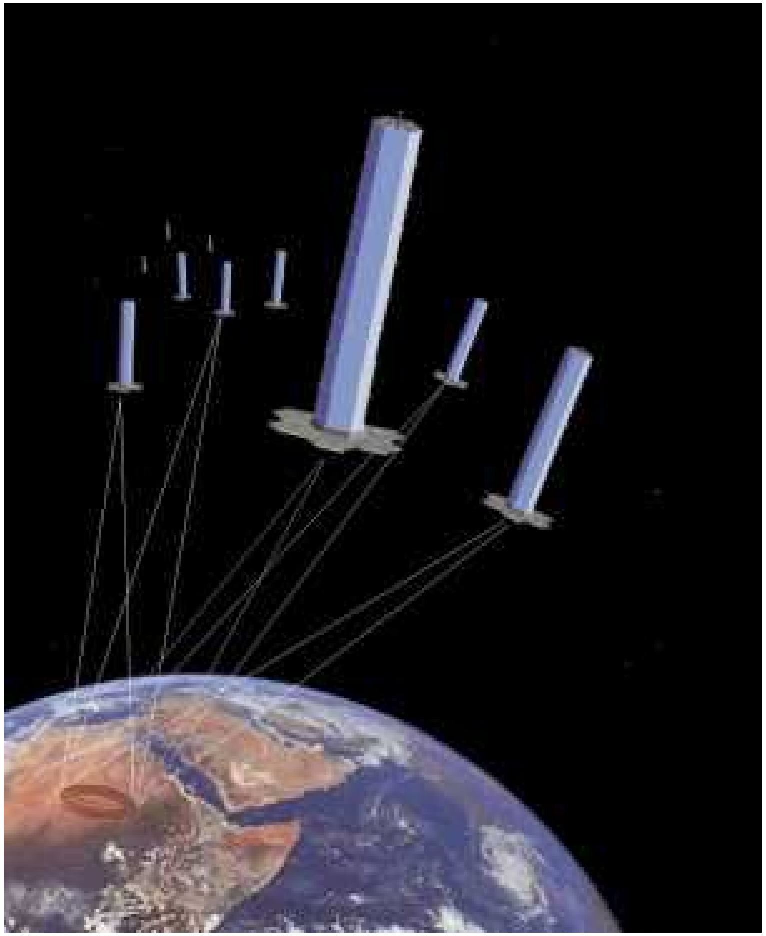
- In both cases, the torque is a *restoring* torque, tending to make the satellite swing like a pendulum



Gravity-Gradient Stabilization

- In the 60s was viewed as "free" attitude control
- In general, "G^2" is not accurate enough, spacecraft can even flip over
- Not really free, because of boom mass

- However, OrbComm and TechSat 21 use gravity gradient with flexible solar panels on an extensible wrapper around the boom
- The Moon is gravity-gradient stabilized; Lagrange (1736-1813) showed this



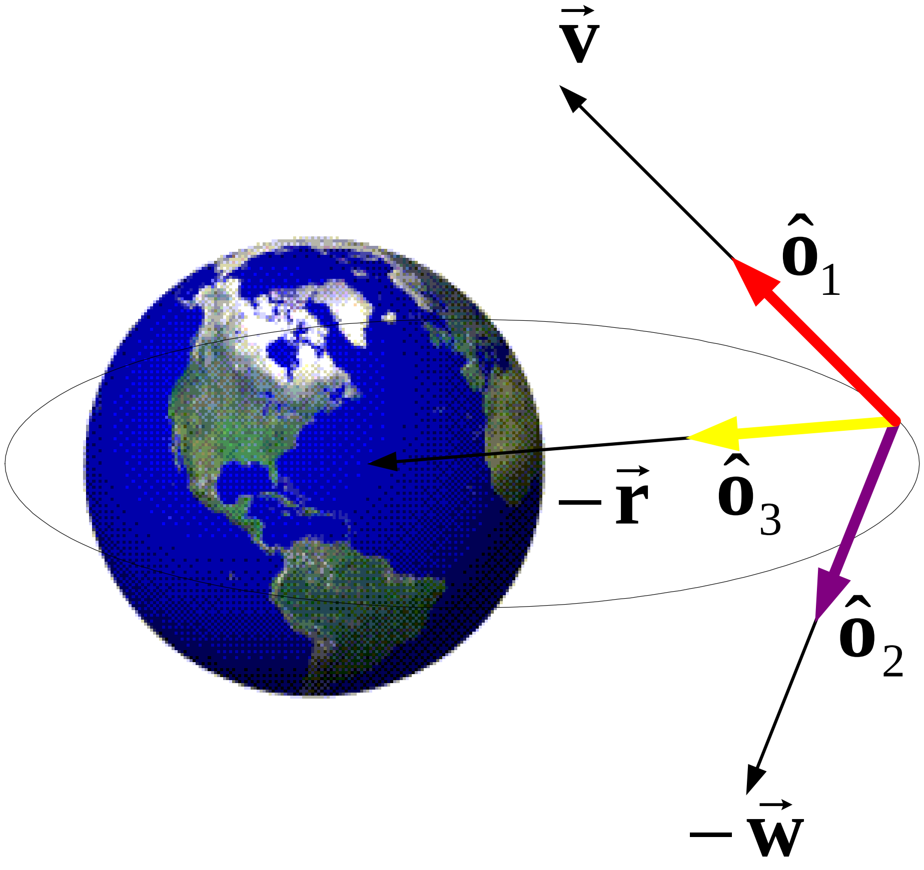
TechSat 21

Augmented G^2 Stabilization

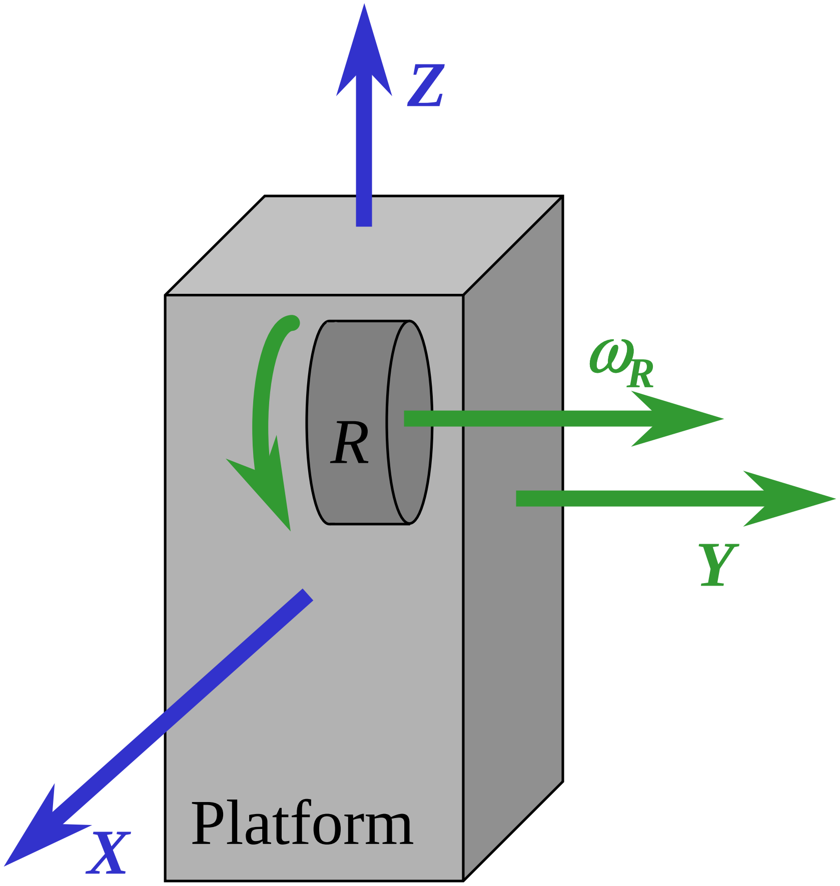
- Problem: with G^2 there is practically no yaw stability
- Solution: Add a small momentum wheel spinning about the pitch axis
- In effect, the wheel is a spin-stabilized s/c, with its angular momentum vector aligned with the orbital angular momentum vector
- Called pitch wheel or yaw wheel
- Can still flip over! (Polar Bear)

Roll, Pitch & Yaw

- Same as for aircraft (usually)
- Roll is rotation about the velocity vector
- Pitch is rotation about the orbit normal vector
- Yaw is rotation about the nadir vector
- Keep these color codes in mind



Effect of Rotor on Spin Stability



- A spinning rotor can stabilize the intermediate axis, destabilize others
- Stability condition

  $I_R\ \omega_R > (I_{xx}-I_{yy})\,\omega_y$
- As with rigid body, energy dissipation changes stability results

  → some stable spins become unstable

Two Spacecraft With Rotors

Defense Support Program

One large rotor
(120 RPM)

Global Positioning System

Four momentum wheels
(several thousand RPM)

Dual-Spin Stabilization

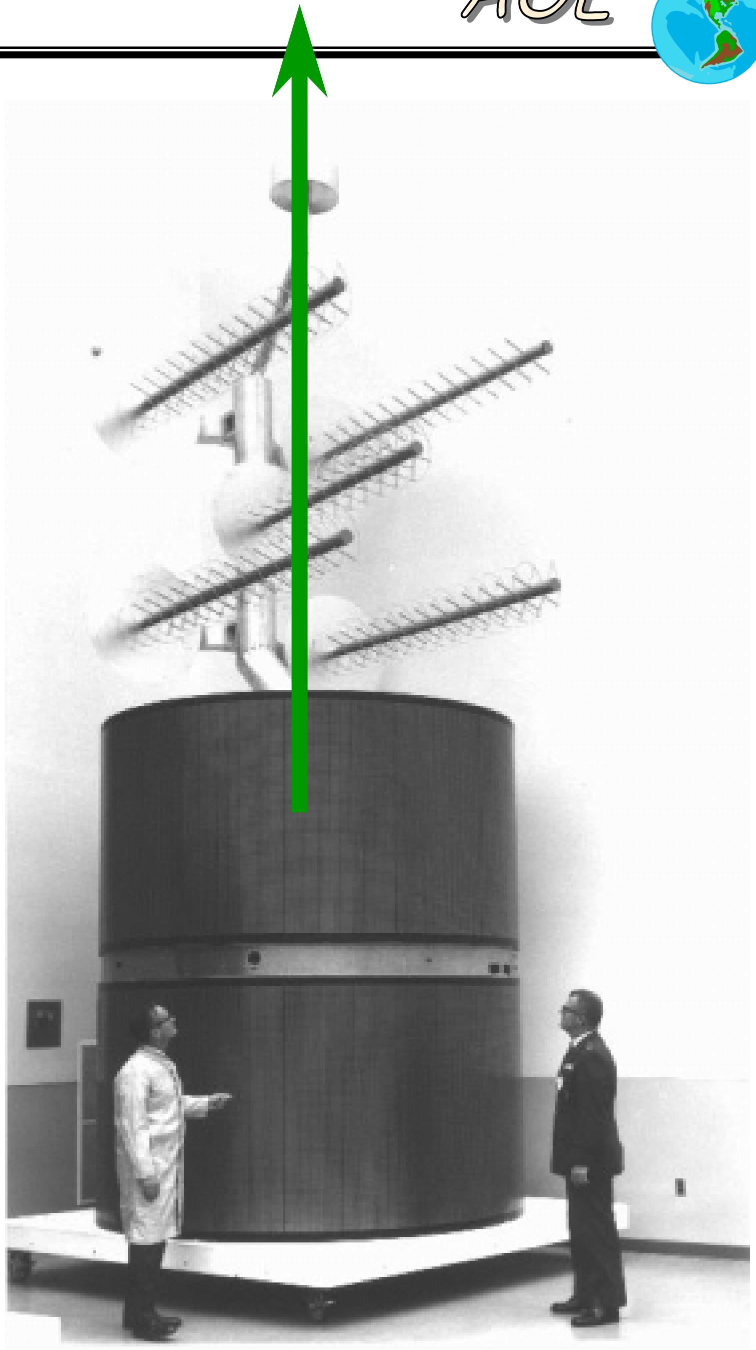
- Spin-stabilized satellites must be major axis spinners: "short and fat"
- Spin axis must in orbit normal direction (well, usually)
- Two problems:
  - launch vehicles are "tall and skinny"
  - antennas need to point at earth
- In mid-60s, two engineers invented a solution
  - Vernon Landon at RCA
  - Tony Iorillo at Hughes
- Make the spacecraft with two parts: one spins relatively fast, the other spins slowly or not at all
- The major axis rule generalizes to make it possible to spin stably about the minor axis
- Solves both problems: fits in launch vehicle, points the despun platform at the Earth

Dual-Spin-Stabilized Satellites

TACSAT I (1969) was the first satellite to successfully spin about its minor axis.

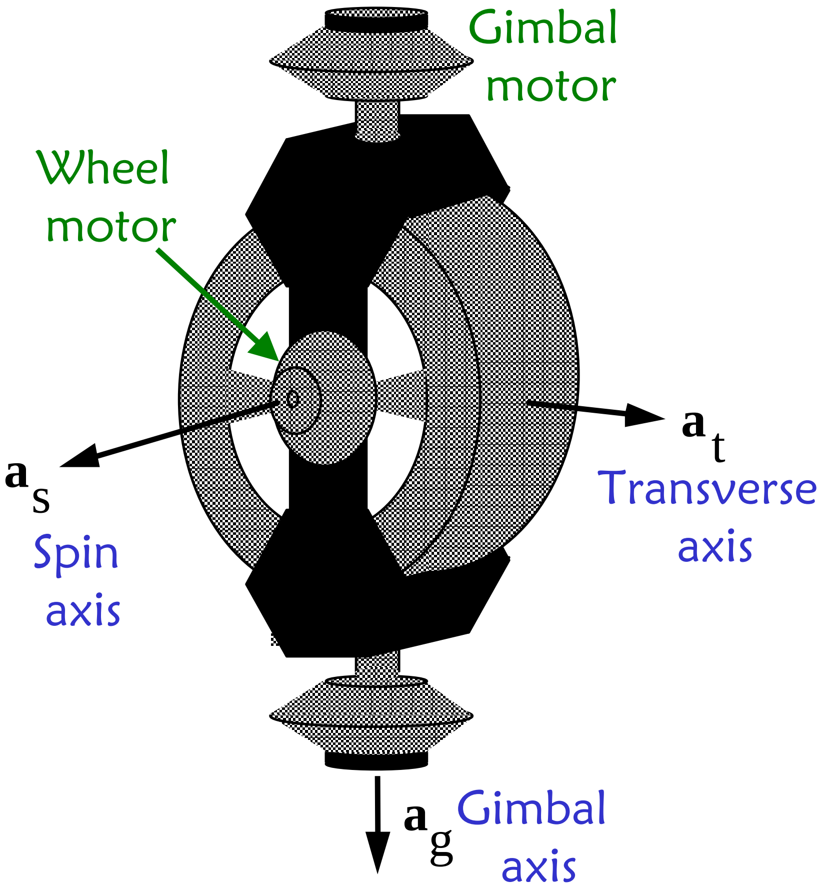
The antenna is the *platform*, and is intended to point continuously at the Earth, spinning at one revolution per orbit.

The cylindrical body is the *rotor*, providing gyric stability through its 60 RPM spin.



Gimbaled Momentum Wheels

- Gimbal axis is fixed in the body frame
- Spin axis is controlled by gimbal motor
- Spin rate is controlled by wheel motor
- Fixed gimbal angle gives *momentum wheel* (MW) or *reaction wheel* (RW)
- Fixed wheel speed gives *control moment gyro* (CMG)



Three-Axis Stabilization

- Instead of keeping the spin axis pointing in a specific direction, keep all 3 axes pointed in specified directions
- Can be done with thrusters, reaction wheels, momentum wheels, control moment gyros, or combination

Magnetic Stabilization

- Spacecraft is moving through Earth’s magnetic field $\mathbf{B}$
- Passing a current through a conductor creates a magnetic moment $\mathbf{m}$, which in turn causes a torque $\mathbf{g} = \mathbf{m} \times \mathbf{B}$
- Companies make magnetic torquer rods and coils specifically for this ACS application
- There’s a simple controller called the B-dot controller that can spin up or despin a satellite using this torque

Rotational Maneuvers

- Many systems require reorienting the spacecraft from one attitude to another
- Similar to three-axis stabilization, but with additional capability
- Uses thrusters, momentum wheels, reaction wheels, or control moment gyros
- Example: Hubble Space Telescope uses momentum wheels, and turns at about the same speed as a minute hand on a clock

Hubble Pointing

Hubble is the most precisely pointed machine ever devised for astronomy.

Requirement: The telescope must be able to maintain lock on a target for 24 hours without deviating more than 7/1,000ths (0.007) of an arc second (2 millionths of a degree) which is about the width of a human hair seen at a distance of a mile.

A laser with the stability and precision of the Hubble, mounted on top of the United States Capitol could hold a steady beam on a dime suspended above New York City, over 200 miles distant. This level of stability and precision is comparable to sinking a hole-in-one on a Los Angeles golf course from a tee in Washington, DC, over 2,000 miles away, in 19 out of 20 attempts.

Course Overview

- Some Mission Analysis concepts
- Kinematics: Vectors, Rotation matrices, Euler angles, Euler parameters (aka quaternions)
- Attitude determination
- Rigid body dynamics (Euler's equations)
- Satellite dynamics applications
- Attitude control