# Spacecraft Dynamics and Control

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Lecture 15: Attitude Dynamics and Control Systems (ADCS)

# Introduction to Attitude Dynamics and Control Systems (ADCS)

In this Lecture we will cover:

- Mission Requirements
- Forms of Attitude Control

**The Problem of Attitude Stabilization**

- Actuators
- Sensors
- Controllers

**Newton's Laws:**

- This time, we only care about Angular Momentum
- $\sum \vec{M}_i = \frac{d}{dt}\vec{H}$

**Next Lecture: Rotating Frames of Reference**

- Equations of Motion in Body-Fixed Frame

# Orientation of a spacecraft

**Let's begin with some examples**

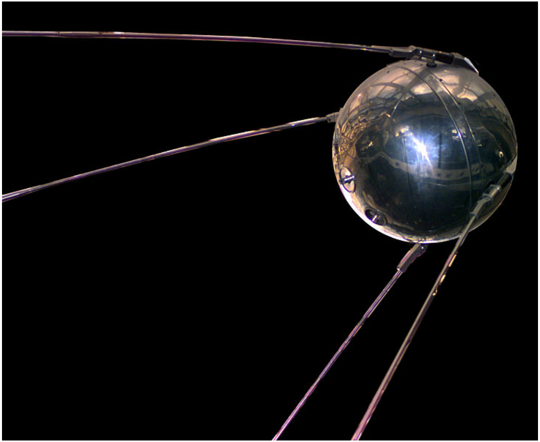

Figure: Sputnik I Satellite

**Orbit:** 947 x 228, $65^{\circ}$ inclination. Spin Stabilized. Two planes of symmetry.

# NASA Tracking and Data Relay Satellite (TDRS)

## Communication relay between ground control and objects in orbit

There have been 13 TDRS missions.

- Enable continuous real-time communications between space and ground.
- GEO, TDRS-K is currently at $\Omega = 150°$ (Final $\Omega = 171°$).

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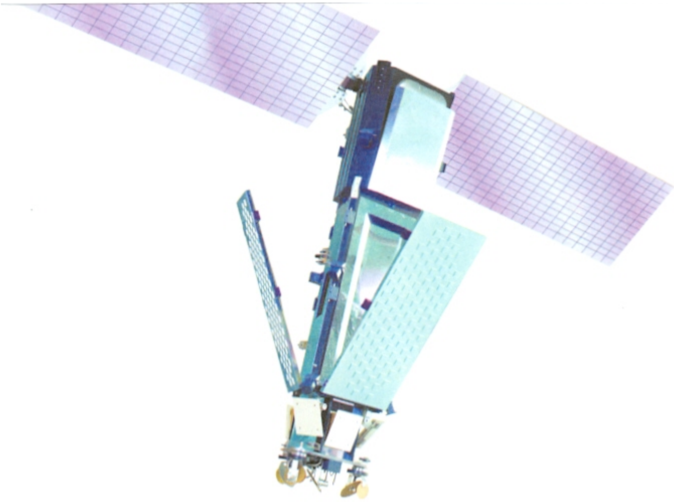
- Approximately 1 plane of symmetry
- TDRS-A was launched in 1983 (currently in graveyard orbit)
- TDRS-B was aboard the Challenger.
- Image is 3rd gen. TDRS (2011+)

# Iridium Satellite Constellation. Launched 1992-1999

## Satellite Telephone Service



Originally commercial, now pseudo-military. 66 active satellites.
**Orbit:** 780km, $75^{\circ}$ inclination, 6 orbital planes.

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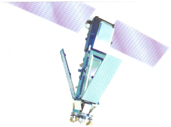


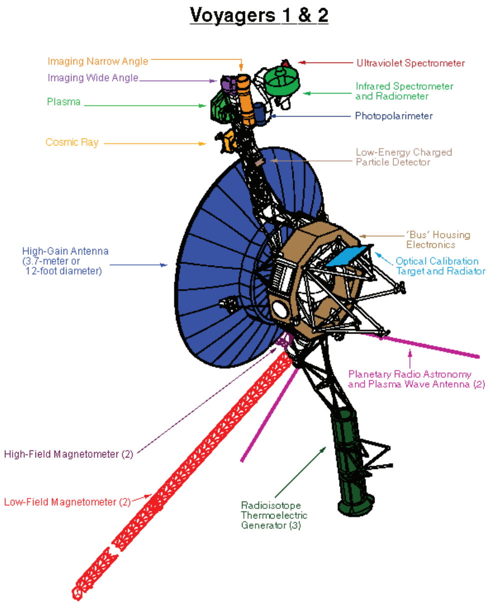
Originally commercial, now pseudo-military. 66 active satellites.
**Orbit:** 780km, $75^\circ$ inclination, 6 orbital planes.

- Approximately 1 plane of symmetry
- Operational in 1998
- Largest US bankruptcy in 1999 (originally to be de-orbited!)
- First Next-gen Iridium satellite launched in 2017.

# Voyager I and II (1977)

Interplanetary Exploration

- Approximately 1 plane of symmetry



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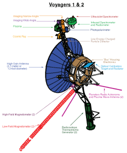
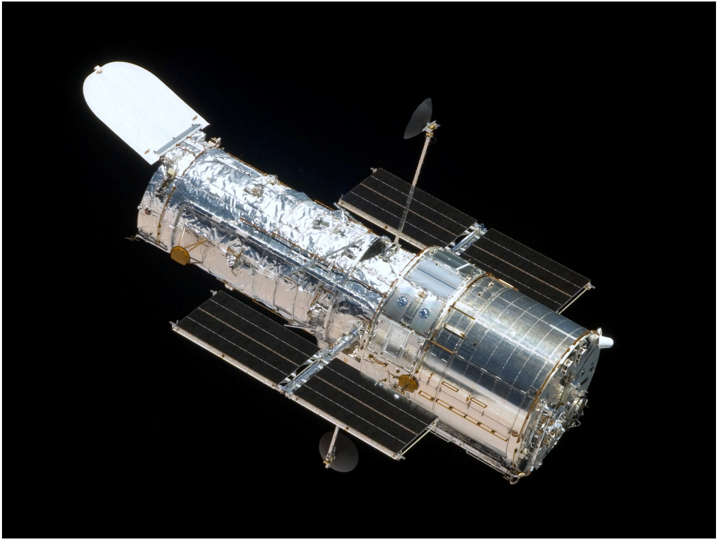


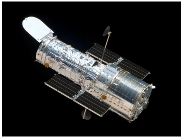

- Requires constant communication link with earth.
- 3-axis stabilized

# Hubble Space Telescope (HST) - 1990



**Orbit:** 613 x 620, $28.5°$ inclination

Hubble Space Telescope (HST) - 1990



**Orbit:** 613 x 620, $28.5^\circ$ inclination

- approximate radial symmetry
- 3-axis stabilized

# NRO Reconnaissance Satellite

## Advanced Orion/MENTOR

- Signals Intelligence
- Duration 1994-???
- L-32 is the largest satellite ever launched with a dish size of $\cong 100$m

Figure: Orion/RIO (The Intercept, 2009)

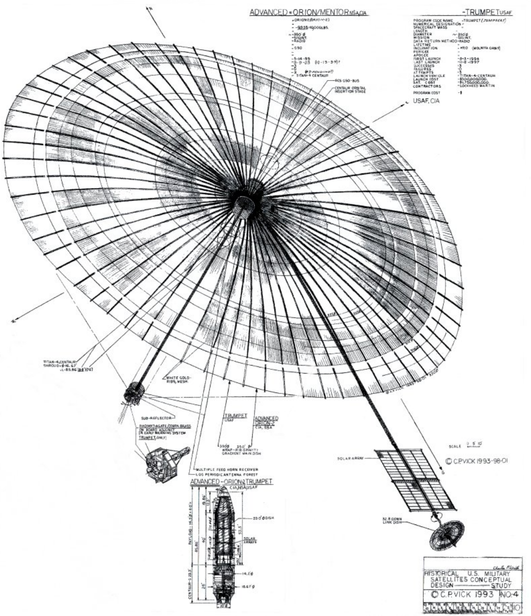



Figure: Hypothetical Rendering

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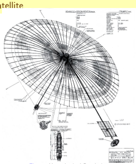


Figure: Hypothetical Rendering

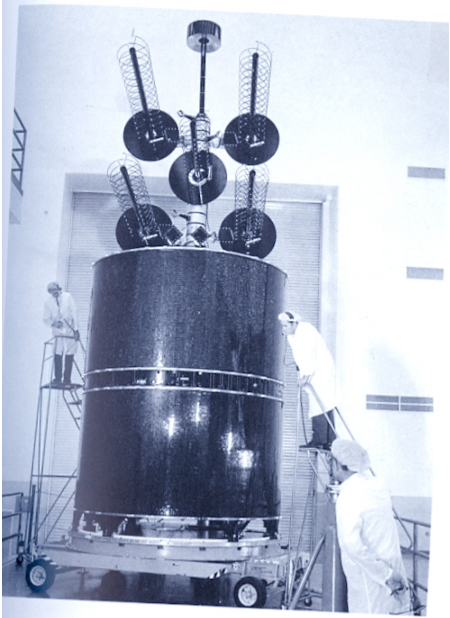
- Classified Top Secret
- Largest in the world quote is from Ben Carlson, NRO director
- Trumpet is in Molniya orbit 39000x1300, $i = 64^\circ$
- Advanced ORION is in GEO (so is PAN - whatever that does)
- Replaces Magnum Series
- 3-axis stabilized
- Single plane of symmetry
- Description of Spy Satellites included in the Snowden Leak

# TACSAT I (1969-1972)

Military Tactical Communications Satellite.

- Approximate radial symmetry
- Dual Spinner

**Orbit:** GEO, $\Omega = 107°$



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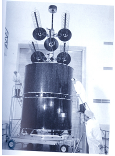
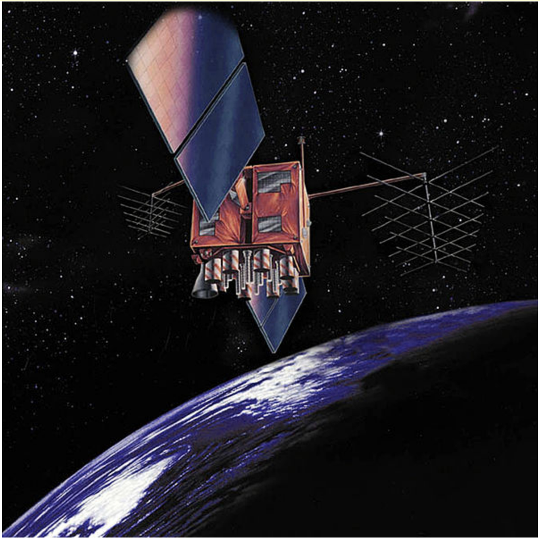


- Largest satellite at time of launch (25ft in length) - gunter's space page
- Used for direct communication with battlefield commanders.
- Not to be confused with TacSat

**TacSat:**

- TacSat is to obtain on-battlefield live imaging.
- TacSat 1 planned launch in January 2004.
- TacSat 1 launch was repeatedly delayed
- TacSat 2 launch in Dec. 2006
- Tacsat 3 launch May, 2009, reentry April 2012
- Last scheduled Tacsat 1 launch was 2009. Canceled for being obsolete.
- Tacsat 4 launch Sept. 2011. 4 hr period, 7000 x 12,000 orbit. $\omega = 210$, $i = 63.4$

# GPS Block IIR (2005-2009)



**Orbit:** 20,182km, $55^\circ$ inclination. Single plane of symmetry
GPS constellation has 24 satellites in 6 planes.

# GPS Constellation

Figure: GPS Constellation is designed to have at least 4 satellites visible at any given time anywhere in the world.

# Strela-3 Satellite Constellation (1985)

Russian Military Communications

- 12 Satellites
- Gravity-Gradient Stabilization

**Note:** 2009 Satellite Collision between Strela 2M and Irridium 33

**Orbit:** 1440 x 1450, $82.5°$ inclination.

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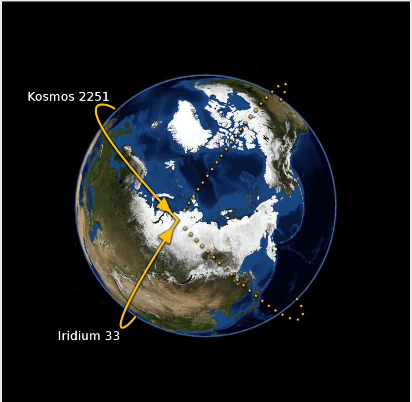
**Note:** 2009 Satellite Collision between Strela 2M and Irridium 33

**Orbit:** 1440 x 1450, $82.5^{\circ}$ inclination.

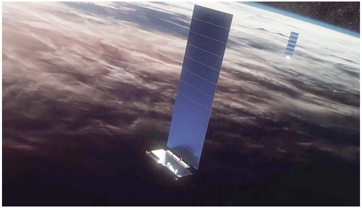
- Relative velocity at impact: 11.7 km/s
- Altitude at impact: 789 km
- Strela Satellite was dead as of 1995 and likely in a decaying orbit.

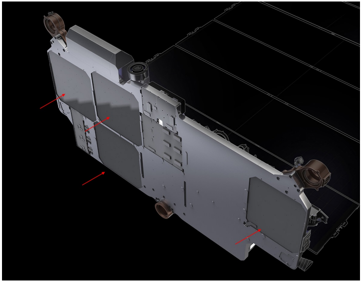



# Starlink

Internet Communications

- 1584-12,000 Satellites
- Currently 7135 in orbit (5504 last year, 350 in April, 2020 - Orbit Data)
- Satellites weigh 500-600lb
- Altitudes are $525 - 572km$ (6 spheres)
- Use Hall-Effect Thrusters (HET-Krypton) for stationkeeping
- 3-axis stabilized (4 reaction wheels)
- star tracker for orientation





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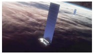

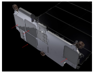

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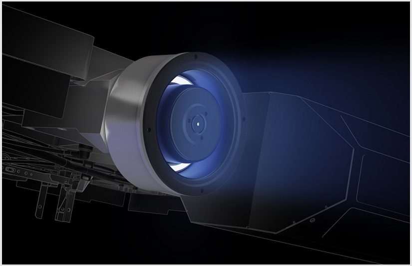
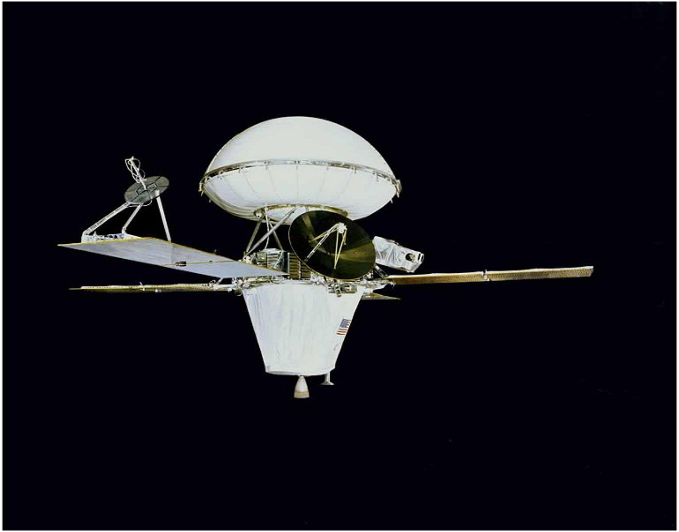
- Around 250 orbital planes, currently



# Viking I



Interplanetary Mission to Mars. Two planes of symmetry.
**Mars Orbit:** 320 x 56,000km, $39.3°$ inclination. $e = .8822$.

Viking I

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- Mars insertion on June 19, 1976.
- Operations terminated in 1980.
- Final Orbit designed to last until 2019
- Current Status: unknown
- Viking 2 orbiter developed ADCS propulsion leak and was shut down in 1978
- Second spacecraft to soft-land on Mars
- The first was the Soviet Mars 3, which lasted 20 seconds (due to a nasty dust storm)

**What can go wrong?**

Figure: Tumbling Satellites are sometimes visible in the Night Sky

# Attitude Determination and Control System (ADCS)

Active attitude control is required for almost all satellite applications.

- Communication
- Reconnaissance (SIGINT)
- Navigation (GPS)
- Exceptions:
  - LAGEOS
  - ECHO I, II

Even Sputnik was spin-stabilized

**Problem:** Unlike aircraft, spacecraft cannot rely on aerodynamic forces to provide stability.

- If a spacecraft is not attitude stabilized, small disturbances will cause it to tumble.

**Question:** How to stabilize a satellite

There are many varieties and methods for attitude control of spacecraft.

- 1-axis Stabilization
  - Spin Stabilization $(.1 - 1^\circ)$
  - Also good for pre-insertion.
- 2-axis stabilization
  - Gravity-Gradient Stabilization $(5^\circ)$
  - Magnetic Torquers $(5^\circ)$
- 3-axis Stabilization
  - Thrusters $(.1 - .5^\circ)$
  - Control-Moment Gyros (CMGs) $(.001 - 1^\circ)$
  - Momentum wheels (Reaction wheels) $(.001 - 1^\circ)$

Lets go through a few of these.

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Lets go through a few of these.

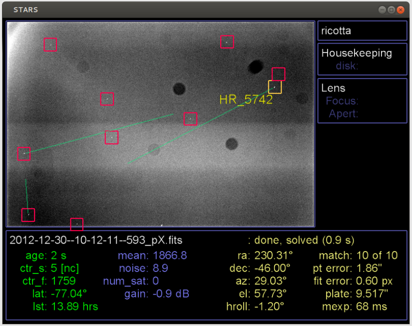
Sensors for Attitude Determination:

**Rate Sensors:**

- Gyroscopes
- Inertial Mass Units (IMUs)
- Other Inertial Navigation Systems (INS)

**Attitude Sensors:**

- Horizon Sensor (IR earth horizon sensor)
- Gyrocompass
- Sun Sensor
- Earth Sensor
- Star Tracker
- Magnetometer (Compass)




http://www.cubesatpointing.com/
https://www.cubesatshop.com/

# No Control (LAGEOS, ECHO)

Figure: LAGEOS Geodesy Satellite



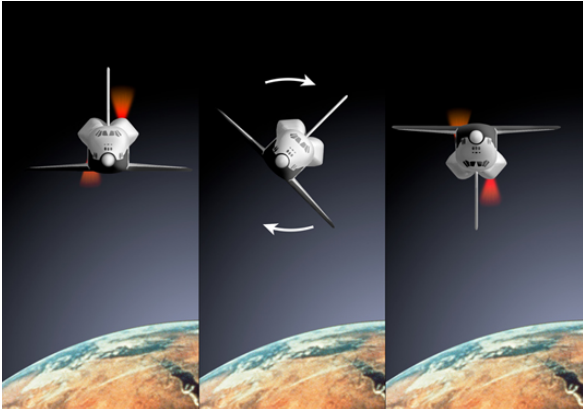
Figure: ECHO II communication satellite

# Mechanisms for Attitude Control

## Thrusters

Thrusters are grouped in pairs in order to provide pure moment

- no change in orbit.



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- Provide discrete units of angular momentum (spin up).

$$\Delta h = F \Delta x \Delta t$$

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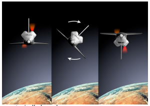

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- Provide discrete units of angular momentum (spin up).

$$\Delta h = F \Delta x \Delta t$$

- Space Shuttle used 6 paired Vernier thrusters.

Figure: Thrusters on MMU

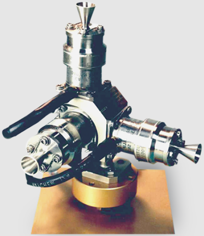
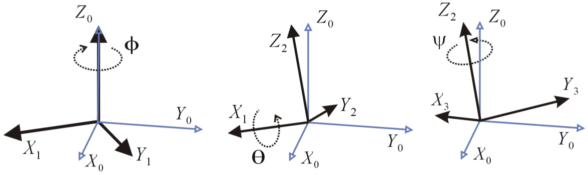


Figure: Cold Gas Thruster

Thrusters may alter orientation and angular velocity.

- e.g. Through rotation matrices




Only two sets of thrusters are needed to achieve any orientation (Euler Angles).

1. Rotate about $\hat{b}_3$ until $\hat{b}_1$ lines in $\hat{a}_2 - \hat{a}_1$ plane.
2. Rotate about $\hat{b}_1$ until $\hat{b}_2$ lines in $\hat{a}_2 - \hat{a}_1$ plane.
3. Rotate about $\hat{b}_3$ until $\hat{b}_1 = \hat{a}_1$ and $\hat{b}_2 = \hat{a}_2$.

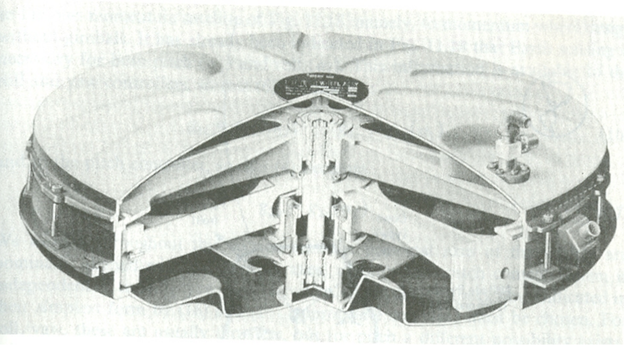
Usually better to have 3 sets of thrusters to minimize fuel

- Otherwise small changes can lead to big rotations.

# Mechanisms for Control

## Reaction wheels (Momentum Exchange Device)

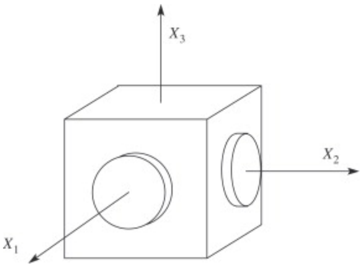
Thrusters are not very accurate: rarely used for tracking control.



**Reaction wheels:** A momentum exchange device uses torque to spin up a wheel. An equal and opposite amount of torque is imparted to the spacecraft. The resulting angular momentum of the wheel and craft are then equal in magnitude and opposite in direction.

# Mechanisms for Control

## Reaction wheels




**Dynamics:** Consider rotation about the $x$-axis.

- Let $J_x$ be the moment of inertia of the Spacecraft about the $x$-axis.
- Let $I_x$ be the moment of inertia of the flywheel.
- By conservation of angular momentum:

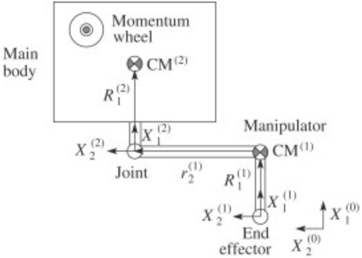
$$I_x(\omega_f + \omega_s) + J_x\omega_s = 0$$

  - $\omega_s$ is the angular velocity of the the craft in inertial space.
  - $\omega_f$ is the angular velocity of flywheel w/r to the craft.

Figure: Spacecraft rotation via 3-1-3 Euler Angles

# Mechanisms for Control

## Reaction Wheels

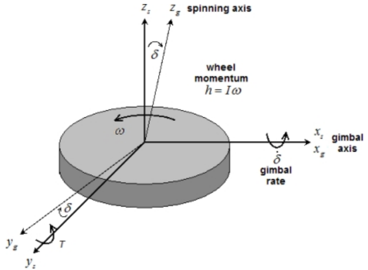



So if the craft has some velocity $\omega_s$ in the $\hat{b}_1$-direction and the reaction wheel is aligned with this axis, we can null out the velocity by spinning up to

$$\omega_f = -\frac{J_x\omega_s + I_x\omega_s}{I_x} = -\frac{J_x + I_x}{I_x}\omega_s.$$

If we have reaction wheels in the $\hat{b}_2$ and $\hat{b}_3$ directions, we can create any angular velocity vector.

- Flywheels can be use to correct for small deviations (Telescopes).
  - However, accumulated momentum may cause the flywheels to spin too fast.
  - Will need to eventually find a way to dump momentum.




Control Moment Gyros are different from reaction wheels in that they have a fixed rate of rotation ($\omega_{CMG}$)

- Thus the magnitude of the angular momentum vector, $\|\vec{h}\|$ will be fixed.
- The direction of the angular momentum vector will vary, however.

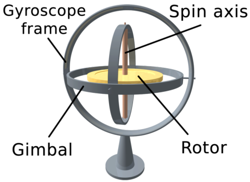
**Single Gimbal** Control is achieved by rotation of the gyroscope through an angle $\delta$.

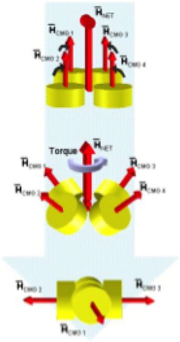
- This can only be used for 2-axis stabilization

# Single-Gimbal Control Moment Gyro

Figure: Effect of Single Control Moment Gyro

Alternatively, a dual-gimbal CMG may be used



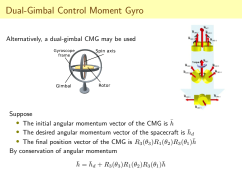




Suppose

- The initial angular momentum vector of the CMG is $\bar{h}$
- The desired angular momentum vector of the spacecraft is $\bar{h}_d$
- The final position vector of the CMG is $R_3(\theta_3)R_1(\theta_2)R_3(\theta_1)\bar{h}$

By conservation of angular momentum

$$\bar{h} = \bar{h}_d + R_3(\theta_3)R_1(\theta_2)R_3(\theta_1)\bar{h}$$




If $\omega$ is rotation vector of the craft, $T_{ext}$ is external torque

$$\dot{H}_s + \omega \times H_s = T_{ext}$$

and $H_s$ is total angular momentum (To be derived in next lecture). Then if $J$ is the inertia tensor of the craft

$$H_s = J\omega + h$$

where $h$ is the CMG angular momentum. If $u$ is the internal torque applied to the CMG, then

$$J\dot{\omega} + \omega \times J\omega = u + T_{ext}, \qquad \dot{h} + \omega \times h = -u$$

# Dual-Gimbal Control Moment Gyro

## Definition 1.

Given $\bar{h}$, the **Momentum Envelope** is set of solutions of

$$\bar{h}_d = (I - R_3(\theta_3)R_1(\theta_2)R_3(\theta_1))\bar{h}$$

for some set of Euler rotations, $\theta_1, \theta_2, \theta_3$.

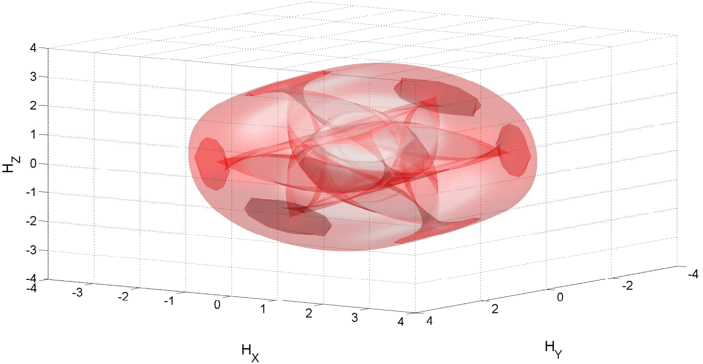
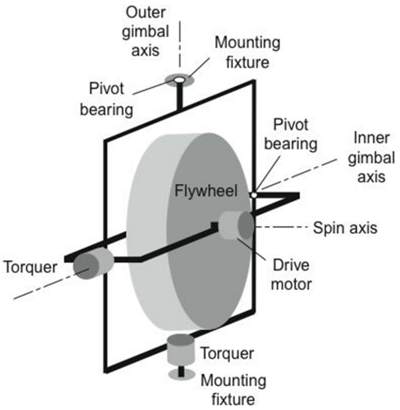


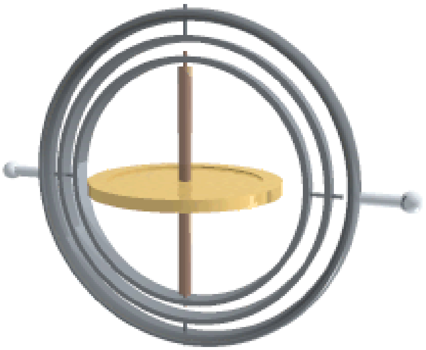

Figure: Momentum Envelope for a pyramidal 4-CMG array. Note the singularities.

# Dual-Gimbal Control Moment Gyro

The effect of the singularities is most easily understood as **Gimbal Lock**

- Two axes of the gyroscope align.
- Rotation about that axis requires no torque.
  - Freely spinning.



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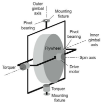
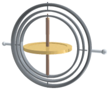
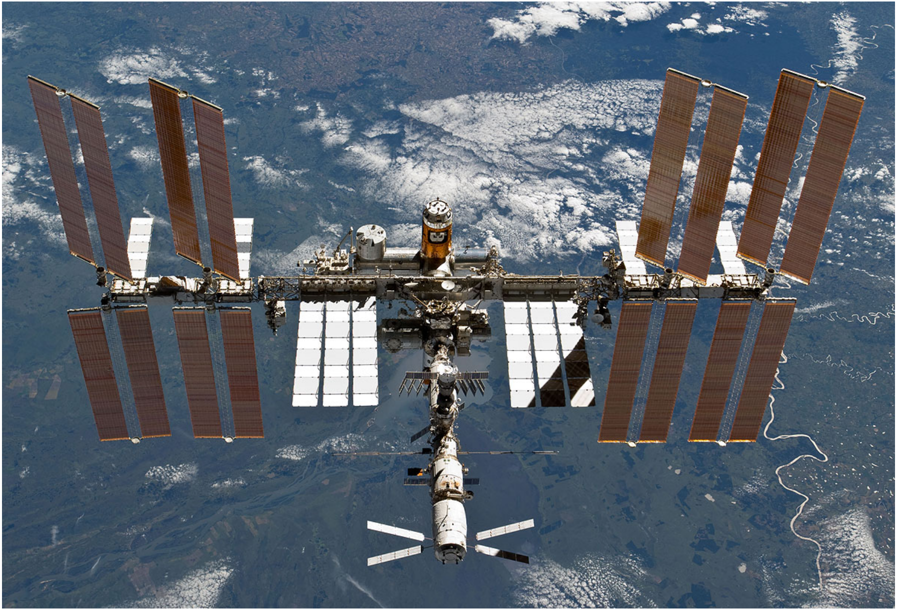


Youtube video on Gimbal Lock (See minute 4:20)

# Control Moment Gyros on the International Space Station



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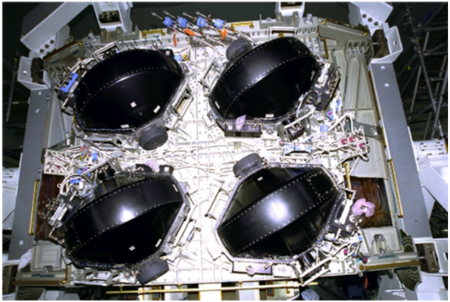


Figure: ISS Z1 truss with 4-CMG array

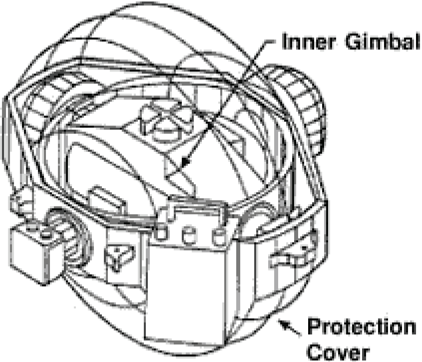



Figure: Cutaway of ISS CMG

The CMGs are double-gimbal, so hardware orientation is not important.

Control Moment Gyros on the International Space Station

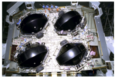


Figure: ISS Z1 truss with 4-CMG array

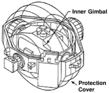
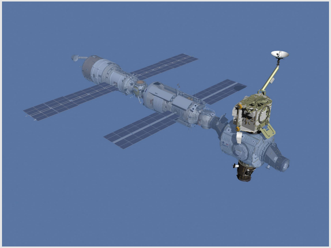


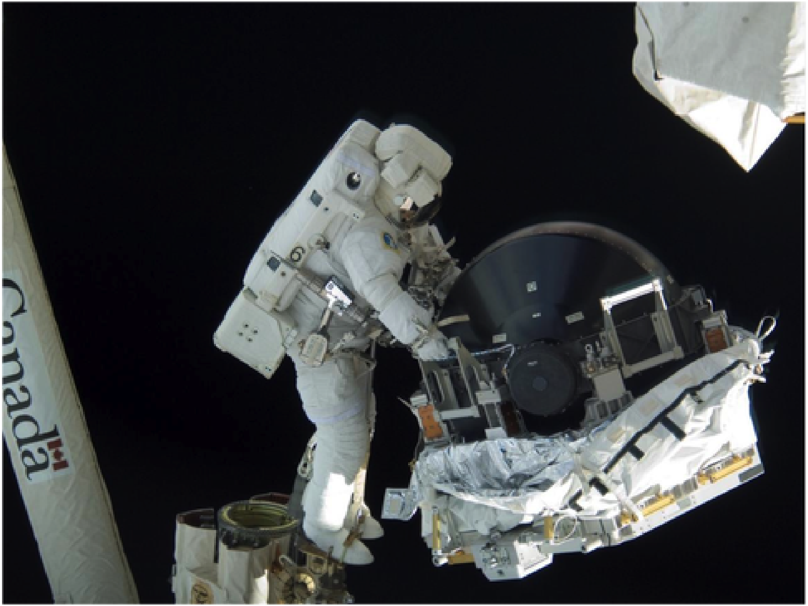

Figure: Cutaway of ISS CMG

The CMGs are double-gimbal, so hardware orientation is not important.

- CMGs are located on Z1 truss.
- CMGs launched with Z1 truss in Oct. 2001.
- Activated Feb 2001 (perviously thrusters were used for attitude)
- CMG1 failed June, 2002 - Replaced Aug, 2005
- Oct. 2006, CMG3 failed (sensor failure?) - replaced Aug. 2007
- Failure possibly due to large gimbal rates during desaturation. Bearing failure.



# Replacement of CMG on the International Space Station



# Control Moment Gyros on the International Space Station

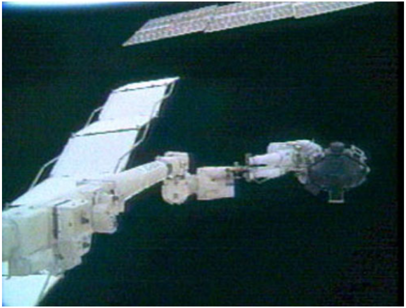
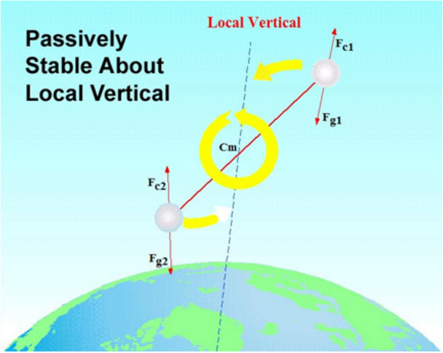


Figure: Replacement of CMG on ISS in 2005 (STS-114)

Gravitational attraction varies as

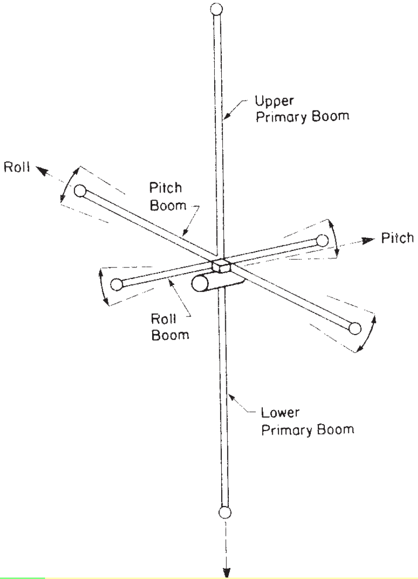
$$\|F\| = \frac{\mu m}{r^2}$$

For very long spacecraft, lower section will feel additional gravitational attraction.



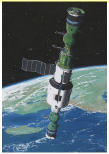
# Mechanisms for Control

## Gravity Gradient Stabilization



# Gravity Gradient Stabilization

## Salyut 6



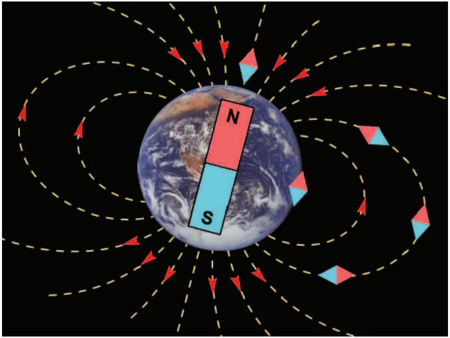
- Any spacecraft will tend to align it minimum moment of inertia axis with the radial vector.
- An extreme case is the use of space tethers (65N on TSS-1R).
  - Failure VERY common due to electrical discharge (TSS-1R), dynamic instabilities.
- ONR TiPS was a successful 4km tether, with lifetime of 10 years.
- TSS-1R failed at 19.7km and produced 15lb force

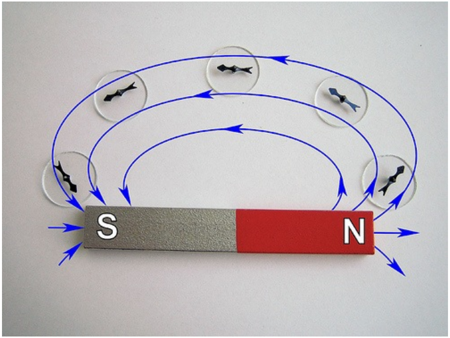
# Magnetic Torquers

In addition to gravity, the **Magnetic Field** of the earth can be used to provide attitude control.

**Idea:** The earth has a magnetic field, $\vec{\mathbf{B}}_e(x, y, z)$.

- the interaction of two magnets produces force




What if we put a magnet on the spacecraft?

- Turn it into a giant flying compass.

# Magnetic Torquers

Instead of using fixed magnets, we use electromagnets to create an arbitrary magnetic dipole moment, $\vec{M}$ for the spacecraft.

Maxwell's Equations lead us to

$$\vec{T} = \vec{M} \times \vec{\mathbf{B}}_e$$

Thus

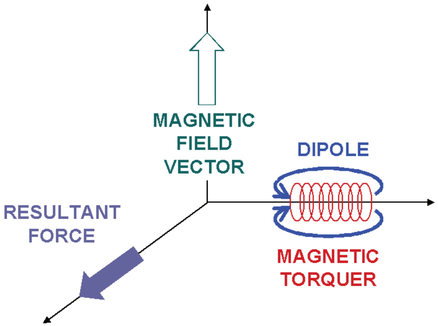
$$\begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} = \begin{bmatrix} 0 & B_z & -B_y \\ -B_z & 0 & B_x \\ B_y & -B_x & 0 \end{bmatrix} \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix}$$

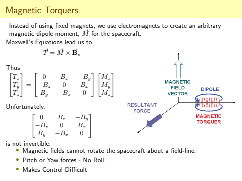
Unfortunately,

$$\begin{bmatrix} 0 & B_z & -B_y \\ -B_z & 0 & B_x \\ B_y & -B_x & 0 \end{bmatrix}$$

is not invertible.

- Magnetic fields cannot rotate the spacecraft about a field-line.
- Pitch or Yaw forces - No Roll.
- Makes Control Difficult






Note how we represent the cross-product as matrix multiplication:

$$\vec{M} \times \vec{\mathbf{B}}_e = \begin{bmatrix} 0 & B_z & -B_y \\ -B_z & 0 & B_x \\ B_y & -B_x & 0 \end{bmatrix} \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix}$$

# Magnetic Torquers

The magnetic dipole moment is created by torque-rods.

Unfortunately the magnitude of the torque is limited by:

- The magnitude of earth's magnetic field is inversely proportional to radius.

$$\|\mathbf{B}_e\| \cong \frac{7.96 \cdot 10^{15} Wb - m}{r^3}$$

- The magnetic dipole of the torque rod ($\|M\| \cong 10Am^2 - 100Am^2$).
- The angle to the field line ($\alpha$).

$$T = \|M\|\|B\| \sin \alpha$$

# Magnetic Torquers

In a 400km orbit with a $100A - m^2$ dipole at $30°$ field orientation, we can obtain a torque of

$$T = \frac{7.96 \cdot 10^{15}}{6778000^3} \cdot 100 \cdot \sin(30°) = 1.28 \cdot 10^{-3} N - m$$

Magnetic Torque is not typically used for active attitude control.

- Used to dump angular momentum over time from
  - Reaction Wheels
  - CMGs
- Combined with momentum wheel for roll-control.

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**Small Satellite ACDS kits:**
http://www.cubesatpointing.com/
https://www.cubesatshop.com/

# Solar Sail Stabilization

## Multi-Functional Transport Satellite (MTSAT)

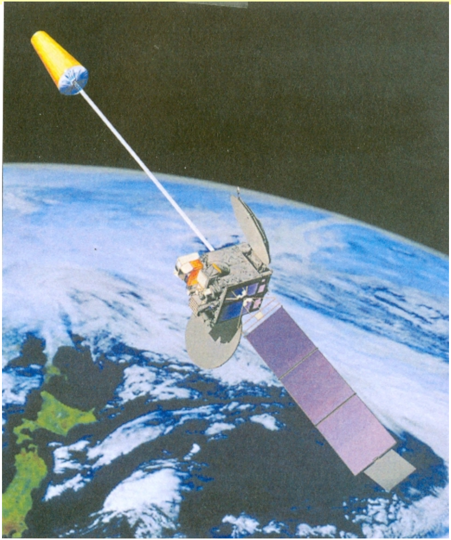


Figure: Japanese Air-traffic Control/Navigation/Meteorology Satellite MTSAT

Solar Sail Stabilization

Multi-Functional Transport Satellite (MTSAT)

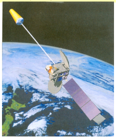


Figure: Japanese Air-traffic Control/Navigation/Meteorology Satellite MTSAT

Solar sails can counteract disturbances.

The rescue mission for the Kepler space telescope was based on combining solar sail (the body) with 2 functioning reaction wheels.

Historically, the most common form of stabilization have been spin stabilization.

**Idea:** Give the craft an angular momentum vector which is fixed in the body-fixed axis.

- Think of rifles vs. muskets

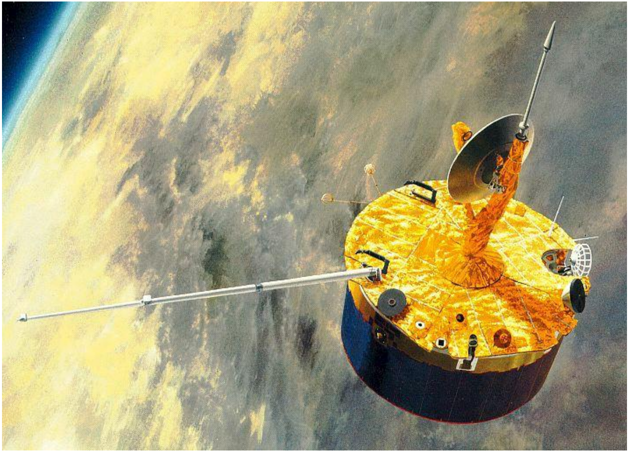
**Positives:**

- By Newton's second Law: A large angular momentum vector requires large torques to change.
- Very little active maintenance required.

**Negatives:**

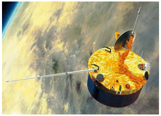
- Spin motion complicates communication, solar power, navigation, etc.
- Changing attitude after spin-up is very difficult.
- Angular momentum vector is not fixed in the body-axes!
  - We will study this issue in more detail.

# Pioneer Venus Orbiter (1978-1992)



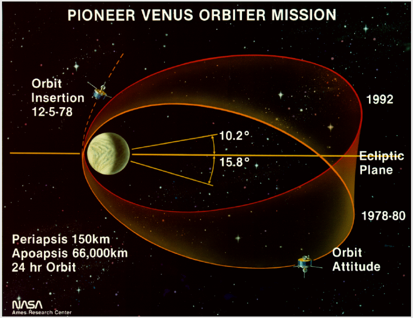
Mapping/Communication. Dual-Spin Stabilized. **Orbit:** Pericytherion: 181.6 km; Apocytherion: 66,630 km; inclination $105°$; 24hr period

Pioneer Venus Orbiter (1978-1992)



Mapping/Communication. Dual-Spin Stabilized. **Orbit:** Pericytherion: 181.6 km; Apocytherion: 66,630 km; inclination $105°$; 24hr period

- Launch May 20, 1978
- Orbit insertion Dec 4, 1978
- Antenna dish was despun to allow contact with earth
- Periapse temporarily raised to 2300km
- Re-entry on Oct 22, 1992
- Orbit change on arrival of Magellan (to observe southern hemisphere)



Spin stabilization can decay.

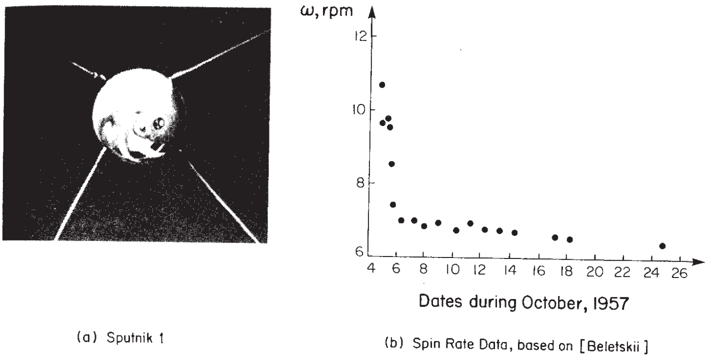



Figure: Decay in Spin Control of Sputnik I Satellite

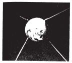
Cause: Atmospheric Motoring

- See Also Explorer 20 and Alouette 1 data

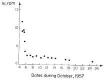
## Mechanisms for Control

### Spin Stabilization

Spin stabilization can decay.



(a) Sputnik 1




(b) Spin Rate Data, based on [Beletskii]

Figure: Decay in Spin Control of Sputnik I Satellite

Cause: Atmospheric Motoring

- See Also Explorer 20 and Alouette 1 data

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- In Modern spacecraft, spin stabilization is typically used at separation from upper stage.
- Spacecraft use yo-yo despin for transition to operational status.

# Conclusion

In this lecture we have covered:

- Mission Requirements
- Forms of Attitude Control

**Next Lecture:**
Equations of Motion

- How to differentiate Vectors in Rotating Frames
- Derivation of the Nonlinear 6DOF Equations of Motion

Euler Angles

- Definition of Euler Angles
- Using Rotation Matrices to transform vectors
- Derivatives of the Euler angles
  - Relationship to $p$-$q$-$r$ in Body-Fixed Frame